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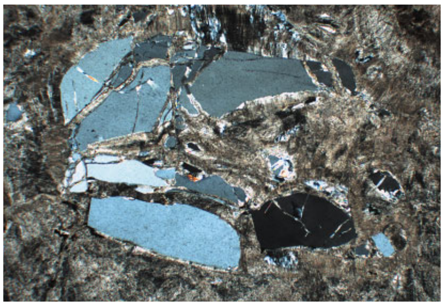
STATE GEOHERITAGE RESERVE R50149 (TRENDALL RESERVE), NORTH POLE, PILBARA CRATON, WESTERN AUSTRALIA — GEOLOGY AND EVIDENCE FOR EARLY ARCHEAN LIFE

by
AH Hickman, MJ Van Kranendonk, and K Grey



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State Geoheritage Reserve R50149 (Trendall Reserve), North Pole, Pilbara Craton, Western Australia — geology and evidence for early Archean life

by

AH Hickman, MJ Van Kranendonk and K Grey

Abstract

State Geoheritage Reserve R50149, also known as the Trendall Reserve, was established by the Government of Western Australia to preserve geological features of exceptional national and international significance. This and five other reserves cover some of the world's most important early Archean stromatolite and microfossil sites in the Pilbara Craton. Since the discovery of fossil stromatolites in the Trendall Reserve was reported in 1999, the North Pole area has been the focus of many field excursions by scientists and documentary-makers from Australia and overseas.

Within the Trendall Reserve, the initial discovery site, now known as the 'Trendall locality', reveals a diverse assemblage of stromatolites and sedimentary facies preserved in carbonate rocks of the 3426–3350 Ma Strelley Pool Formation. Stromatolites are laminated organo-sedimentary structures built by microorganisms, predominantly cyanobacteria, although for Archean stromatolites the role of cyanobacteria in relation to other bacteria and archea is unclear.

Detailed examination of Archean fossil stromatolites can provide key evidence on the origin of life as well as on ancient depositional environments. Modern stromatolites occur in diverse forms and inhabit a range of environments including shallow-water marine, lacustrine, and hydrothermal hot-spring settings. In the Proterozoic, stromatolites were much more morphologically diverse and widespread and were established in many niches that today are occupied by other organisms. However, fossil stromatolites are rarely preserved in early Archean rocks, and this makes the few outcrops that do contain them especially important. Stromatolites at the Trendall Reserve are particularly significant because their complex morphologies demonstrate that even some of the oldest known Archean stromatolites were not simple structures.

This Record reviews previous research on the Strelley Pool Formation of the Trendall Reserve, and discusses the significance of the findings in relation to the regional geology of the Pilbara Craton. Local background information, a geological review, and a detailed description of the Trendall locality, are also provided.

KEYWORDS: Trendall Reserve, Trendall locality, stromatolites, origin of life, carbonate rocks, North Pole, Pilbara Craton, Archean, Strelley Pool Formation, field excursions

Introduction

Evidence for the earliest life on Earth is restricted to a relatively small number of outcrops of Archean sedimentary and volcanic rocks worldwide, and some of the most important of these are located in the Pilbara region of Western Australia. In April 2009, the significance of one Pilbara site, named the Trendall locality after its discoverer AF Trendall, was acknowledged by the establishment of State Geoheritage Reserve R50149, also referred to as the Trendall Reserve (Grey et al., 2010). This reserve, located in the North Pole Dome area of the East Pilbara Terrane (Figs 1, 2), covers a 2.5 km^2 area of outstanding geoscientific and geoheritage significance that contains some of the world's most abundant and best preserved evidence for early life on Earth (Hofmann et al., 1999; Hofmann, 2000; Grey et al., 2002; Allwood et al., 2006a; Van Kranendonk, 2007).

Regional setting of the Trendall Reserve

The Trendall Reserve is situated in the North Pole Dome in the centre of the East Pilbara Terrane of the Pilbara Craton (Figs 1 and 2). Understanding the geological setting of the Trendall Reserve is important to understanding the full significance of its fossiliferous outcrops. Although the sedimentary facies in the reserve are broadly analogous to facies of modern depositional environments, the tectonic setting of the entire succession of the East Pilbara Terrane, the Pilbara Supergroup (Fig. 3), has no close modern

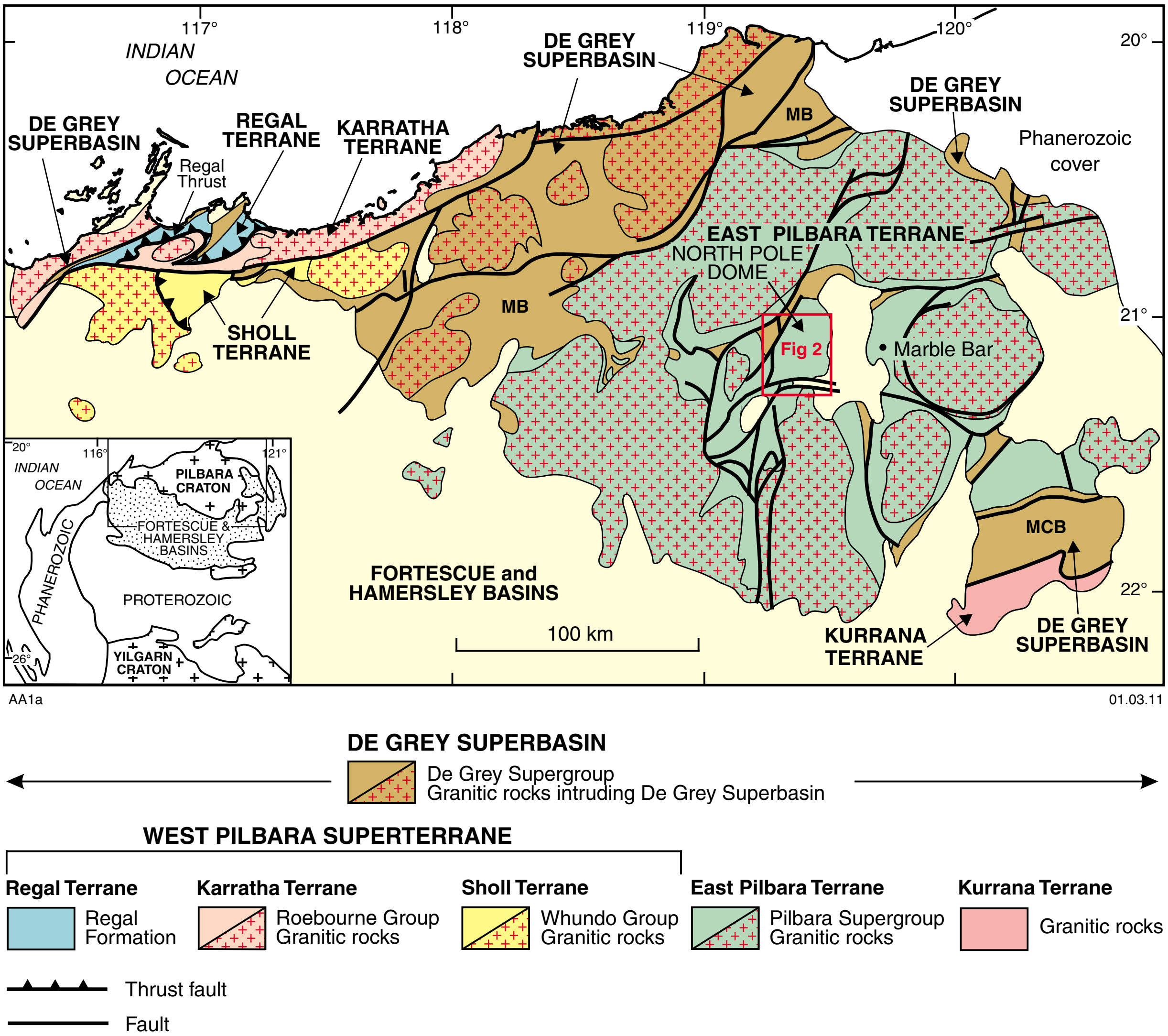

Figure 1. **Simplified geological map of the Pilbara Craton, showing the location of the North Pole Dome within the East Pilbara Terrane. MB — Mallina Basin; MCB — Mosquito Creek Basin**

analogues. The most obvious evidence for this is the distinctive regional outcrop pattern of the East Pilbara Terrane (Fig. 1). The 40 000 km^2 area of the terrane is composed of ten major granite–greenstone domes separated by faults (Hickman and Van Kranendonk, 2004). The only geodynamic process to satisfactorily explain all features of these major structures is partial convective overturn of upper and middle crust, involving diapiric doming (Hickman, 1984; Collins, 1989; Hickman and Van Kranendonk, 2004; Van Kranendonk et al., 2004a, 2007a,b). This process took place over 300 million years (3525–3225 Ma; Hickman and Van Kranendonk, 2008), and produced the environments in which early life evolved.

The geological succession of the Trendall Reserve represents part of the Pilbara Supergroup (Fig. 3). The Pilbara Supergroup is 15–20 km thick in most greenstone belts of the East Pilbara Terrane, and is composed of three volcanic groups and one sedimentary formation (Hickman, 2011). The Strelley Pool Formation (Hickman, 2008) is the host unit of the fossils in the Trendall Reserve, and separates the Warrawoona Group from the Kelly Group across a regional unconformity. The stratigraphic succession of the North Pole Dome (Fig. 2) lies within the Panorama greenstone belt (Van Kranendonk et al., 2002), and is metamorphosed only to prehnite–pumpellyite facies (Terabayashi et al., 2003; Van Kranendonk and Pirajno, 2004). This relatively low metamorphic grade, which is partly due to limited granitic intrusion of the North Pole Dome, accounts for the exceptionally good preservation of the rocks and fossils in the area.

Importance of the Trendall Reserve

The Trendall Reserve contains some of the world's best fossil evidence for ancient life on Earth. This evidence is provided by fossil stromatolites, laminated organo-sedimentary structures built by the activities of microorganisms, predominantly cyanobacteria, and possibly other microorganisms such as other bacteria, archea, and algae (Awramik et al., 1976). Stromatolites are widespread throughout Earth's geological record from the Neoarchean onwards, but Paleoarchean stromatolites such as those in the Trendall Reserve are very rare, and where they do occur they are commonly far less well preserved than much younger stromatolites. A few researchers (Lowe, 1994; Grotzinger and Rothman, 1996; Lindsay et al., 2003a,b, 2005; Brasier, 2009; Wacey, 2009; Wacey et al., 2006, 2010) have suggested that the Paleoarchean stromatolites of the Pilbara are non-biological in origin, and were formed as purely physical structures such as ripple marks or as shapes produced by chemical precipitation. Certainly, a minority of the Paleoarchean stromatolites in the Trendall Reserve grew on top of pre-existing structures such as ripple marks or crystal mounds (Allwood et al., 2009), a situation also present in some of the world's Proterozoic stromatolites. However, detailed observation can generally distinguish stromatolites from non-biogenic structures, and this Record reviews a range of criteria showing that many of the stromatolites in the Trendall Reserve have morphologies characteristic of a biological origin, and broadly similar to various Proterozoic stromatolites. Almost all researchers who have examined the best preserved stromatolites in situ within the Trendall Reserve have concluded that their biogenicity is beyond reasonable doubt (Hofmann et al., 1999; Hofmann, 2000; Allwood et al., 2006a,b, 2007a,b, 2009; Van Kranendonk, 2007, 2011).

Although the rock outcrops in the Trendall Reserve are now internationally famous for their Paleoarchean stromatolites, additional fossil evidence for ancient life is also starting to emerge from this area. Sugitani et al. (2010) reported putative microfossils in the Strelley Pool Formation very close to the northern boundary of the Reserve, and it seems probable that further investigation will reveal that microfossils are more widely preserved in the formation. The discovery of structures interpreted to be microbial mats at the Trendall locality (Van Kranendonk and Nijman, 2001; Allwood et al., 2009) suggests that microfossils should be widely present. Putative microtubular trace fossils (ichnofossils) have been described from the Euro Basalt that stratigraphically overlies the Strelley Pool Formation (Banerjee et al., 2007).

The geoheritage significance of stromatolitic carbonate and chert units in the Trendall Reserve was first outlined by Grey et al. (2002), who based their assessment on work by Hofmann et al. (1999), Hofmann (2000), and Van Kranendonk (2000). Extensive research since 2002 has confirmed the importance of the Trendall locality, which is a relatively small outcrop of carbonate rocks, chert, conglomerate, and volcaniclastic rocks within the larger area of the Trendall Reserve. This locality has become the most visited and studied stromatolite site in the Pilbara (a summary of research is provided in this Record). Several detailed investigations (Hofmann et al., 1999; Van Kranendonk and Nijman, 2001; Van Kranendonk et al., 2003; Brown et al., 2004, 2006; Allwood et al., 2006a, 2007a,b, 2009, 2010; Marshall et al., 2007; Grey, 2008; Van Kranendonk, 2011) have been undertaken.

Older stromatolites are present in the nearby c. 3480 Ma Dresser Formation (Figs 2, 3) but the 3426–3350 Ma stromatolites within the Trendall Reserve are more numerous, more morphologically diverse and complex, and individual biostromes extend beyond the Reserve over a strike length of at least 10 km. The host formation of the stromatolites in the Trendall Reserve, the Strelley Pool Formation, outcrops throughout many greenstone belts of the East Pilbara Terrane (Hickman, 2008), and several other sites containing stromatolites have been documented (Hickman, 1980; Lowe 1980, 1983; Zegers, 1996; Van Kranendonk and Johnston, 2009).

The Trendall Reserve is also important for the evidence it contributes to knowledge of early Archean crustal evolution in the Pilbara Craton. The Strelley Pool Formation is a sedimentary formation that separates two major volcanic groups, the 3525–3427 Ma Warrawoona Group and the 3350–3315 Ma Kelly Group (Figs 3, 4). It provides a 75 million-year record of deposition across at least 30 000 km^2 of the East Pilbara Terrane. Some of the most complete exposures of the Strelley Pool Formation, and of the volcanic groups below and above it, are available within the Trendall Reserve. Following detailed investigation of the Strelley Pool Formation, Lowe (1983) described it as 'a unit of fundamental importance for interpreting Archean sedimentation and surficial environments'.

Astrobiology

Part of the impetus for detailed investigation of the Trendall locality, and other fossiliferous sites in the East Pilbara Terrane, has come from the importance of these sites to the relatively new science of astrobiology. Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe, and includes research into the origin, early evolution, and diversity of life on Earth. Early life on Earth may have been similar to any life that once existed on other planets and moons of our solar system. On this basis, Earth's Paleoarchean fossils and their paleoenvironments should provide a guide on how and where to find traces of extinct primitive life elsewhere.

Early investigations of the Trendall locality

AF Trendall

In 1984, AF Trendall, then Director of the Geological Survey of Western Australia (GSWA), discovered what he interpreted to be stromatolitic carbonate rocks on the east bank of the Shaw River (within the area of the Trendall Reserve on Figs 2, 4). This was the first discovery of early Archean stromatolites in the southwestern part of the North Pole Dome, although stromatolites of similar age had already been identified elsewhere in the East Pilbara Terrane (Hickman, 1980; Lowe, 1980; Walter et al., 1980; Schopf, 1983). In September 1984, GSWA palaeontologist K Grey visited the Shaw River area in an

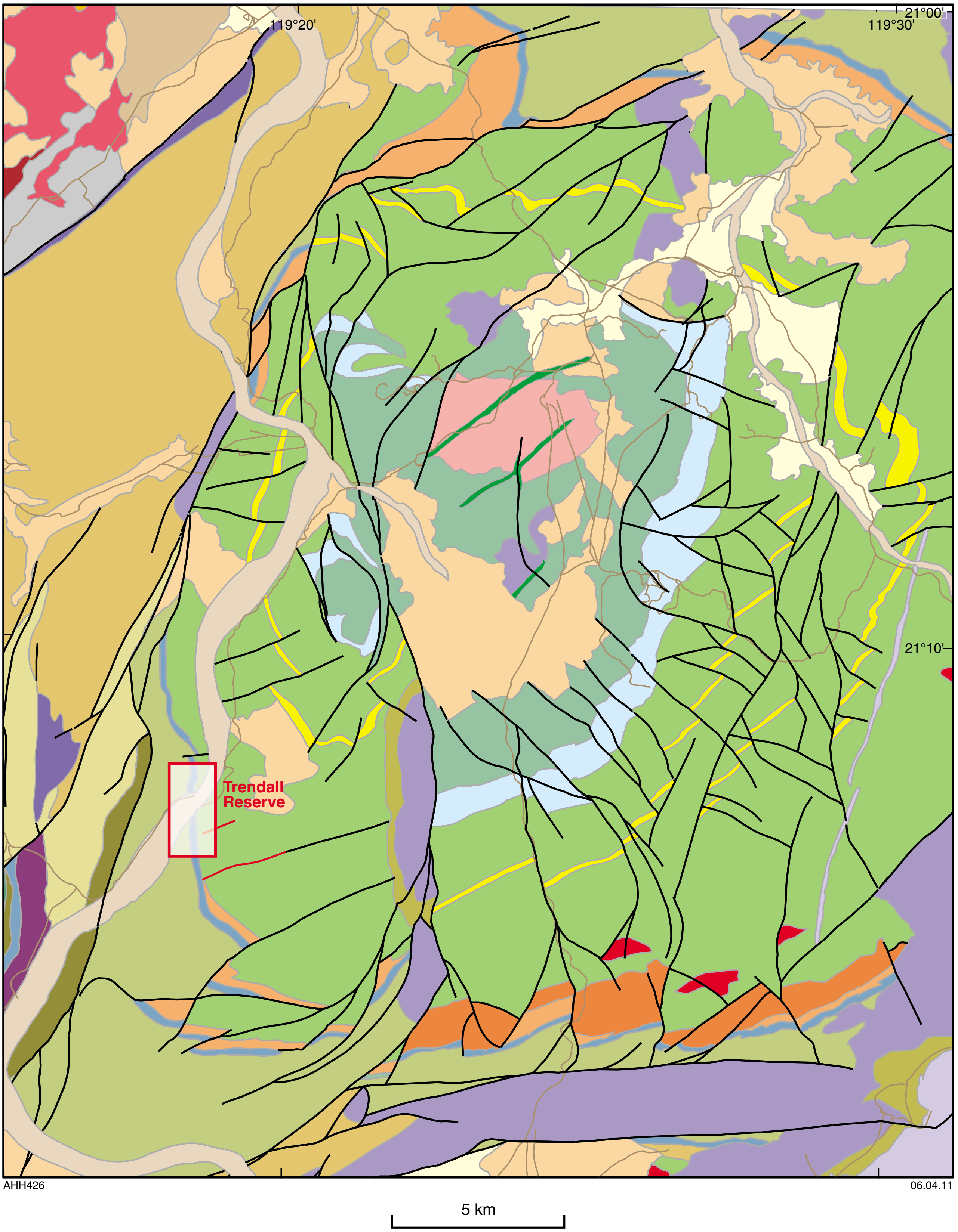

Figure 2. Geological map of the North Pole Dome, showing the location of the Trendall Reserve.

CENOZOIC
Alluvial units: gravel and sand in river channels
Sheetwash units: silt and clay in distal outwash fans
Colluvial units: sand and silt in scree and proximal outwash fans
Residual units: calcrete and silcrete; locally overlain by colluvial units
FORTESCUE GROUP
Dolerite dyke
Kylena Formation: basalt and dolerite dykes
Hardey Formation: sandstone: minor shale
Mount Roe Basalt: basalt
CROYDON GROUP
Lalla Rookh Sandstone: sandstone and conglomerate
GORGE CREEK GROUP
Cleaverville Formation: banded iron-formation
Dalton Suite: mafic and ultramafic intrusive rocks
SOANESVILLE GROUP
Honeyeater Basalt: basalt
Corboy Formation: sandstone, shale, and chert
KELLY GROUP
Euro Basalt: basalt
STRELLEY POOL FORMATION
Sandstone, chert, and carbonate rocks
WARRAWOONA GROUP
Panorama Formation: felsic volcanic rocks, sandstone, and chert
Duffer Formation: felsic volcanic rocks and chert
Mount Ada Basalt: basalt
Antarctic Creek Member: sandstone and chert
Dresser Formation: chert and basalt
North Star Basalt; basalt
Coucal Formation: felsic volcanic rocks and chert
Double Bar Formation: basalt
GRANITIC ROCKS (VARIOUS AGES)
Tambina Supersuite: tonalite and granodiorite; includes dykes
North Pole Monzogranite: biotite monzogranite
Callina Supersuite: tonalite and granodiorite

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attempt to confirm the biogenicity of the stromatolites, but she was unable to relocate the site. Trendall re-visited the outcrops in 1987 and 1988, and then again in an important fourth visit in October 1990. On this occasion, Trendall was accompanied by RT Thorpe (a geochronologist with the Geological Survey of Canada) and GSWA geologist AH Hickman, who mapped the regional geology of the area in 1972 (Hickman and Lipple, 1975). At the site later to become known as the 'Trendall locality' (Grey et al., 2002), the group examined the carbonate platform that Trendall had previously observed to contain *Conophyton*-like structures. These structures are not exposed in three dimensions, and various alternative origins, including soft-sediment deformation and chevron folding, were considered. The group then discovered smaller conical structures in adjacent outcrops of chert (silicified carbonate rocks). These had similar cross-section profiles to the structures on the carbonate platform, but they were unlike any known fold structures. On his return to Canada, Thorpe provided photographs of the outcrops to HJ Hofmann (a leading authority on stromatolites with the Department of Geology, University of Montreal). Hofmann discussed the photographic evidence with Grey, and they decided that a more detailed field investigation was required.

HJ Hofmann

In 1997, Hickman took Hofmann and Grey to the Trendall locality. The group quickly established that the stratigraphic unit (Strelley Pool Formation) containing the stromatolite-like structures had a considerable strike length, outcropping in the chert ridges on both banks of the Shaw River. They found considerable evidence to support a biogenic interpretation for the large conical structures, including observing short sections of three-dimensional preservation around the axis that demonstrated a conical shape, the steepness of the cones being much greater than the angle of repose, and the presence of adventitious (developed in an unusual place and subsidiary to the main structure) columns on the flanks of the cones. During this visit, they excavated a bedding plane containing numerous well preserved and closely spaced small conical stromatolites, about 10 cm in height (Hofmann et al., 1999, fig. 2d); these have since become known as the 'egg-carton' stromatolites (Fig. 5). The three-dimensional preservation of these structures left little doubt that they were conical. It is difficult to produce cones naturally without biological processes being involved (Batchelor et al., 2004; Petroff et al., 2010), so the party concluded that there was convincing evidence that the structures were microbialites. Following the 1997 field investigation, and subsequent laboratory work, Hofmann et al. (1999) and Hofmann (2000) concluded that the coniform stromatolites at the Trendall Locality were most probably formed by microbial accretion, similar to processes that formed much younger stromatolites. They concluded that the site was exceptionally important because of the excellent preservation of its stromatolites compared to stromatolites of similar Archean age elsewhere in the Pilbara.

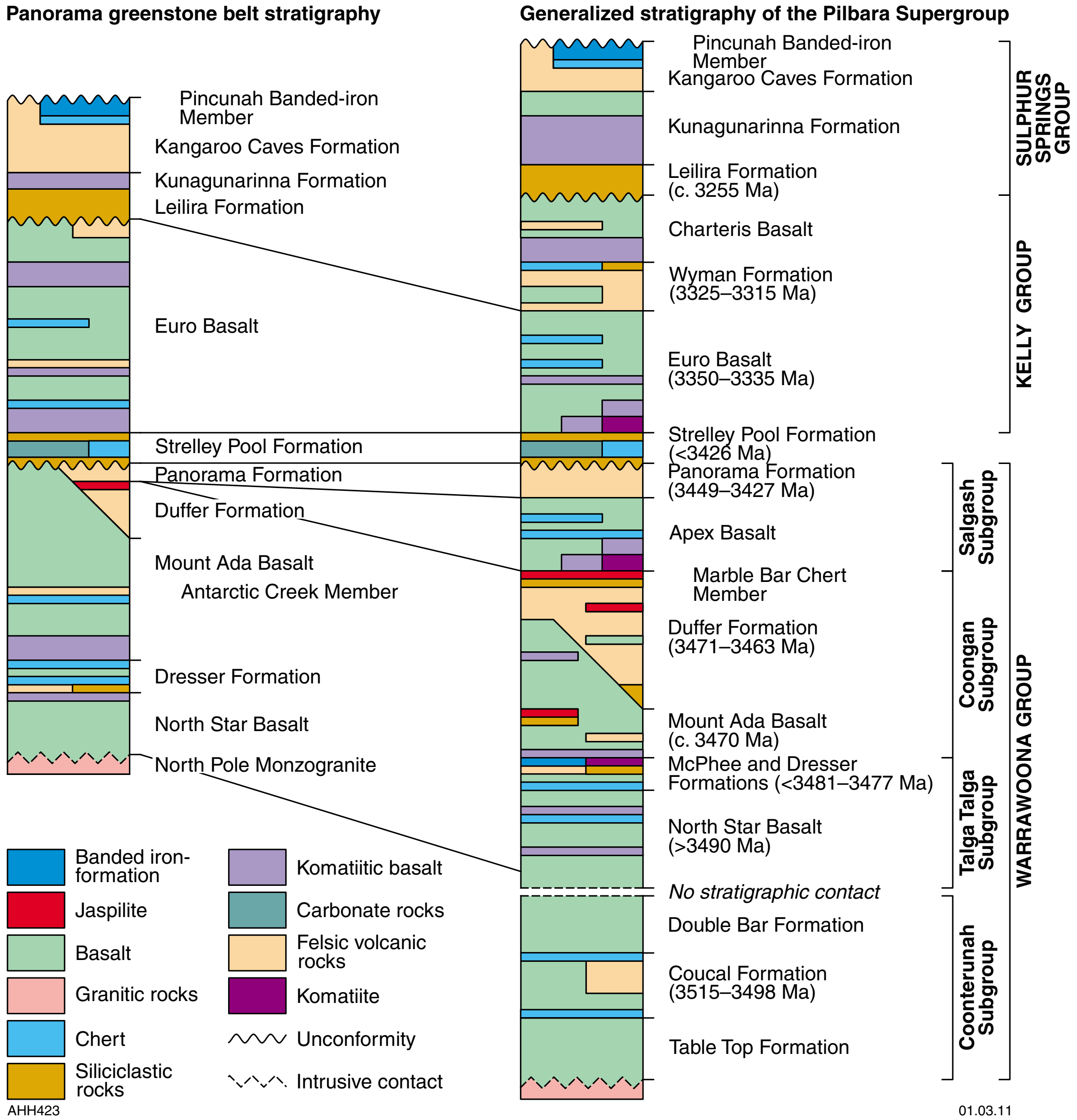

Figure 3. Stratigraphy of the Pilbara Supergroup within the Panorama greenstone belt (left), compared to the generalized stratigraphy of the entire East Pilbara Terrane (right).

International authorities on early life

Between 29 June and 6 July 1999, a field excursion to Archean stromatolites sites of the east Pilbara was attended by an invited group of ten international authorities on early life. The purpose of the excursion was to obtain objective scientific opinion on the biogenicity of the stromatolites at all the sites visited, and to witness the collection of a 1 m-long slab of chert containing the 'egg-carton' stromatolites discovered at the Trendall locality in 1997 (see above). This slab contained exceptionally well preserved conical stromatolites that in the opinion of GSWA and Hofmann needed to be protected from damage or complete destruction by future casual or commercial collectors. The plan was to document the setting of the 'egg-carton' stromatolites before the slab was removed for its relocation to the WA Museum in Perth.

Leaders of the excursion were K Grey, AH Hickman, MJ Van Kranendonk, IR Williams (all from GSWA), and HJ Hofmann (University of Montreal). The Director and Assistant Director of GSWA also attended parts of the excursion. A workshop immediately preceding the field excursion included introductory presentations by Grey, Hickman, and Van Kranendonk (GSWA), Hofmann (Department of Geology, University of Montreal), DJ Des Marais (Ames Research Center, Moffett Field, California), JW Schopf (Department of Earth and Space Sciences, University of California, Los Angeles), and MG Sommers and SM Awramik (Department of Geological Sciences, University of California, Santa Barbara).

The final site visited on the stromatolite excursion was the Trendall locality, where the group spent three days studying the outcrops for evidence on the biogenicity

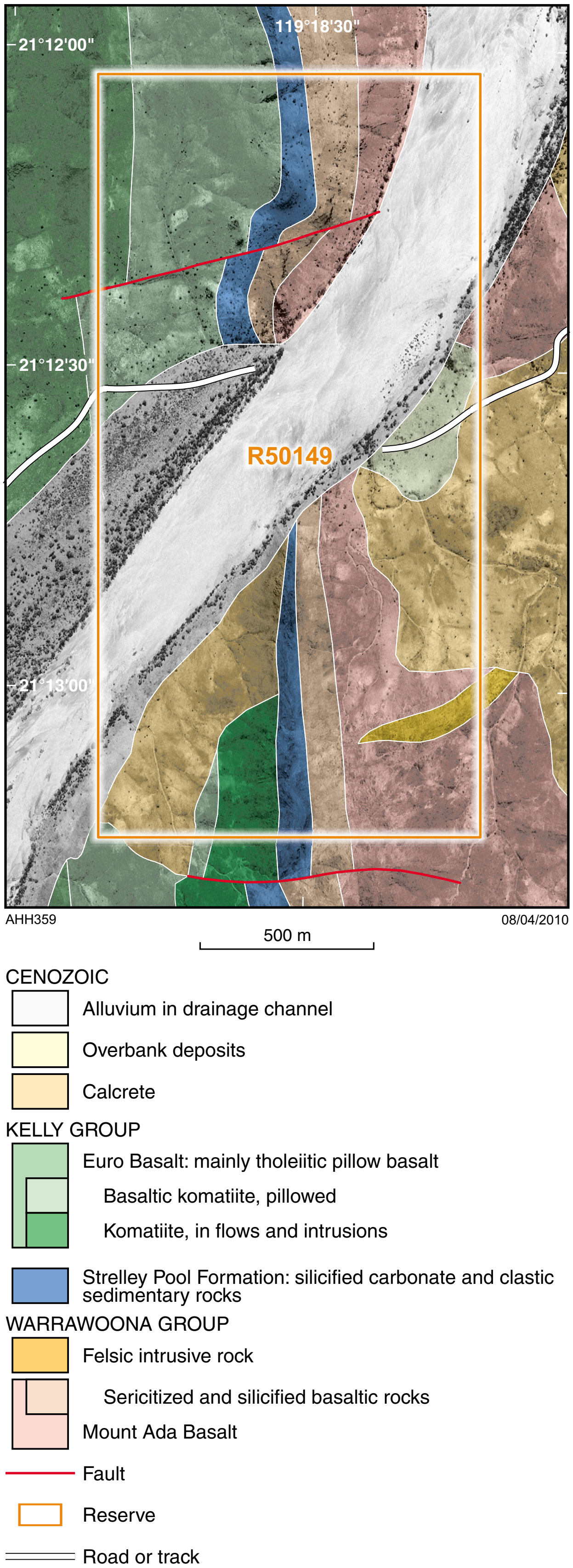

Figure 4. Geological map of the Trendall Reserve, State Geoheritage Reserve R50149 (from Grey et al., 2010).

and depositional environment of the stromatolites. This detailed inspection and assessment was filmed for the ABC Quantum program, and extracts from the filming, including on-site interviews with several of the participants, were televised a few months later. The consensus reached was that the field evidence supports microbially mediated accretionary growth as the process for the formation of the conical, columnar, and domal stromatolites at the Trendall locality. Evidence for hypersalinity of the depositional environment included dolomite or ankerite pseudomorphs, probably replacing gypsum crystal rosettes, and wavy laminated rocks possibly formed by the transformation of anhydrite to gypsum.

The visit by international authorities and the attendant publicity established the Trendall locality as one of the most significant early life locations so far discovered and paved the way for a flood of investigations (see below).

GSWA 1:100 000-scale mapping

The Trendall Reserve is located on the North Shaw 1:100 000 geological sheet, which was mapped by the Australian Geological Survey Organization (AGSO, now Geoscience Australia) and GSWA between 1994 and 1998 (Van Kranendonk, 1999). Based on this work, Van Kranendonk (2000) provided a description of the Shaw River outcrops of the Strelley Pool Formation within the Reserve, including additional photographs of the stromatolites and stratigraphic sections measured on both sides of the river (Van Kranendonk, 2000, fig. 15, columns 3 and 4). His observations included: a) the Strelley Pool Formation is between 24 and 28 m thick, and commences with a basal conglomerate that overlies silicified and sericitized mafic volcanic rocks; b) stromatolites and evaporites occur at several different stratigraphic levels in the chert and laminated carbonate layers of the lower half of the formation; c) a unit of conglomerate is present 6 m to 10 m from the top of the formation; d) green chert and volcaniclastic mudstone and siltstone form the uppermost part of the formation beneath the overlying Euro Basalt. In 2000, the altered mafic

Figure 5. Field photograph of examples of the 'egg carton' stromatolites at the Trendall locality. Scale: lens cap, 6 cm diameter (this slab is now housed in the Western Australian Museum).

volcanic rocks underlying the Strelley Pool Formation were interpreted to belong to the 3460–3450 Apex Basalt, but subsequent geochronology indicates that these underlying rocks in fact belong to the c. 3470 Ma Mount Ada Basalt (Van Kranendonk et al., 2006a).

Van Kranendonk and Nijman (2001) provided a description of the Trendall locality in a field guide for an excursion through the East Pilbara Terrane. This account included a detailed sedimentary facies map of the rock pavements at the site, and a description of the stromatolite types. The dominant stromatolite morphology recognized was coniform and slightly elliptical, with individual structures reaching up to 1 m in height. Another morphology was described as rounded branching columns, generally on the sides of larger domal stromatolites.

Another significant feature of the Trendall locality described by Van Kranendonk and Nijman (2001) was the widespread intrusion of the carbonate rocks by veins of black chert that were demonstrably associated with silicification of the carbonate rocks. Van Kranendonk and Nijman (2001) interpreted the black chert veins as syndepositional with deposition of the Strelley Pool Formation, partly because the veins had not been observed above or below this formation, and partly because clasts of black chert were present in the lowest conglomerate unit of the upper clastic part of the Strelley Pool Formation. Veins of black chert were also present in the upper clastic member of the formation. These observations led Van Kranendonk and Nijman (2001) to conclude that the Strelley Pool Formation was partly hydrothermal in origin, as discussed below.

Research on the Trendall Reserve

Background

Until publication of the papers by Hofmann et al. (1999) and Hofmann (2000), the existence of the Trendall locality was not generally known. From 1999 onwards, a number of field excursions were run to the Trendall locality, and there was considerable media coverage of the geoscientific and geoheritage importance of the site. This importance was not limited to obtaining a better understanding of early life on Earth, but also included the potential value of the site to astrobiology. Consequently, a number of research projects were developed to examine a range of issues.

Hydrothermal models

The first question to be addressed by research in the Trendall Reserve was the depositional environment of the Strelley Pool Formation. Following sedimentological evidence from Lowe (1980, 1983) and DiMarco and Lowe (1989), the preferred depositional model was a regionally extensive shallow-water marine basin that included evaporites. However, this established interpretation was seriously questioned when it was proposed that the Strelley Pool Formation was partly hydrothermal in origin (Van Kranendonk, 2001; Van Kranendonk and Nijman, 2001). This alternative model was consistent with the stratigraphic interpretation, current at that time, that the Strelley Pool Formation was conformable on the felsic volcanics of the Panorama Formation (Van Kranendonk et al., 2001, 2002). In the hydrothermal model, the depositional environment was interpreted as a series of caldera lakes developed on the cooling, but still hydrothermally active, volcanic pile of the Panorama Formation. This new hydrothermal model had major implications for using the stromatolites of the Strelley Pool Formation as reference material in astrobiological research. For example, Van Kranendonk and Nijman (2001) considered that at the Trendall locality there was a close spatial relationship between stromatolite growth and the location of the hydrothermal chert veins interpreted as filling hydrothermal vents. This led them to suggest that the stromatolites were produced by thermophilic organisms, and that the depositional environment was probably an alkaline caldera lake fed by swarms of hot springs. In this scenario, they suggested that hydrothermal circulation could have been driven by heat from the North Pole Monzogranite.

A hydrothermal origin for the carbonate rocks of the Strelley Pool Formation was subsequently tested and abandoned by Van Kranendonk et al. (2003) based on REE+Y patterns that indicate a normal marine origin (see below). Additional evidence inconsistent with the hydrothermal model was provided when Bagas (2003) reported an erosional contact between the Strelley Pool Formation and the Panorama Formation in the Kelly greenstone belt. Subsequent work has confirmed that the Panorama Formation and the Strelley Pool Formation are separated by a regional unconformity (Van Kranendonk et al., 2006b; Hickman, 2008).

Lindsay et al. (2003b, 2005) interpreted the bedded carbonates of the Strelley Pool Formation in the East Strelley greenstone belt as hydrothermal deposits. One of their arguments was that a number of silica and carbonate veins underlying the formation represent the remnants of conduits for hydrothermal fluids from underlying volcanic and granitic rocks. However, the observation that many of the veins intrude through the entire thickness of the Strelley Pool Formation (Van Kranendonk et al., 2003; Van Kranendonk, 2006a) argued against this interpretation. The proposed hydrothermal origin for the Strelley Pool Formation was rejected by Hickman (2008) because the underlying granitic and volcanic rocks in the East Strelley greenstone belt had already been deformed, metamorphosed, and eroded before the Strelley Pool Formation was deposited. Based on a detailed study of the Strelley Pool Formation in the East Strelley greenstone belt, Wacey et al. (2010) also rejected the hydrothermal model, noting that the silica veins which underlie the formation are far too thin and limited in extent to have been conduits for hydrothermal deposition of the formation.

Carbonate geochemistry

Van Kranendonk et al. (2003) tested the hydrothermal model for the carbonates of the formation using REE+Y data from samples collected at and near the Trendall

Locality, and also from the western part of the East Strelley greenstone belt where Lowe (1983) reported coniform stromatolites. They found that the REE+Y patterns for carbonates of the Strelley Pool Formation are similar to those of modern seawater, and that the REE+Y patterns for stromatolites of the formation firmly refute a hydrothermal origin. Subsequently, Allwood et al. (2010) reported on REE+Y patterns in both the carbonate and chert units of the Strelley Pool Formation and in chert of formations underlying the unconformity. They found that the 'stromatolite reef' carbonate facies of the formation has REE+Y patterns similar to other Archean marine precipitates, but that chert in the volcaniclastic facies near the top of the formation shows patterns indicative of precipitation from hydrothermal and mixed marine-hydrothermal fluids. This feature is consistent with the upper part of the Strelley Pool Formation being deposited in a different environment from that of the underlying carbonate and siliciclastic facies of the formation. The change from a marine to mixed marine-hydrothermal environment occurs above an erosional surface that is overlain by boulder conglomerate.

Hyperspectral mapping

Evidence on the limited degree to which hydrothermal fluids contributed to the deposition of the lower and central stratigraphic levels of the Strelley Pool Formation was obtained from a hyperspectral mapping project across the North Pole area (Brown et al., 2004, 2006; Brown, 2006). Brown et al. (2006) used the hyperspectral data to interpret intense hydrothermal alteration of the paleosurface that immediately underlies the unconformity at the base of the Strelley Pool Formation. This alteration produced pyrophyllite in the Panorama Formation and along the contacts of granitic dykes that radiate from the North Pole Monzogranite through the Mount Ada Basalt (Van Kranendonk, 2000). These dykes are truncated by the unconformity at the base of the Strelley Pool Formation, and this formation contains no pyrophyllite. Brown et al. (2006) suggested that the upper part of the argillic alteration zone, which probably included sinters, vents, and exhalative mineralization, was most likely eroded prior to deposition of the Strelley Pool Formation, because none of these features are preserved beneath the unconformity. Van Kranendonk and Pirajno (2004), Brown et al. (2006), and Van Kranendonk (2006a) suggested that silicification of carbonates and clastic rocks in the Strelley Pool Formation was probably part of a low-temperature alteration event related to 3350 Ma eruption of the overlying Euro Basalt.

Stratigraphy, sedimentary facies, and stromatolites

The first geological map of the Trendall locality was compiled by Van Kranendonk and Nijman (2001), and the first stratigraphic sections of the Strelley Pool Formation at the Trendall locality were provided by Van Kranendonk (2000). Based on a more detailed study of the Strelley Pool Formation at Shaw River (Allwood et al., 2004a,b, 2005a,b, 2006a,b), Allwood et al. (2007a, plates 1–5,) illustrated 27 vertical stratigraphic sections along a 10 km strike length of the formation; eleven of these sections are within the Trendall Reserve. Allwood et al. (2007a) documented the spatial and temporal variability of the stromatolites, sedimentary facies, and evidence on depositional environments. Results of the investigation by Allwood et al. (2004a,b, 2005a,b, 2006a,b, 2007a,b) included discovery of a range of stromatolite types throughout the entire 10 km strike length of the study area, and recognition of relationships between stromatolite morphologies and sedimentary facies. One of the findings was that stromatolite diversity and abundance was greatest in those sedimentary facies lacking evidence of any significant hydrothermal, volcaniclastic, or terrigenous input. Allwood et al. (2006a, 2007a) presented strong evidence in support of a biological origin for stromatolites in the Trendall Reserve.

Van Kranendonk (2006b) and Allwood et al. (2007a) subdivided the Strelley Pool Formation of the Shaw River area into four informal members. Allwood et al. (2007a) provided the following description from base to top: Member 1, a basal unit of chert boulder conglomerate with carbonate matrix; Member 2, a laminated chert/carbonate (dolomite) unit with stromatolitic structures and beds of pseudomorphed evaporite crystals; Member 3, a unit of banded black and white chert with laminated iron-rich stromatolitic structures; and Member 4, a clastic to volcaniclastic unit which fines upwards and southwards.

Member 1 was described as a laterally extensive but discontinuous chert boulder conglomerate interpreted as a high-energy, transgressive, rocky coastline deposit. The conglomerate fills relict topography at the lower contact, including paleocliffs, fissures, and cavities (Fig. 6). Bed thickness is highly variable and commonly reflects the size of the largest boulder in the bed. Bed thickness is also controlled by paleotopographic relief of the underlying Warrawoona Group.

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Figure 6. Example of a fissure at the base of the Strelley Pool Formation, showing clastic rocks of the formation penetrating underlying tuffaceous mudstone of the Panorama Formation. Scale card is 18 cm long. From Allwood et al. (2007a)

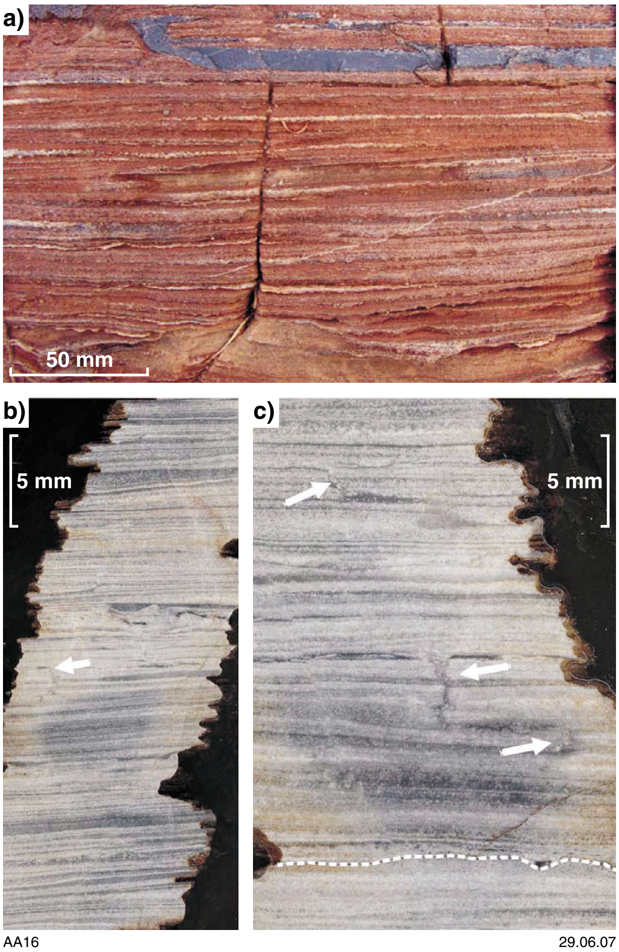

Figure 7. Flat-laminite facies of the Strelley Pool Formation: a) outcrop 2 km north of the Trendall locality; b) and c) cut slabs of the facies showing desiccation cracks (arrows) and grain-size variations between laminae. Lighter laminae are dolostone; darker laminae are chert. From Allwood et al. (2007a)

Member 2 was interpreted as a peritidal carbonate platform succession, consisting of carbonate and chert rocks dominated by a pervasive fabric of rhythmically interlaminated carbonate/chert couplets (Fig. 7). This member contains abundant and diverse stromatolitic facies, including large complex cones (Fig. 8), 'egg-carton' laminite (Fig. 5), and a wavy laminite stromatolite facies (Fig. 9); columnar stromatolites were collected from this horizon by Grey in 1999 (Fig. 10). Member 3 consists of banded black and white chert with up to 15% bundled iron-rich laminae and rare silicified chert-pebble conglomerates and crystal pseudomorph beds. The iron-rich laminae commonly form cm-scale wrinkles, bumps, domes and pseudocolumns, with rare decimetre-scale cuspate domes.

Member 4 was described as a silicified, fining-upward, siliciclastic and volcaniclastic succession that varies greatly in thickness across the map area. The lower half of Member 4 comprises moderately to poorly sorted, granule- to boulder-sized, subrounded to rounded, clast-supported conglomerate composed of chert clasts and sandstone. This grades upward to bedded black (carbonaceous) chert

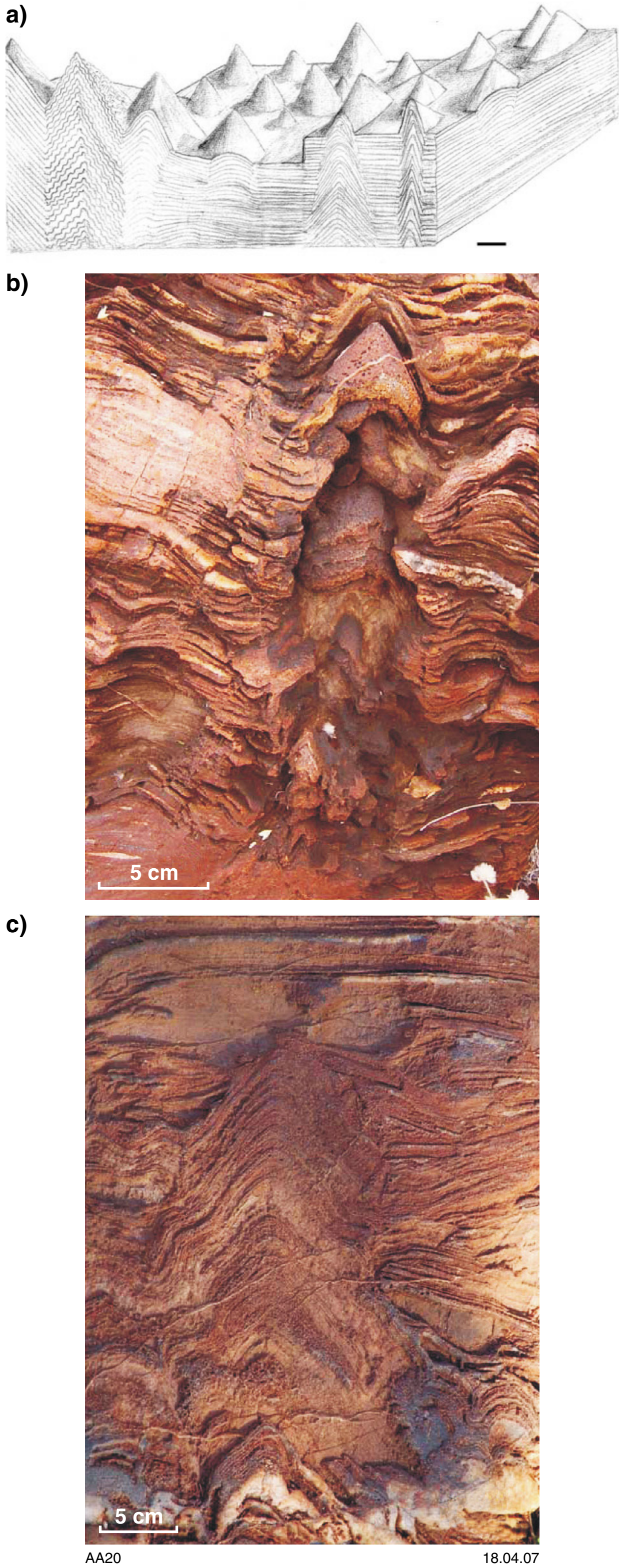

Figure 8. Large complex cones in the stromatolite facies of the Strelley Pool Formation: a) 3D reconstruction; scale bar 5 cm; b) conical stromatolite exposed in relief in an outcrop near the Trendall locality; c) outcrop 4 km north of the Trendall locality showing a cross section through a conical stromatolite. From Allwood et al. (2007a)

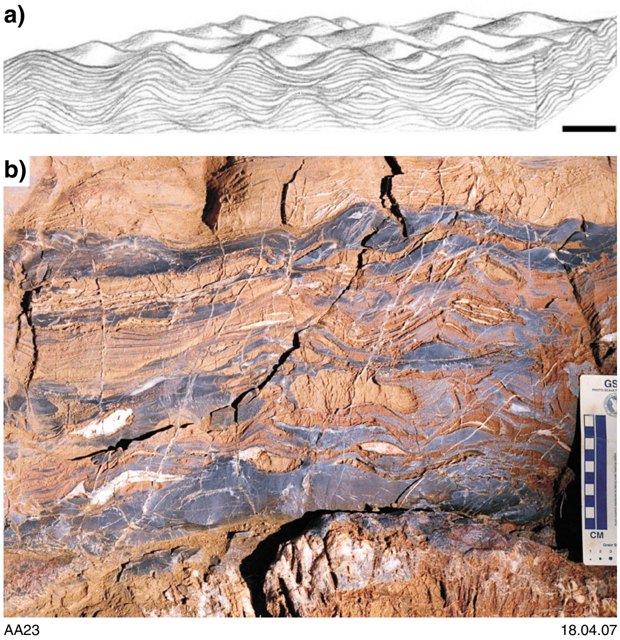

Figure 9. Wavy-laminite stromatolite facies of the Strelley Pool Formation: a) 3D reconstruction; scale bar is approximately 5 cm; b) outcrop showing structures in cross section, partially replaced by black chert and overlying a bed of evaporite crystal pseudomorphs; scale card increments are 1 cm. From Allwood et al. (2007a).

and interbedded, silicified, grey-green volcaniclastic (tuffaceous) mudstone and rare sandstone. Graded bedding is common, and cross-bedding, small channels, and scour structures occur locally.

Van Kranendonk (2007, 2011) documented detailed evidence of stromatolite morphology and the various preserved features that point to a biological origin. Specifically, branching structures, distinct growth walls on domical stromatolite margins, and an interference of stromatolite form with structures produced through current action were cited as key indicators of biogenicity for stromatolites in the lower carbonate member of the formation. Stromatolites were also identified within the siliciclastic upper member of the formation, both as laminar mats and as small domical forms. These latter forms were also shown to contain convincing morphological evidence for a biogenic origin, comparable to modern stromatolites.

Discovery of kerogen

Marshall et al. (2007) reported that samples of bedded black chert collected from the upper part of the Strelley Pool Formation, 500 m north of the Trendall locality, contained kerogen. Most samples came from the upper clastic member above the upper conglomerate, but one sample was collected from black and white bedded chert immediately beneath this conglomerate. The kerogen was reported to be black, consistent with a thermal history exceeding 250ºC, and to occur in clasts and clots mixed with detrital minerals and rock fragments in the chert matrix. The bulk kerogen δ13C values ranged from –28.3 to –35.8‰, and Marshall et al. (2007) commented that the kerogen is depleted in ^{13}C to a degree typically ascribed to biological processes, although they noted that abiotic processes could be responsible. The kerogen was found to be highly aromatic, with bulk atomic H/C ratios ranging from 0.02 to 0.46; for comparative purposes, Marshall et al. (2007) noted that semi-anthracitic coals have H/C ratios of c. 0.05 whereas anthracite has H/C ratios of c. 0.03. One of the most significant features noted by Marshall et al. (2007) was that there are very close similarities between the aliphatic and aromatic product profiles of the kerogen of the Strelley Pool Formation and Mesoproterozoic kerogen of known biological origin.

Microbial mats

Lowe (1983) suggested that the wavy laminated carbonate (or chert, where totally silicified) of the Strelley Pool Formation may represent a bacterial mat community, or even a distinct class of stromatolites, but he subsequently recanted this interpretation (Lowe, 1994). Van Kranendonk (2000) interpreted the wavy lamination in chert of the formation to have originated by the diagenetic transformation of bedded anhydrite to gypsum, a process involving significant volume gain. Van Kranendonk and Nijman (2001) described ‘stromatolite mats’ in the upper clastic member of the Strelley Pool Formation. The mats were described as forming 2–5 mm-thick layers of blue-black chert, in which a wavy laminite structure defined by carbonaceous material and sand grains is well preserved. This carbonaceous clastic rock closely resembles samples from the same stratigraphic level in which Marshall et al. (2007) reported kerogen of probable biological origin (see above).

Allwood et al. (2009) reported microscopic evidence suggesting microbial mat surfaces played a key role in the formation of the stromatolites of the Strelley Pool

Figure 10. GSWA sample 139009 from the Trendall Reserve. Two elongate branches (centre and right) developed from a flat-laminated base. Columns up to 15 cm high with convex to steeply convex laminae. A poorly developed cone (centre left) is partially contiguous with the centre column and another slightly sinuous branch is present on the far left.

Formation. In domical stromatolites, they observed discrete layers of organic material at regular intervals through the structures. An absence of thickening of these layers in topographic lows was interpreted as evidence of adhesion of the organic material to the steep sides of the domes. Variable stromatolite morphology was interpreted to partly reflect differences in the proportions of microbial mat formation relative to other processes of deposition, and morphological diversity was therefore not necessarily evidence of biodiversity. Allwood et al. (2009) also observed that most stromatolites appeared to have commenced development on elevated features such as intraclasts, cobbles, boulders, ripple crests, or mounds, suggesting microbial selection of microenvironments with least clastic deposition.

Paleosol?

Since Buick et al. (1995) first recognized the existence of a major erosional unconformity beneath the Strelley Pool Formation in the East Strelley greenstone belt, several researchers have examined the underlying rocks for evidence of a Paleoarchean paleosol. In 2004, geoscientific drilling in the East Strelley greenstone belt as part of the Archean Biosphere Drilling Project (ABDP) provided an intersection of the unconformity at a depth of 174 m. Altinok and Ohmoto (2006) reported that sericitization and silicification extends for an interval of 20 m beneath the unconformity and, although some evidence of hydrothermal alteration was observed, they interpreted most features of the alteration to be consistent with the profile of an Archean paleosol. In the area of the Trendall Reserve, Ohmoto et al. (2006) reported numerous iron-rich pods (mainly composed of hematite, pyrophyllite, and sericite) in the pyrophyllite alteration zone in basalt beneath the unconformity. They argued that the presence of clasts of pyrophyllite- and hematite-rich rock in the conglomerate at the base of the Strelley Pool Formation was evidence that the alteration pre-dated the unconformity, and therefore could not be hydrothermal alteration resulting from heating during deposition of the overlying Euro Basalt (Van Kranendonk and Pirajno, 2004). They discounted the possibility that the iron-rich pods might be oxidized sulfide or siderite deposits because in all areas they are restricted to approximately the same depth (20 m) beneath the unconformity and because there are very few veins of quartz, sulfide or carbonate close to the pods. Ohmoto et al. (2006) concluded that the alteration zone beneath the unconformity was formed by >3430 Ma lateritic soil-forming processes.

Johnson et al. (2008, 2009) reported that geochemical data from beneath the unconformity, over a strike length of 120 km, are similar to data from the c. 2200 Ma Hekpoort lateritic paleosol in South Africa. If correct, their interpretation would imply that formation of the alteration profile beneath the unconformity involved Archean microbial activity, and that that there was oxygen in the Archean atmosphere at 3430 Ma.

However, the hyperspectral mapping of Brown et al. (2006) established that the pyrophyllite alteration beneath the unconformity is continuous with hydrothermal alteration along the margins of felsic intrusions related to the North Pole Monzogranite, and extends to depths of several kilometres, as indicated by the mapping of Van Kranendonk (2000). Another issue is that the depth extent of the hematite alteration beneath the present land surface needs to be established by deep drilling to discern if the iron alteration may relate to Mesozoic–Cenozoic surficial weathering processes, which are common in the region.

Summary of geology

Lithostratigraphy

Warrawoona Group and regional unconformity

Throughout the East Pilbara Terrane, the contact between the Strelley Pool Formation and the underlying Warrawoona Group varies from an angular erosional unconformity to a paraconformity (Hickman, 2008). The stratigraphic base of the Strelley Pool Formation is exposed at various localities within the Trendall Reserve, and is also exposed in other areas along the Shaw River (Van Kranendonk and Nijman, 2001; Allwood et al., 2007a). Allwood et al. (2007a) described the basal contact of the Strelley Pool Formation in this area as ‘mainly paraconformable or conformable’, but noted that the underlying rocks vary along strike and that the nature of the contact also varies between areas. Plate 1 of Allwood et al. (2007a) indicates that within the central part of the Trendall Reserve, at the Trendall locality and in outcrops 500 m to the north on the west bank of the river, the Strelley Pool Formation is underlain by a thin unit of fine-grained volcaniclastic rocks and chert assigned to the Panorama Formation. However, sections measured immediately south of the Trendall locality, and 2 km to the north, indicate that the formation directly overlies altered basaltic rocks of the Mount Ada Basalt. Approximately 3 km north of the Trendall locality, rocks assigned to the Panorama Formation are also preserved beneath the Strelley Pool Formation, and overlying the Mount Ada Basalt. Essentially the same succession is shown 3 km south of the Trendall locality. Allwood et al. (2007a) found that bedding in the Panorama Formation rocks has the same dip as bedding in the overlying Strelley Pool Formation; this observation gives no indication that this contact represents part of a regional unconformity, as maintained by Van Kranendonk et al. (2006) and (Hickman, 2008).

Very importantly, Van Kranendonk (2010b; Fig. 11) illustrated one outcrop within the Trendall Reserve that confirms the local existence of two unconformities between the Strelley Pool Formation and the Mount Ada Basalt, with the Panorama Formation sandwiched in between. The maximum depositional age of the Panorama Formation in this outcrop was interpreted from SHRIMP zircon U–Pb data as 3447 ± 12 Ma (GSWA 160958, Van Kranendonk, 2010b), which is consistent with regional geochronological data on the Panorama Formation. Approximately 20 km north of the Trendall Reserve, a date of 3434 ± 5 Ma was obtained on the Panorama Formation (GSWA 142952, Nelson, 2000).

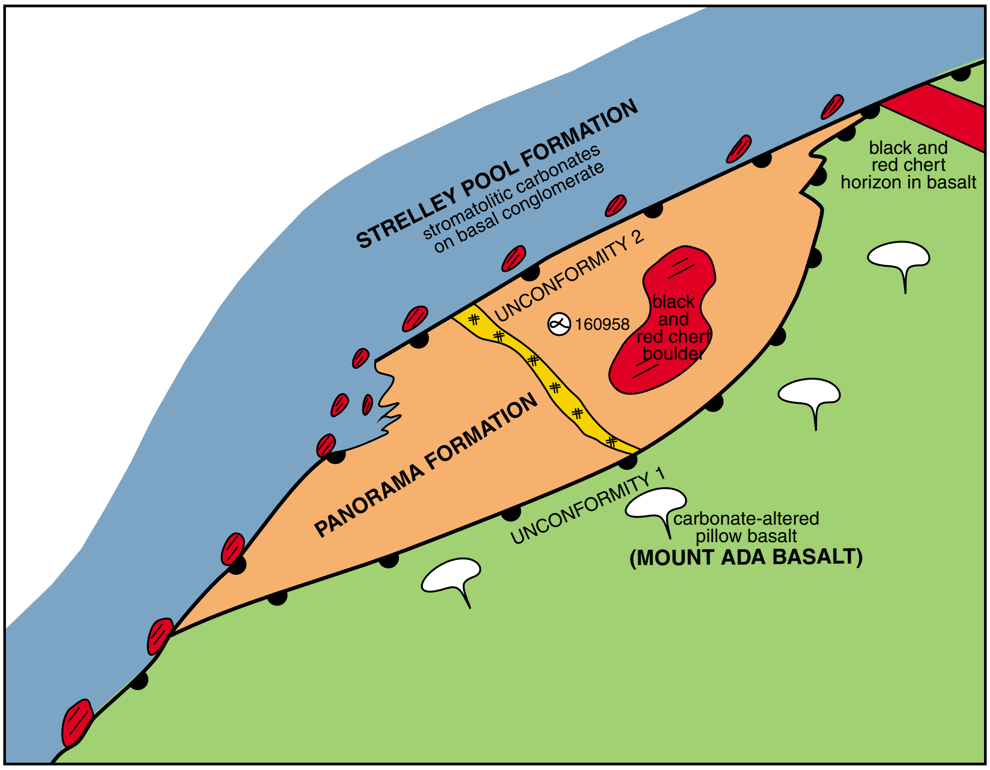

Figure 11. Geological sketch map from north of the Shaw River, showing unconformable relationships between the Strelley Pool Formation, Panorama Formation felsic volcaniclastic rocks, and carbonate-altered, pillowed metabasalt (Mount Ada Basalt). Note the presence of jaspilitic chert boulders in the upper two units and the onlap of the Strelley Pool Formation on the layered chert of the Mount Ada Basalt. α symbol denotes location of geochronology sample 160958, dated at ≤3447 ± 12 Ma. From Van Kranendonk (2010b)

The major stratigraphic significance of these observations from the area of the Trendall Reserve can be appreciated from the regional lithostratigraphy of the Pilbara Supergroup in the East Pilbara Terrane (Fig. 3). Within the Trendall Reserve, the unconformity between the Mount Ada Basalt and the Panorama Formation reveals that many kilometres of the Warrawoona Group succession is locally absent; the missing units are the 3471–3463 Ma Duffer Formation (elsewhere up to 8 km thick) and the c. 3460–3450 Ma Apex Basalt (generally 3–4 km thick). This establishes that in this part of the East Pilbara Terrane there is a significant local erosional unconformity within the Warrawoona Group. Previously, the oldest erosional unconformity in the Pilbara Supergroup was interpreted to lie at the base of the Strelley Pool Formation (Buick et al., 1995; Van Kranedonk et al., 2006) and have an age between 3426 and 3350 Ma (Van Kranendonk et al., 2007b).

Perhaps the most interesting unit directly underlying the Strelley Pool Formation in the Trendall Reserve area is a unit of banded black, grey, and red jaspilitic chert. This jaspilitic chert is up to 15 m thick in the northern section of the outcrop along the west side of the Shaw River (Allwood et al., 2007a), although it is absent in most sections. Boulders and pebbles of jaspilitic chert make up much of the basal conglomerate of the Strelley Pool Formation. Van Kranendonk and Nijman (2001) interpreted the jaspilite conglomerate at the base of the Strelley Pool Formation to belong to the Panorama Formation. Similar conglomerate occurs within the Panorama Formation 15 km north of the Trendall Reserve, where Van Kranendonk (1999, 2000) mapped a complex succession within a section of the formation he referred to as the 'Panorama volcano'. There, a lower unit of jaspilitic banded iron-formation, up to 40 m thick, is disrupted and overlain by a range of rocks that include volcanic jaspilite breccia and debris flows containing clasts of jaspilite (Van Kranendonk, 2000). The present interpretation is that the basal conglomerate of the Strelley Pool Formation contains fragments of jaspilitic chert recycled from the banded black, grey, and red jaspilitic chert of the Panorama Formation immediately underlying the unconformity.

Strelley Pool Formation

In most greenstone belts of the East Pilbara Terrane, the Strelley Pool Formation is between 20 m and 100 m thick (Hickman, 2008), although it is locally up to 1000 m thick (Van Kranendonk, 2010a). Detailed stratigraphic logging of the formation in the East Strelley and Panorama greenstone belts (Lowe, 1983; Van Kranendonk, 2000, 2006b; Allwood et al., 2007a; Wacey et al., 2010) has revealed a reasonably consistent vertical succession of facies in these areas, and the formation was subdivided into a number of informal members: five members according to Lowe (1983) and Wacey et al. (2010); four members according to Van Kranendonk (2006b) and Allwood et al. (2007a); and three members according to Van Kranendonk (2010b). The stratigraphic logs compiled by Allwood et al. (2007a) and Wacey et al. (2010) reveal that the various divisions of the formation show significant lateral changes of thickness over short distances, and such lateral changes are consistent with deposition in shallow-water marine and fluviatile environments. In the nine other greenstone belts of the East Pilbara Terrane that contain the formation its succession is more variable. Hickman (2008, table 2) synthesized the available regional data and found that the lithological facies of the formation, the magnitude of the time-break represented by the basal unconformity, and the degree of deformation and metamorphism in the underlying rocks change markedly from northwest to southeast across the East Pilbara Terrane. His conclusion was that the various sedimentary successions currently assigned to the Strelley Pool Formation in different greenstone belts may have been deposited at various times during the 75 million year break between the Warrawoona and Kelly Groups.

Kelly Group

In this Record, the base of the Kelly Group is taken as the base of the c. 3350 Ma Euro Basalt, following a recently revised stratigraphic interpretation (Hickman, 2008). However, readers of the literature will be aware that the lithostratigraphy of this part of the Pilbara Supergroup has been changed twice in recent years. Prior to 2004, the Strelley Pool Formation (under the name of 'Strelley Pool Chert') was included within the Warrawoona Group, and considered to conformably overlie the Panorama Formation (Van Kranendonk et al., 2002). Van Kranendonk et al. (2004b, 2006) changed this interpretation to include the Strelley Pool Formation within the Kelly Group. Hickman (2008) reviewed all available stratigraphic and geochronological evidence from the East Pilbara Terrane and concluded that the Strelley Pool Formation should be excluded from both volcanic groups (Warrawoona and Kelly) because it was deposited during a 75 million-year period without known volcanic eruptions. Recent geochemical evidence (Allwood et al., 2010) adds some support to this interpretation by indicating no significant hydrothermal input during deposition of the main part of the formation. Hickman (2008) suggested that the upper part of the Strelley Pool Formation, above the erosional surface and overlying conglomerate within the formation, and which contains volcaniclastic units, might be of similar age to the overlying Euro Basalt.

Within the Trendall Reserve, the lower part of the Euro Basalt consists of several hundred metres of massive to pillowed komatiitic basalt containing thin chert units. Above this is a thick succession of alternating tholeiitic and komatiitic pillow basalts.

Geological features at the Trendall locality

A detailed map of the geology of the Trendall locality is presented in Figure 12 (from Van Kranendonk, 2007). At this locality, the formation lies across an unconformity on pyrophyllite-altered, schistose metabasalt of the Mount Ada Basalt. Van Kranendonk (2010a) divided the local succession of the Strelley Pool Formation into three distinct members. The basal clastic member is composed of black and red layered chert boulders that pass along strike into a 1–2 m thick unit of chert pebble conglomerate. The middle carbonate member is composed of planar and stromatolitic carbonate laminite and coarse evaporitic crystal splays. The upper clastic member consists of coarse- to fine-grained clastic sedimentary rocks. Allwood et al. (2007a) described an additional member of jaspilitic chert, up to 5 m thick, between the middle carbonate and upper clastic members, but this is less than 0.5 m thick in the succession at the Trendall locality. All members of the formation are transected by a younger suite of zoned black chert and white quartz veins that extend up to the top of the formation, but not into the overlying pillow basalts of the Euro Basalt (Van Kranendonk, 2006a, 2010b). The stratigraphic contact between the upper clastic member and the Euro Basalt is locally conformable (Van Kranendonk, 2010a). Allwood et al. (2007a) described the topmost beds of the Strelley Pool Formation in this area as silicified grey-green tuffaceous mudstone interbedded with black chert.

Basal clastic member

At the Trendall locality, the base of the Strelley Pool Formation is lined by widely spaced boulders of laminated black and red chert, or jaspilite. Along strike to the south, the same horizon consists of jaspilite pebble conglomerate (Fig. 13a) 1–2 m thick. Boulders are encrusted by the overlying carbonate member. Chert boulders and pebbles in this basal member were derived from layered red and black chert beneath the basal contact of the formation. The boulder beds have been interpreted to represent the deposits on a rocky shoreline at the transition from a subaerial environment of erosion to shallow water deposition (Allwood et al., 2006a, 2007a). East and north of the Shaw River area, the basal clastic member of the Strelley Pool Formation is mainly composed of silicified sandstone and lenticular basal conglomerate.

Middle carbonate member

Laminated carbonates

The dominant lithology of the middle carbonate member is planar-bedded, millimetre-scale carbonate laminite. Planar laminite passes along strike into a texturally identical rock with a variety of structures formed by the growth of stromatolites (Hofmann et al., 1999; Hofmann, 2000; Van Kranendonk et al., 2003; Allwood et al.,

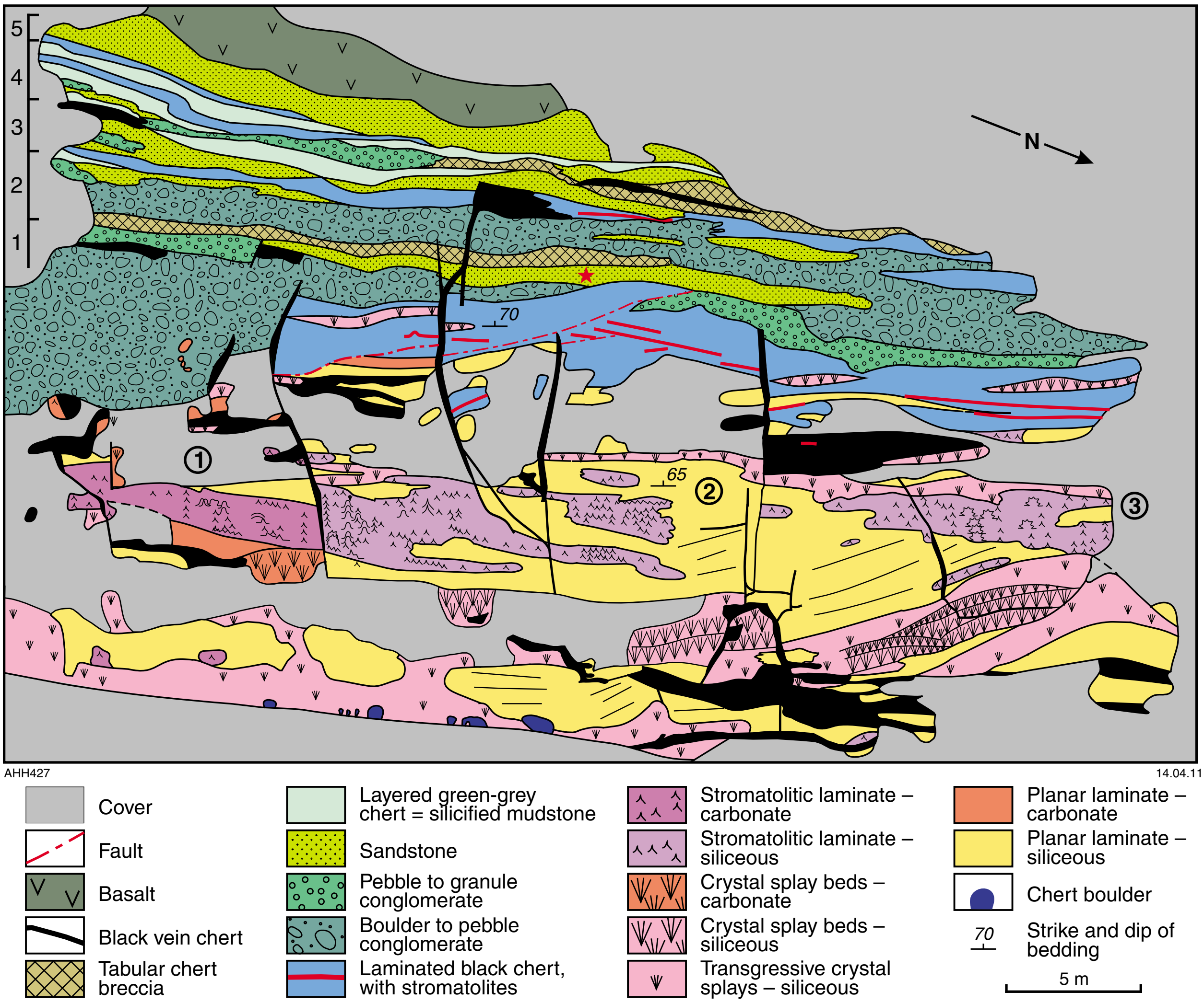

Figure 12. Outcrop map of the Trendall locality, based on 1 m spaced grid mapping. Numbers in upper left denote fining-up sedimentary cycles, interpreted as receding fans. Circled numbers indicate positions of onlapping conIform stromatolite biostromes (purple areas), which are capped by a layer of crystal splays — probably originally aragonite, but now medium-grained dolomite — above which stromatolites change morphology to domical-columnar forms (heavy red lines). Note the basal unit of isolated boulders of layered black and red chert, which are encrusted by the overlying carbonate. Star denotes position of sandstone with black, kerogen-rich laminates. From Van Kranendonk (2007)

2006a; Van Kranendonk, 2007, 2011). Allwood et al. (2007a) interpreted this member as a peritidal carbonate platform succession, consisting of carbonate and chert rocks dominated by a pervasive fabric of rhythmically interlaminated carbonate/chert couplets. Van Kranendonk (2010b) observed that where the rocks are incompletely silicified, and primary sedimentary carbonate rock is preserved, laminae are defined by couplets of light brown siderite/dolomite alternating with dark brown-weathering, heavily silicified carbonate, dominated by polygonal microquartz. He noted that in, one area, repeated cyclical bundles of 7–11 carbonate–chert couplets are present, with each bundle capped by a slightly thicker dark brown lamina (Fig. 14). Van Kranedonk (2010b) suggested that the scale of the bundling may be due to winter–summer cycles and the cause may have been climatic effects; for example, under varying insolation associated with the sunspot cycle (Foukal, 2003).

The middle carbonate member contains abundant and diverse stromatolitic facies, including large complex cones, 'egg-carton' laminite, and a wavy laminite stromatolite facies. The ratio of carbonate to chert varies from >80% in some areas to <2% elsewhere, depending mostly on the degree of alteration. In thin section, both carbonate and chert have a roughly equigranular, polygonal, neomorphic fabric. The rare earth element chemistry of carbonate and chert indicate that both are primary hydrogenous marine sediments (i.e. sediments that formed from dissolved seawater components; Allwood et al., 2006b).

Allwood et al. (2007a) distinguished the upper part of the middle carbonate member as a separate member, which they referred to as 'Member 3'. This member consists of banded black and white chert with up to 15% bundled iron-rich laminae and rare silicified chert-pebble conglomerates and crystal pseudomorph beds. The unit

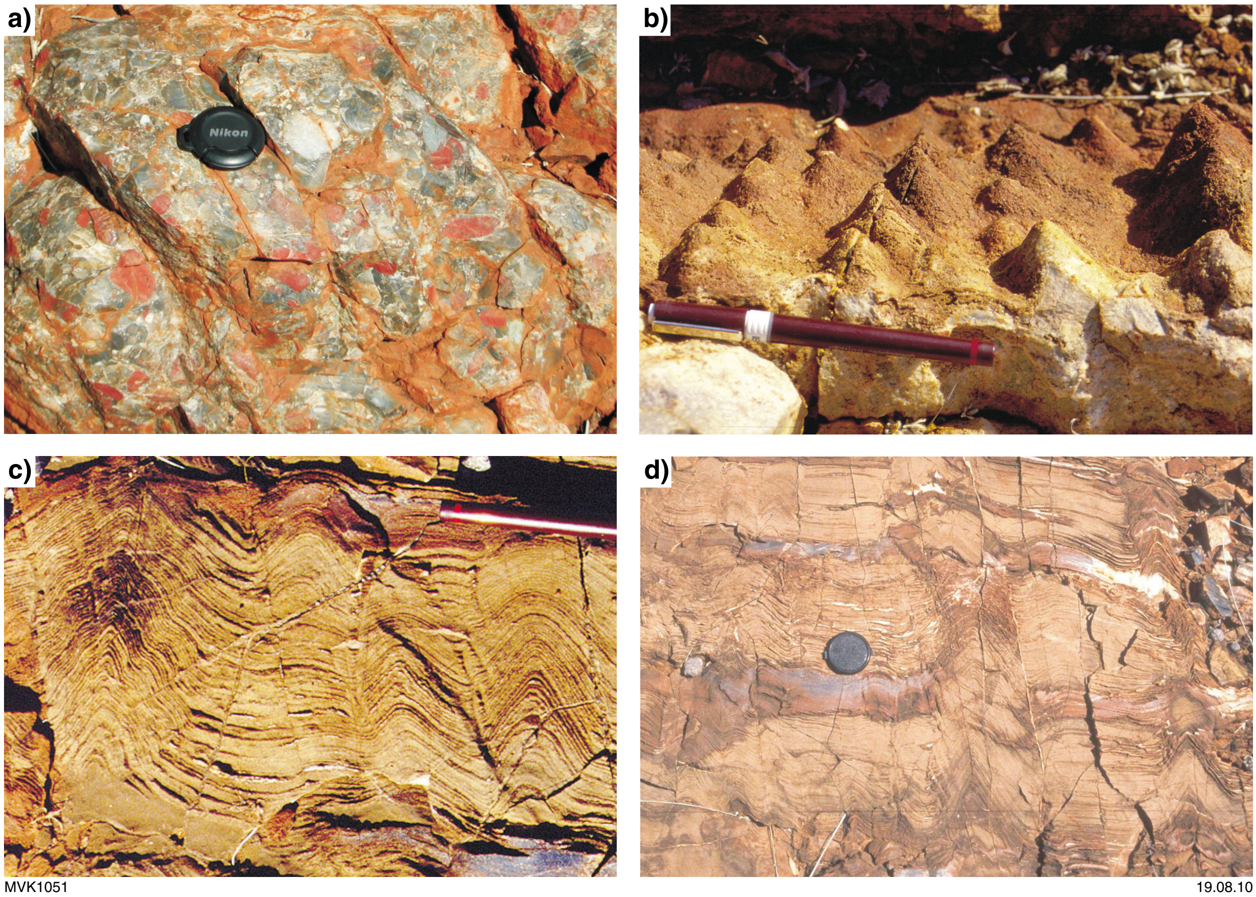

Figure 13. Outcrop features of the Trendall locality: a) basal chert-pebble conglomerate; b) oblique bedding-plane view of coniform stromatolites (rock slab now in the Western Australian Museum collection; c) cross-sectional view of well-laminated dolostone with variable stromatolite forms and conical lamination; d) cross-sectional view of large, columnar coniform stromatolites with asymmetrical limbs

is extremely thin or absent in some sections measured by Allwood et al. (2007a), presumably due to erosion prior to deposition of the upper clastic member, as indicated by the transgressive basal contact of the conglomerate of the upper clastic member (Fig. 12). The iron-rich laminae commonly form cm-scale wrinkles, bumps, domes, and pseudocolumns, with rare decimetre-scale cuspate domes. Some of these features are illustrated under **'Stromatolites'** below.

Detailed mapping shows that stromatolite forms vary along strike over distances of 1–1000 m (Van Kranendonk and Nijman, 2001; Allwood et al., 2006a; Van Kranendonk, 2007). In the Trendall locality outcrop, the largest and most complex stromatolites define three stacked, offset biostromes (Fig. 12) that are aligned at an angle of up to 15º from bedding and pass along strike into planar-bedded carbonate laminite.

Stromatolites

The dominant stromatolite morphology is stacked, generally slightly elliptical cones (Fig. 13b–d; Hofmann et al., 1999; Hofmann, 2000; Van Kranendonk, 2000; Allwood et al., 2006a). Some authors have questioned the biogenicity of the stromatolites by arguing that their laminae are isopachous, and that isopachous laminae are diagnostic of abiotic precipitation (Pope and Grotzinger, 2000; Lindsay et al., 2003a; Lindsay et al., 2003b). However, close examination of the laminae in the large cones reveals that they vary in thickness, and that they thicken both over the crestal zones and in the troughs between the cones (Hofmann et al., 1999; Hofmann, 2000; Allwood et al., 2006a; Van Kranendonk, 2007). This is an extremely important observation because it is one of the features that support a biological origin for the conical stromatolites. Figure 15 shows that at millimetre scale the majority of laminae in one of the cones vary in thickness along their length, and divide, pinch out, and are intercalated and lensoid. The non-isopachous nature of the lamina can also be demonstrated by a plot comparing the thickness in the crestal zone with the thickness on the flanks (Fig. 16).

The coniform stromatolites initiate from points on a flat surface, and form structures that extend up-section for distances between a few centimetres and a metre. These stromatolites are typically up to 20 cm in diameter, and have steep lateral slopes that dip at angles between 70° and 80°, well in excess of the angle of repose for sedimentary grains (Fig. 17a). Although seen mostly in vertical section, the conical morphology is demonstrated by short

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Figure 14. Detail of laminated carbonate, showing cyclical bundling (macrolaminae) of 7–11 dark–light dolomite couplets (from the stromatolite shown in Fig. 18b).

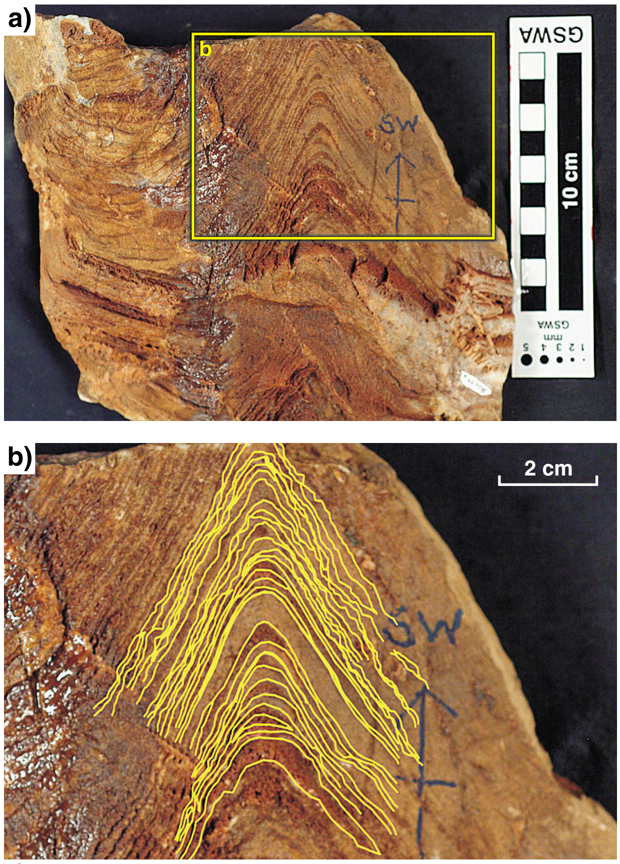

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Figure 15. Variability of thickness in alternating light and dark laminae in GSWA sample F46708, a large conical stromatolite collected from the Trendall locality by AF Trendall in 1984: a) original photograph, b) line drawing of selected laminae selected laminae

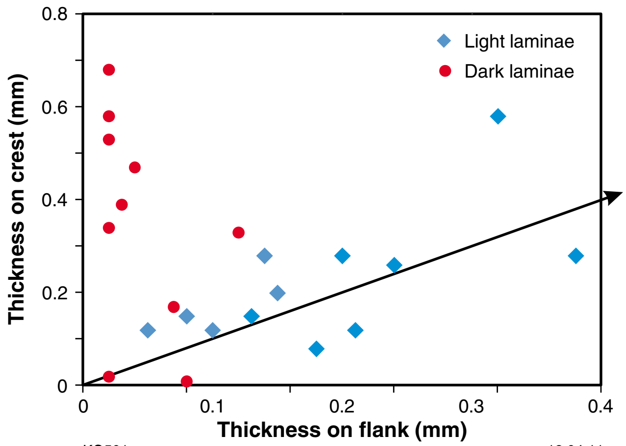

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Figure 16. Scatter diagram showing variation in lamina thickness at the crest and on the flank in GSWA sample F46708, a large conical stromatolite from the Trendall locality. Alternating light and dark laminae are shown separately. Isopachous laminae (laminae of equal thickness) would plot along the trend line; the broad scatter indicates that the laminae are not isopachous. Moreover, dark laminae are usually thicker in the crestal area than light laminae. None of these features are consistent with the laminae having formed as an abiogenic precipitate.

weathered segments, such as that shown in Figure 17b, in which a steep-sided cone has developed above flat laminae. The axis of this cone does not lie in a single plane but deviates from the vertical, probably in response to current direction.

Individual bedding planes may contain many cones of similar dimension, or of varied size (Fig. 18a). Only rarely do stromatolite columns initiate on pre-existing topographic features (Allwood et al., 2009), and in such cases upward accretion is not maintained (Allwood et al., 2007b). Large conical structures maintain their profile because accretion is greatest at the cone axis. Cross-sectional views show that whereas most stromatolites are symmetrical, others are asymmetrical, with consistently longer northern limbs than southern limbs (Fig. 13d; Hofmann et al., 1999), suggesting growth on a local paleoslope of 15° dip, or in a consistent current direction. Conical stromatolites at the Trendall Reserve are characteristically slightly elliptical in plan view, probably due to a preferred current direction during their growth.

Where weathered or cut surfaces transect the apex of a cone, the apex is pointed (tangential sections give the apices a more rounded appearance).

Axial zones in conical stromatolites

Axial zones are a feature found in most conical stromatolites throughout the fossil record (Fig. 19), and are even observed in conical mats forming today (Walter et al., 1976), including mats that are unlithified. The earliest investigations of the conical stromatolites of the Strelley Pool Formation led to the comment that axial zones are ‘non-existent or exceedingly narrow and hardly

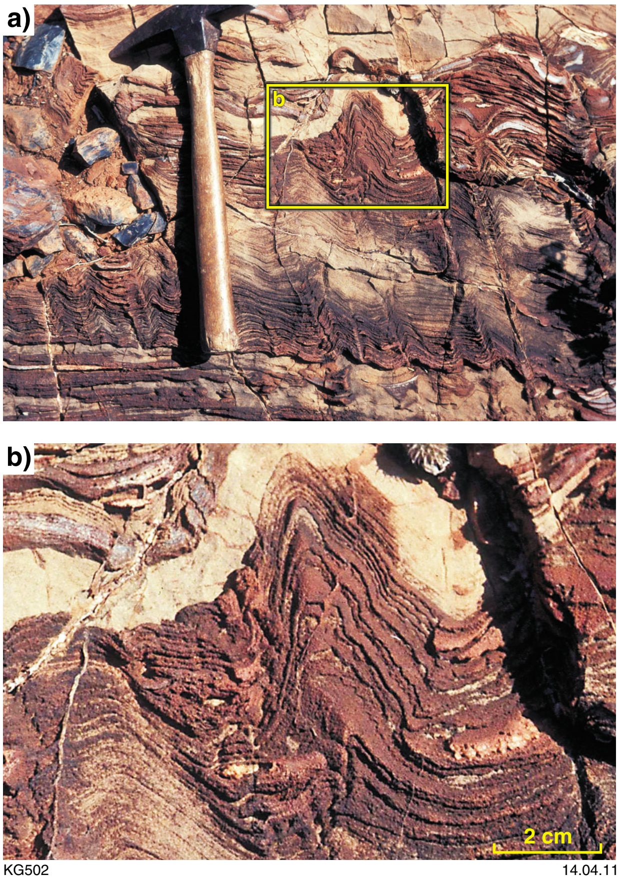


Figure 17. Conical stromatolites in the Strelley Pool Formation at the Trendall locality: a) cones developing above flat laminae showing one column centre that is partially weathered out, demonstrating the laminae are conical in three-dimensions; b) close-up view of a cone in (a). Note that the axes of the cones may deviate from the vertical, probably in response to current direction.

distinguishable' (Hofmann et al., 1999, p. 1259; Hofmann, 2000), but recent examination has revealed that axial zones are present. This is well displayed in cut slabs through a large conical stromatolite collected by Trendall in 1984 (Fig. 20). The axial zone forms as a second order feature at the axis tip of each lamina and is a narrow region in which there is a distinct steepening of the slope just below the apex; the apex itself is commonly lensoid with one or more laminae laterally offset as they are stacked. The presence of an axial zone adds another layer of complexity to the stromatolite morphology and, given that the axial zone can be demonstrated to have formed through biological activity (Walter et al., 1976), indicates that physical and chemical processes alone could not account for the formation of conical stromatolites at the Trendall Reserve.

Adventitious branching in conical stromatolites

Some conical stromatolites show incipient branching, and may form structures up to 35 cm in height (Fig. 18b). Others contain columnar branches off one side of the cone shape (Fig. 18c; Hofmann et al., 1999, figs 2b and c; Van Kranendonk, 2007, 2011). This type of adventitious branching provides very important evidence that the stromatolites formed biogenically. Early suggestions that such structures might be due to slumping have been discounted because slump structures would be inclined downwards, whereas adventitious branches point upwards.

The adventitious column commonly referred to as the 'Mickey Mouse ears' consists of two adjacent and partially linked cones situated on the flank of a much larger cone (Hofmann et al., 1999, figs 2a and b; Fig. 21). The axis of the main cone is vertical, whereas the axis of the first adventitious cone is inclined towards the main cone axis at about 70° from the horizontal. Lower sections of the cone are nearly vertical, but the cone curves gradually towards the apex of the large cone. A smaller cone grows on the down-slope flank of the first adventitious cone. The axis of this cone points at about 75° from the horizontal and in the opposite direction from the axis of the first adventitious cone. Although lower laminae are continuous with those of the main cone, middle laminae terminate abruptly against the wall of the small cone and upper laminae drape over it. The laminae in the first adventitious cone show a similar cycle of continuity, abrupt termination, and draping in relation to the second, smaller adventitious cone.

The adventitious cones are interpreted to have been topographically high, with a synoptic profile several centimetres higher than that of the main cone flank. Such features are incompatible with non-biological precipitation because deposition from a fluid should form a single continuous sheet. We are unaware of any established non-biological process that would result in the contemporaneous development of adventitious columns within continuous laminae on the flanks of large (>1 m) cones. Additionally, we do not consider that differential precipitation (Allwood et al., 2009) can satisfactorily account for the formation of cones. This would require a fluid medium in which the concentrations of near-saturated minerals allow (a) simultaneous, but differential, deposition on flanks, crests and troughs resulting in thickness variations, and (b) non-deposition near adventitious columns but simultaneous deposition within the adventitious cones. Another feature supporting a biological origin is seen in the regular spacing of the 'egg-carton' stromatolites (Fig. 5). This spacing was probably controlled by competition for nutrients (Petroff et al., 2010).

Other stromatolite morphologies

Another stromatolite morphology in the carbonate laminite consists of rounded, branching columns (Fig. 18d). Locally, these form isolated structures, but the majority of these types form on the flanks of large domical stromatolites with maximum amplitude of 25 cm and a maximum height up section of 1.2 m. Up to 10 small lateral branches have been observed on the flanks of the largest conical forms.

Closer inspection of laminations shows that stromatolite forms display a variety of layering relationships, including onlap of sediment along the sides of coniform stromatolites (Fig. 22a), and growth of coniform stromatolites within, and contemporaneous with (i.e. along strike of), sedimentary rocks deposited from ocean currents (Fig. 22b;

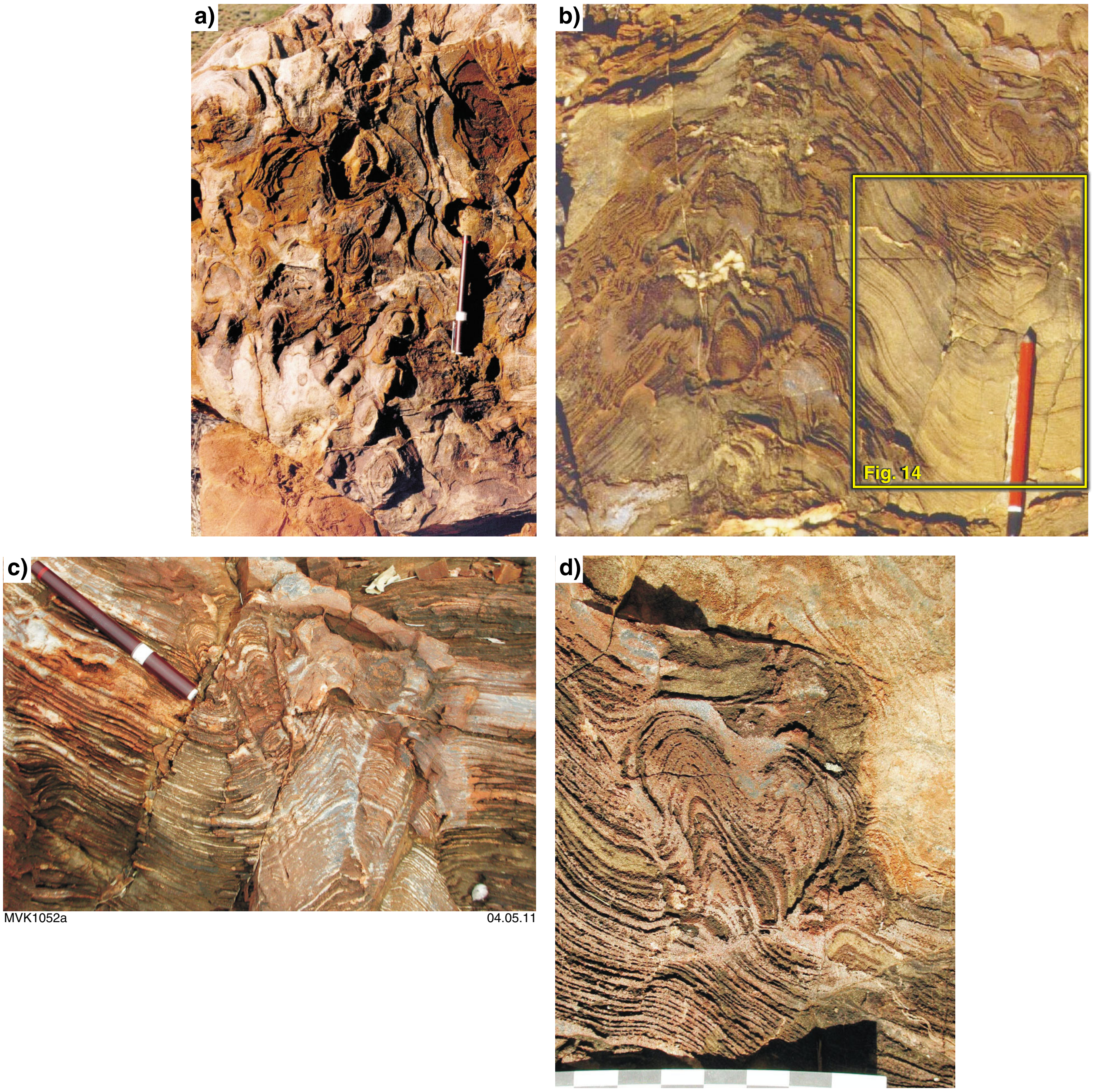
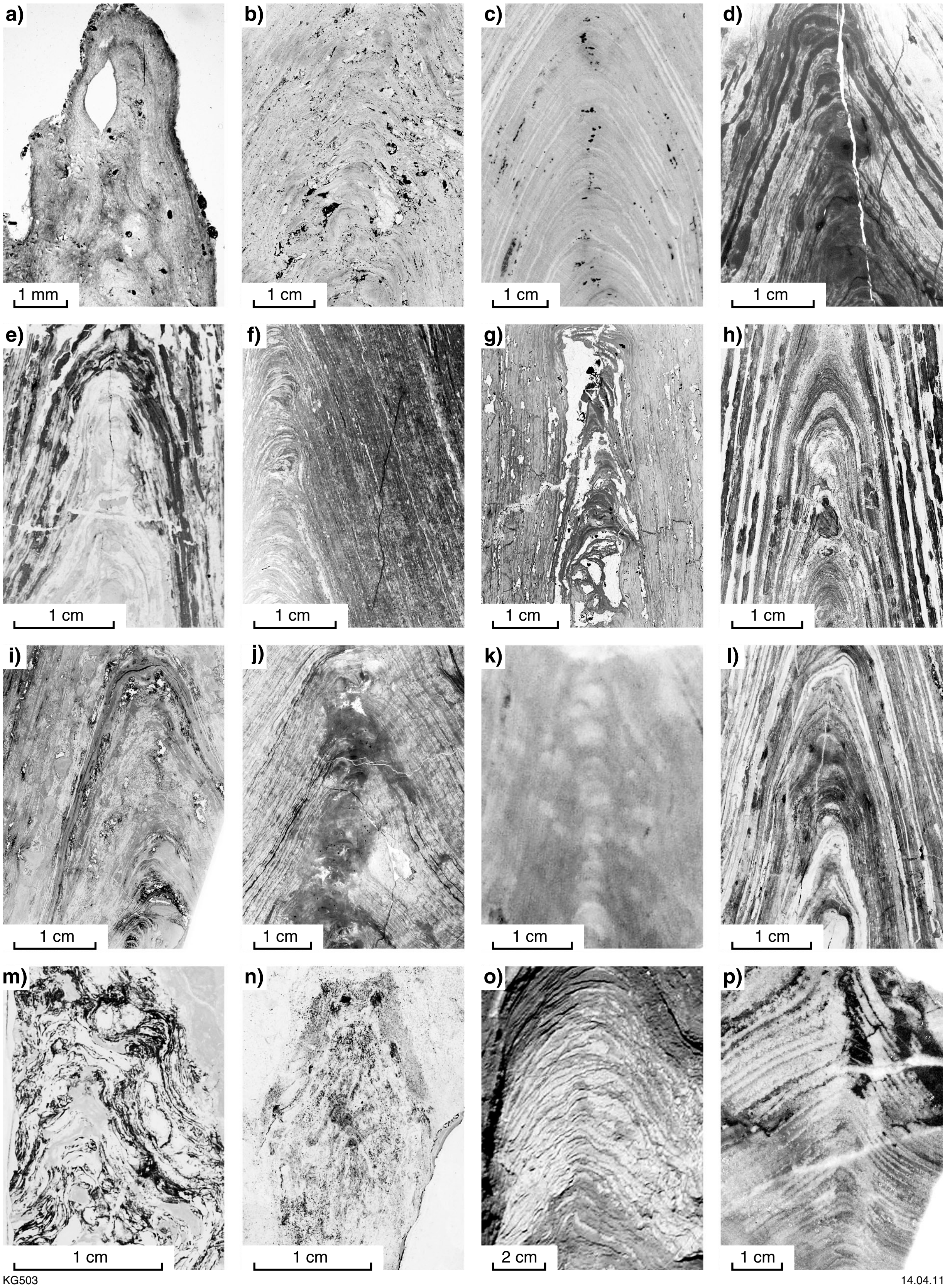


Figure 18. Stromatolites of the Trendall locality: a) bedding-plane view of coniform stromatolites of different sizes, all showing parallel elongation; b) large, incipiently branching coniform stromatolite with branched columnar form on upper right flank; c) coniform stromatolites with branched offshoots on upper left flank; d) close-up of upper right part of (b), showing branched columnar stromatolite ('Mickey Mouse ears'; scale in centimetres).

Van Kranendonk et al., 2003; Van Kranendonk, 2007, 2011). These features show that the rocks are not abiogenic precipitates 'modified by ocean currents', as suggested by Lindsay et al. (2005), but rather are structures that formed *during* accumulation of carbonate sedimentary material affected by currents.

The interaction between stromatolite growth and water currents is exceptionally well shown in Figure 23, which shows a steep-sided coniform stromatolite that displays continuous growth upwards from fine to moderately laminated carbonates at the base (bottom third of picture), through an 8-cm-thick bed of flat-pebble conglomerate (central third of picture), into finely laminated carbonates (top of picture). This demonstrates that coniform stromatolites are not precipitates from solutions of either evaporitic or hydrothermal origin, but formed as a result of living microbial activity (Van Kranendonk, 2007, 2011).

High in the middle carbonate member, where the rocks have been almost completely silicified and bedding is developed at a finer-scale, crescentic, wind-blown ripples (Fig. 24a) are associated with small, domical-columnar stromatolites (Fig. 24b) and centimetre-high domical-columnar stromatolites defined by rusty red and yellow weathering laminates (Fig. 24c). Although the domical-columnar forms display broadly isopachous laminations at outcrop scale, thin section observations show that these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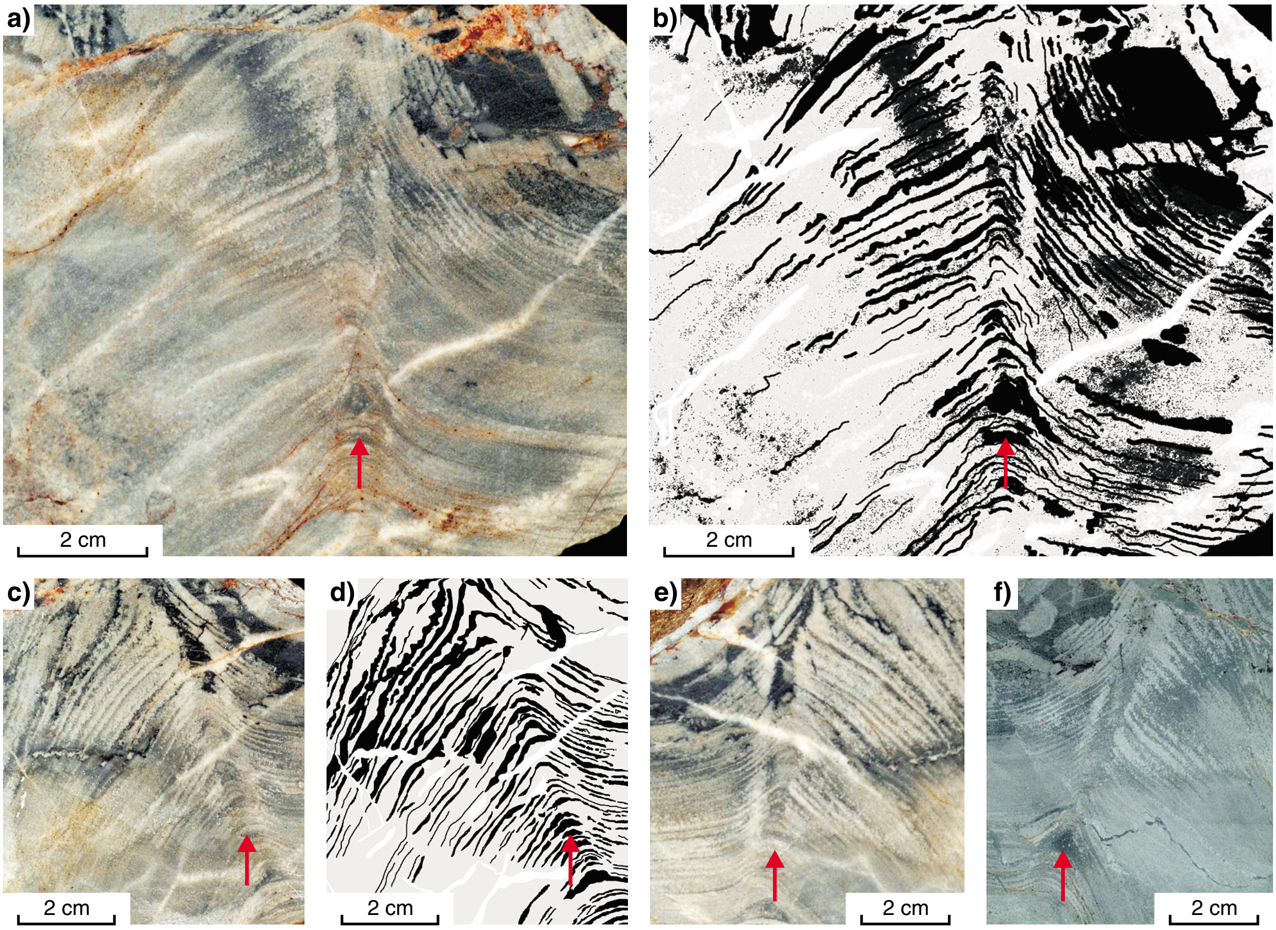

Figure 20. Polished cut slabs of large cones in the Strelley Pool Formation from the Trendall locality showing axial zones in a large cone GSWA sample 54977, (GSWA Fossil no. F46708) from the Trendall locality. a) and b) cut face and line drawing through axial zone at cone centre; c) and d) cut face and line drawing through axial zone on parallel slab about 7 mm from slab (a); e) reverse slab to (c) cut parallel to weathered surface illustrated in Fig. 15; f) thin section from between faces (c) and (e). The axial zone is very narrow (5–10 mm) and difficult to target. A vein of quartz recrystallization in the trough on either side of the zone partially obscures the break of slope between the axial zone and the cone flank. The line drawings emphasize the lensoidal nature of the laminae within the axial zone.

Figure 19. (facing page) Continuity of axial zone through geological time: a) recent, pinnacle mat, 'Pamelup Pond', Lake Preston, WA, 0 Ma; b) *Conophyton basalticum*, Antrim Plateau Volcanics, east Kimberley, WA, 513 ± 12 Ma; c) *Conophyton* new form, Kanpa Formation, Officer Basin, WA, c.750 Ma; *Conophyton* new form, Stag Arrow Formation, Collier Group, Bangemall Basin, WA, 1465–1070 Ma; e) Scorpion Group, Bangemall Basin, WA, 1797–1462 Ma; f) *Conophyton* new form, Kiangi Creek Formation, Edmund Group, Bangemall Basin, WA, 1620–1465 Ma; g) unnamed, Dungaminnie Formation, Nathan Group, McArthur Basin, NT, c.1575 Ma; h) unnamed, Pear Tree Dolomite, Limbunya Group, Birrindudu Basin, NT, >1640 Ma; i) unnamed, Amelia Dolomite, McArthur Group, McArthur Basin, NT, >1650 ± 3 Ma; j) unnamed, Hinde Dolostone, Tolmer Group, Birrindudu Basin, NT, 1825 to 1700 Ma; k) *Conophyton* new form, ?Pentecost Sandstone, Kimberley Group, Montgomery Reef, WA, 1704 ± 14 Ma; l) *Ephyaltes edingunnensis*, Yelma Formation, Earaheedy Basin, WA, 2027 ± 23 to1698 ± 12 Ma; m) stromatolite form 2 Grey 1994, Juderina Formation, Yerrida Group, Yerrida Basin, WA, c.2173 ± 11 Ma; n) unnamed, Black Flag Group, Kanowna, Eastern Goldfields, WA, 2704 ± 8 to 2676 ± 5 Ma; o) unnamed, Tumbiana Formation, Fortescue Group, Pilbara, WA, c. 2720 Ma; p) unnamed, Strelley Pool Formation, Trendall Reserve, Pilbara, WA, 3426–3350 Ma.

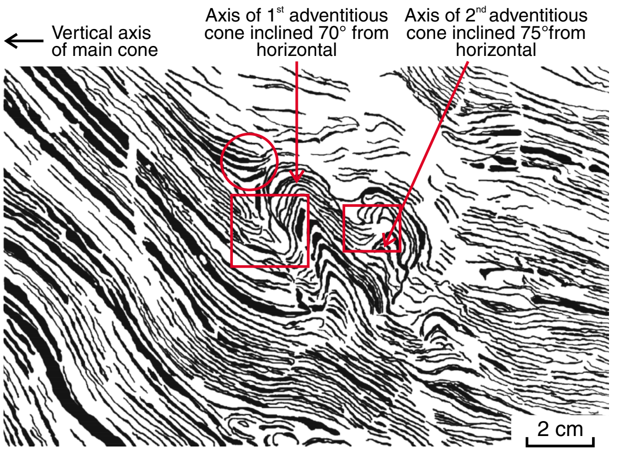

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Figure 21. Line drawing of adventitious cones on the flanks of a large conical stromatolite in outcrop. The axial angles are inconsistent with slumping (arrows), as is abrupt termination of laminae against column margins (rectangles) and overlap of columns by external laminae (circle). Angles shown on the figure are apparent, and relative to bedding at the base of the structure.

Figure 22. (below) Bedding features of silicified carbonates at the Trendall locality: a) detailed, cross-sectional outcrop view of the flank area of a coniform stromatolite, showing onlap of carbonate beds against stromatolite flank (arrows; from Van Kranendonk et al., 2003); b) cross-sectional outcrop view of silicified carbonates, showing coniform stromatolite ('c' at bottom middle) growing within rippled carbonate sediment (circle) and overlain by flat-pebble conglomerate (above short-dash line) that terminated stromatolite growth. Overlying laminated sediment displays high amplitude, symmetrical swale, the geometry of which suggests microbial binding of clastic sediment under high-energy conditions (from Van Kranendonk, 2007).

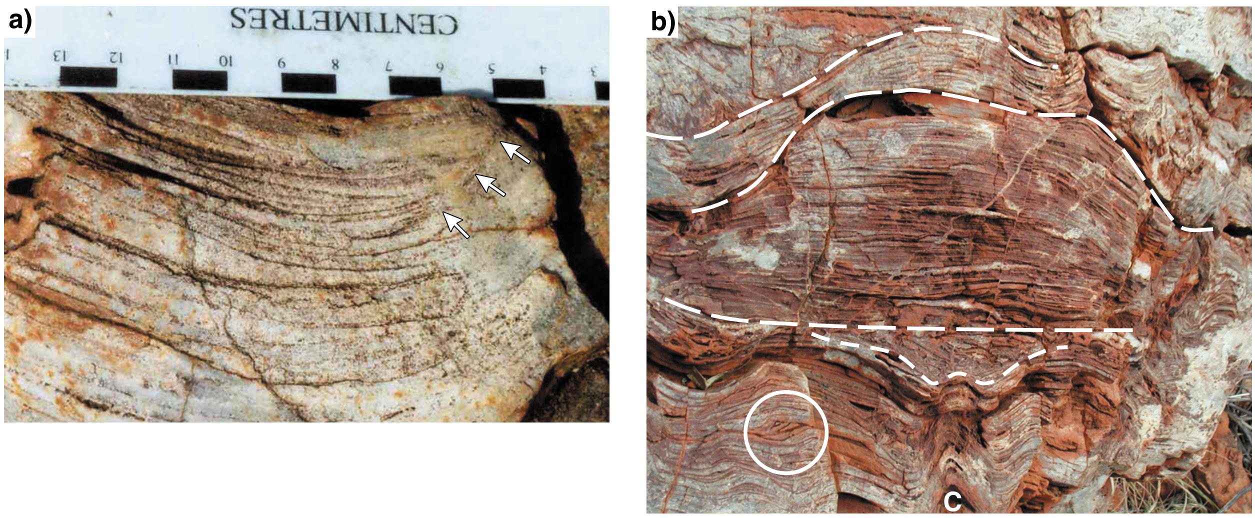

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Figure 23. Steep-sided coniform stromatolite of the Strelley Pool Formation, which passes up from finely bedded carbonate at the base, through a layer of flat-pebble conglomerate, into finely bedded carbonate at the top. Arrows point to coniform peak of the stromatolite in the uppermost carbonate (from Van Kranendonk, 2007). The slope of the flanks is well above the angle of repose, making abiogenic sedimentary accretion an unlikely origin. In order to maintain the slope and accumulate sediment or precipitate, some sort of sticky surface must have been present. The most likely mechanism is precipitation induced by the presence of a biofilm.

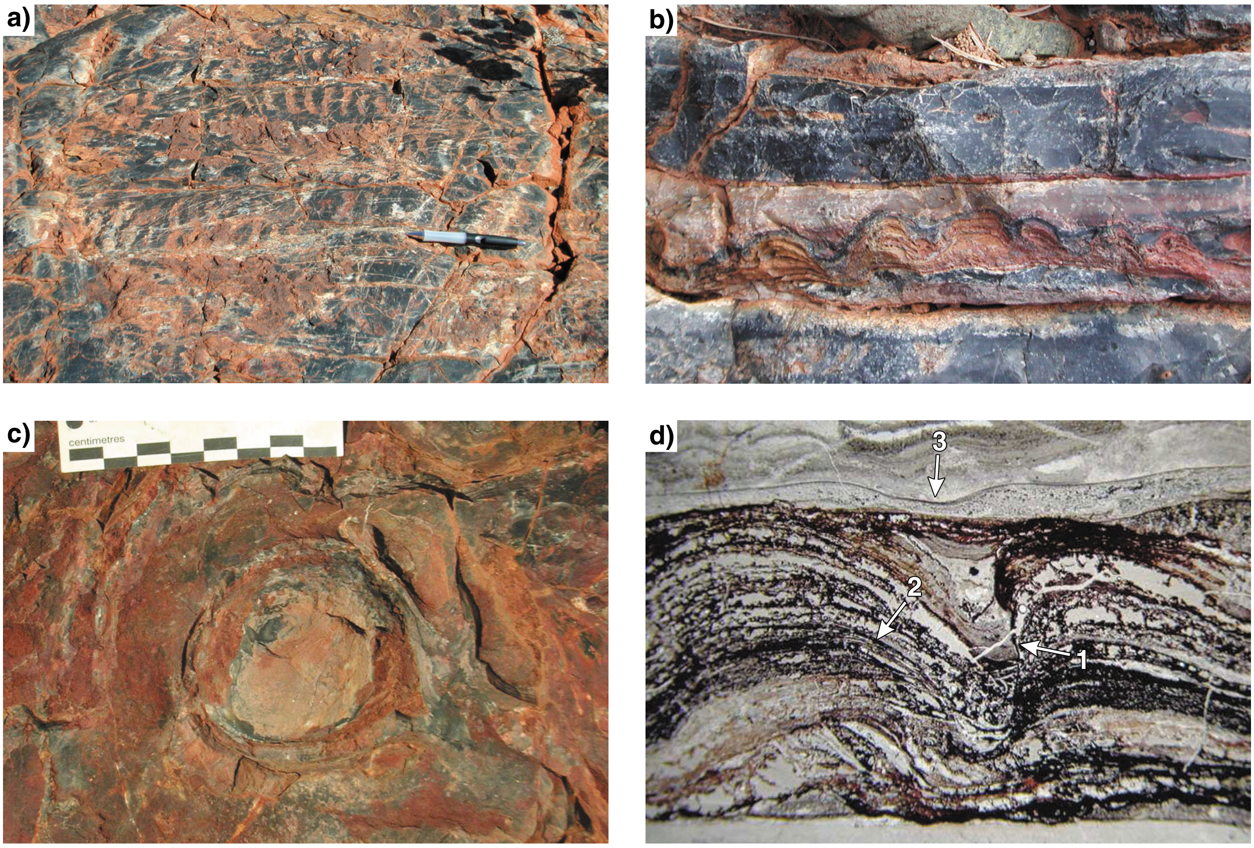

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Figure 24. Features of the upper part of the carbonate member of the Strelley Pool Formation: a) small, crescent-shaped, wind-blown ripples in silicified carbonate; b) cross-sectional outcrop view of centimetre-high, domical-columnar stromatolites in silicified carbonate (represented as red lines on Fig. 12); c) plan view of surface outcrop, with small domical-columnar stromatolites in silicified carbonate; d) cross-sectional thin section view of centimetre-high, domical-columnar stromatolites, showing: steep-sided growth walls that truncate growth laminae (arrow 1), internal discordances of laminae (arrow 2), and growth termination by influx of clastic sediment (arrow 3; from Van Kranendonk, 2007), together with wispy, discontinuous laminae of variable thickness on the micrometer scale, a feature typical of many younger stromatolites.

stromatolites have steep-sided growth walls that truncate laminae, internal discordances of laminae, and growth termination by influx of clastic sediment (Fig. 24d). These morphological features indicate dynamic growth within a changing environment and support a biogenic origin for these structures.

Radiating crystal splays

A prominent feature of the Strelley Pool Formation is the widespread development of weakly upward-radiating crystal fans. Together with the desiccation cracks and wind-blown ripples, the presence of crystal fans indicate periods of exposure during accumulation of the carbonate member (Van Kranendonk et al., 2003; Allwood et al., 2006a; Van Kranendonk, 2010b). Significantly, stromatolite abundance is locally directly affected by the formation of crystal fan beds, with the latter forming a cap on the large biostromes (Fig. 12). Above the fans, stromatolite growth is much less abundant and of different morphology (small domical forms above vs. large coniform varieties below). These observational data suggest that marine precipitation of carbonate rocks occurred under (at least) periodically evaporative conditions.

Two textural types of straight to weakly radiating vertical crystal splays have been recognized. One type grew across planar-bedded and stromatolitic laminite (Fig. 25a). A second type includes the largest crystal splays, ≥50 cm long, in which no trace of bedding is evident (Fig. 25b). Also included in this category are up to five sharp-bounded ‘beds’ of radiating crystal splays, 30 cm thick, that define a broad dome in the northern, more silicified part of the outcrop (Figs 12, 25c). The development of these massive crystal splays is associated with termination of stromatolite growth, as shown, for example by a 20–80 cm thick, massive layer of radiating crystal splays that overlies the main stromatolitic unit. More specific evidence of this is provided where a set of radiating crystals grew on top of a single stromatolite column and terminated its growth (Fig. 25d). This is evidence that episodes of crystal splay growth occurred during periods of subaerial exposure. Although the original mineral species forming the crystal splays is unknown due to diagenetic carbonate alteration and silicification, preserved cross-sections of some large silicified crystals are pseudo-hexagonal (Fig. 25e).

The crystal splays are unrelated to the development of stromatolitic morphology. All varieties of stromatolite

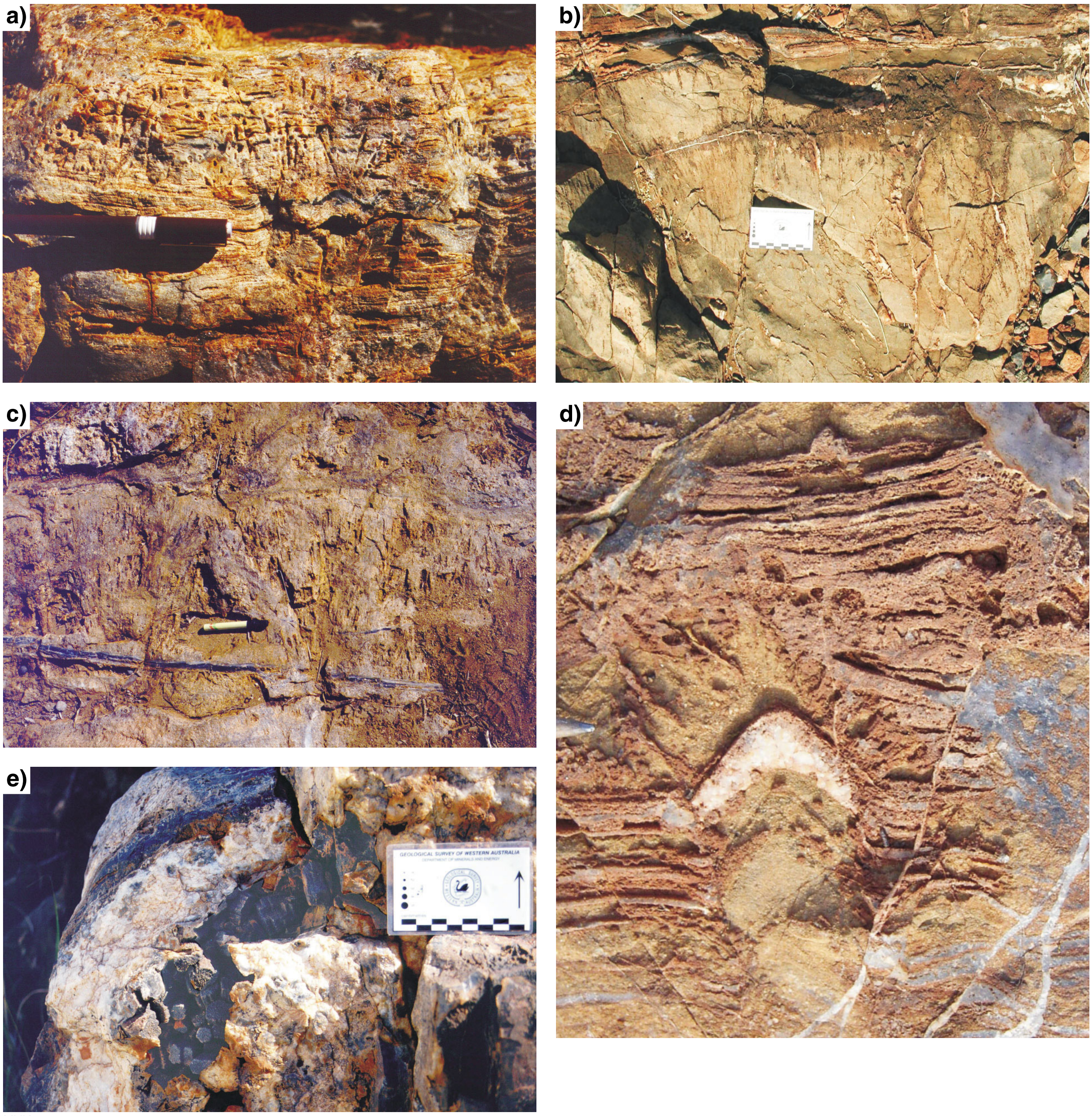

Figure 25. Features of radiating crystal splays in the Strelley Pool Formation: a) weakly radiating crystals cutting bedding in silicified carbonate; b) large, weakly radiating crystal fans in dolomite; c) large sets of radiating crystal fans in silicified carbonate; d) small coniform stromatolite capped by radiating splay of crystals; e) cross-sectional view of pseudo-hexagonal crystals now completely silicified.

morphology are located some distance from the crystal splays, and the millimetre-scale laminite of the stromatolites are overgrown by the crystal splays.

Upper clastic member

At the Trendall locality, the upper clastic member is composed of five fining-up successions. Van Kranedonk (2010b) interpreted these to represent a series of receding alluvial fans (Fig. 12). The basal conglomerate is very coarse grained, with subrounded boulders up to 40 cm in diameter. Blocks of layered and massive blue-black chert are the dominant clast lithology, but boulders of dark brown carbonate — some with stromatolites — are locally common, providing evidence of erosion of the middle carbonate member. About 250 m south of the Trendall locality, the conglomerate includes fragments of komatiitic basalt. The basal conglomerate locally fills a 6.2 m deep channel bound by normal faults that are lined by veins of black hydrothermal silica, consistent with geochemical evidence of hydrothermal activity during or shortly after deposition of the upper clastic member (Allwood et al., 2010).

One of the coarse sandy layers of the member contains 2–5 mm-thick layers of blue-black chert in which evidence of stromatolitic mats has been observed (Fig. 26a; thick red lines on Fig. 12). In thin section, the mats display good preservation of wavy laminite structure and contain clots of organic material and gas bubbles suggestive of decayed organic matter (Fig. 26b,c). It is unknown how widespread or common these stromatolites are in the clastic succession, but they are at least locally prevalent. Microfossils have been reported by Sugitani et al. (2010) from this same unit along strike, and Marshall et al. (2007) identified what is most probably organic kerogen in these same rocks.

Hydrothermal veins

A suite of black silica veins transects the outcrop and displays a variety of textures. Whereas some veins are composed of massive black silica, others are zoned with a white quartz core, locally with euhedral quartz crystals (Fig. 27). Other zoned veins contain massive black silica

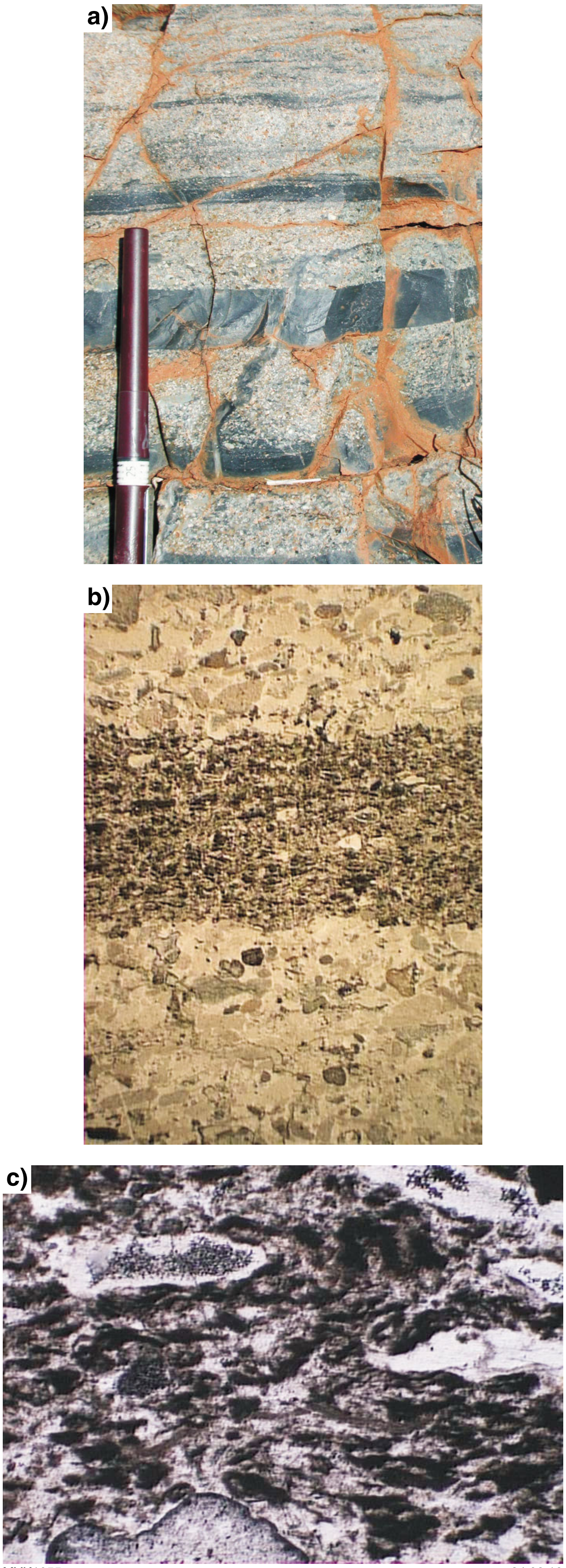

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Figure 26. Features of silicified microbial mats in sandstone from the upper clastic member of the Strelley Pool Formation at the Trendall locality: a) general appearance of mats in silicified sandstone with transecting black chert vein; b) whole thin section view (plane-polarized light) of microbial mat in sandstone, showing clotted texture of kerogen and scattered sand grains (width of view = 2 cm); c) detailed photomicrograph (plane-polarized light) of clotted kerogen texture and silica-filled fenestrae (width of view = 1 mm).

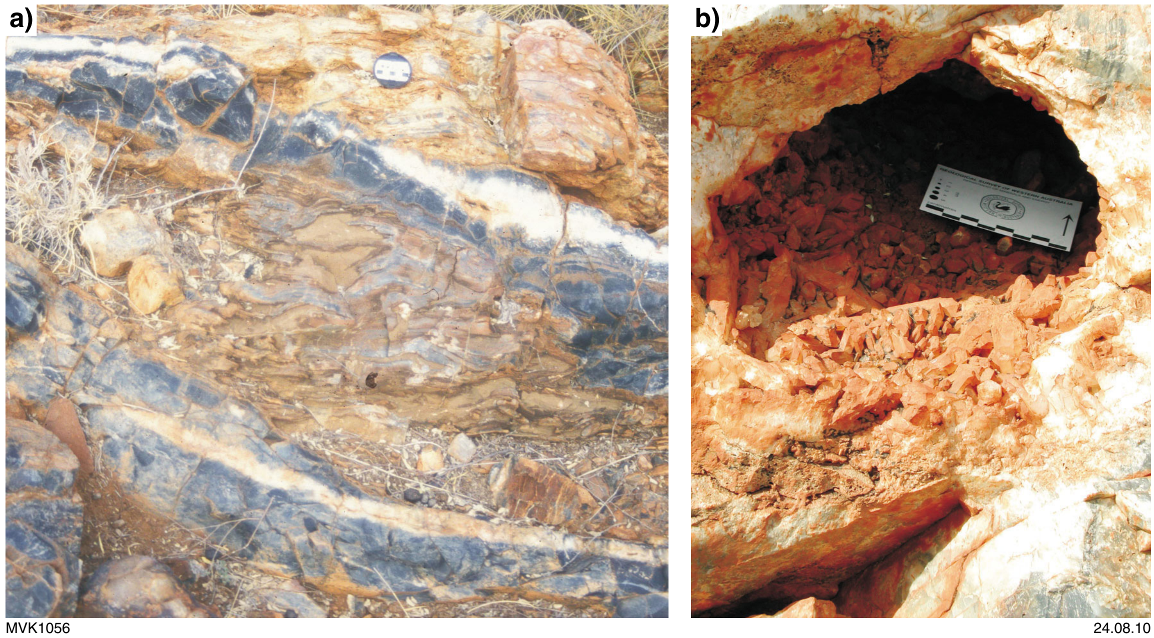

Figure 27. Hydrothermal quartz veins at the Trendall locality: a) zoned hydrothermal silica veins cutting dolomite, with black chert margins and white quartz cores. Note how fingers of silicification emanate out from the veins parallel to bedding in the dolomite; b) open central zone of hydrothermal quartz vein, lined with euhedral quartz crystals (coated with iron oxides).

margins and a core of pebble breccia derived through phreatomagmatic brecciation and thermal rounding of host rocks. One massive sill displays a pseudo-conglomeratic breccia texture derived from nearly in situ breakup of the country rock during silica intrusion (phreatic brecciation).

Future investigations

Several important questions remain to be answered in regard to the local geology, and there is considerable scope for further research. Outstanding questions include:

1. What is the precise depositional age range of the Strelley Pool Formation within the Trendall Reserve?
2. Were the hydrothermal silica veins in the formation all related to heating by the overlying Euro Basalt?
3. Would whole-rock major and trace element geochemistry support the various siliciclastic and volcaniclastic facies recognized in the formation?
4. If the basal conglomerate represents a shoreline deposit as suggested by Allwood et al. (2006a), where did the adjacent landmass lie, and in which direction did the depositional basin deepen?
5. Abundant stromatolites should be accompanied by microfossils, so are microfossils also widespread in the formation?
6. Was any of the alteration beneath the basal unconformity produced by early Archean weathering?

Answers to questions 1 and 2 require geochronology on samples collected from the formation itself. No attempt has yet been made to date samples of the Strelley Pool Formation in the Panorama greenstone belt. Based on zircon U–Pb geochronology on the formation in other greenstone belts (reviewed by Hickman, 2008), the formation is likely to contain zircon derived mainly from erosion of the underlying Warrawoona Group. However, the youngest grains in any sample will provide some constraint on maximum depositional age. If the volcaniclastic rocks of the upper clastic member are genetically related to the overlying Euro Basalt, these rocks could include c. 3350 Ma zircon from ash-fall tuff derived from early volcanism of the Euro Basalt in an adjacent area. Conversely, if the lower and middle members were deposited shortly after deposition of the Panorama Formation, no c. 3350 Ma zircon (ash-fall or reworked detrital) would be present in the main part of the formation.

The origin and age of the hydrothermal silica veins that occur in all parts of the formation will remain contentious until they have been more closely mapped and dated. Dating may be possible if hydrothermal zircon or fresh sulfide minerals are present.

The geochemical compositions of the lower and upper parts of the formation are different based on previous REE+Y data (Allwood et al., 2010). Previous geochemistry focused on the distinction between marine and hydrothermal environments, but whole-rock major and trace element geochemistry should provide information on sediment provenance. Geochemical data should also assist in separation of sedimentary facies within the middle carbonate member.

Regarding question 4, the paleogeography of the formation in the Trendall Reserve is still poorly defined. Facies studies by Allwood et al. (2007a) indicated a marked deepening of the depositional basin to the south during deposition of the upper clastic member, whereas paleocurrent observations by Van Kranendonk (2010a) suggested deepening of the basin to the east or northeast. Stratigraphic logging (Allwood et al., 2007a) established local lateral variations of between 20 and 30 m in the relief of the basal unconformity, with the consequence that local paleocurrent directions may not reliably reflect regional variations of basin depth. The remarkable similarity in the Strelley Pool Formation successions (including the upper clastic member) of the Trendall Reserve and the East Strelley greenstone belt indicate no prevailing slope over a northwest–southeast distance of at least 25 km.

No microfossils have yet been reported within the Trendall Reserve but Sugitani et al. (2010) reported putative microfossils in the Strelley Pool Formation about 1.5 km north of the Trendall Reserve. The discovery of structures interpreted to be microbial mats at the Trendall locality (Van Kranendonk and Nijman, 2001; Allwood et al., 2009) suggests that more detailed investigation is likely to yield microfossils.

Evidence to most satisfactorily address question 6 would require deep drilling of the unconformity at the base of the Strelley Pool Formation. Samples used in geochemical and microbiological research on this zone should be collected from below the level of recent alteration and organic contamination. Based on geoscientific drilling projects in other areas of the Pilbara (Hickman, 2005), this would require drilling to depths considerably greater than 100 m.

More detailed documentation of stromatolite morphologies is required to allow comparisons and contrasts to be made with similar, but better documented, stromatolites from the Proterozoic. The presence of axial zones in the stromatolites of the Strelley Pool Formation is a significant discovery for two reasons: 1) axial zones appear to be an inherent biological component of living bacterial mats; and 2) axial zones are a feature of stromatolites of accepted biogenic origin throughout the geological record.

Visiting the Reserves

Anyone intending to visit any State Geoheritage Reserve, for viewing, research work, or any other purpose, must first seek Government authority by submitting a 'Proposed Activity at a State Geoheritage Reserve' form to the Executive Director of the Geological Survey of Western Australia. Proposals will be assessed by a panel of experts convened by the Executive Director. Any proposals that involve ground-disturbing activities, such as sampling of rocks or fossils, must be accompanied by detailed research proposal, including background information, project aims, methods, and an undertaking to provide reports on results to the Executive Director. Applications must be lodged on an official application form (Appendix 2). Full information on management procedures is provided in Grey et al. (2010), which can be viewed and downloaded free-of-charge through the website of the Department of Mines and Petroleum.

Conclusions

The Trendall Reserve contains some of the world's most valuable evidence on Paleoarchean life, and is a key area for understanding the diversity of ancient stromatolites between 3426 and 3350 Ma. The stromatolites preserved in the rocks of this Reserve inhabited only a small part of a far more extensive shallow-water basin. This basin covered at least 30 000 km^2 of the East Pilbara Terrane, and included depositional environments ranging from shallow-water marine to beach, estuarine, sabkha, fluviatile, and lacustrine. The basin existed for 75 million years between two major periods of volcanic eruption.

Further research is required to provide answers to such questions as the precise age range of the Strelley Pool Formation within the Reserve, the age and origin of silica veins in the formation, and if an Archean paleosol underlies the basal unconformity of the formation. However, to minimize the impact of future sample collection, all future research projects within the Reserve will require the prior approval of the Executive Director of GSWA. To ensure that all future research projects contribute to our geoscientific knowledge of the Reserve, results must be reported to GSWA.

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Appendix 1

State Geoheritage Reserves (Western Australia)

State Geoheritage Reserves are created under Section 41 of the Western Australian *Land Administration Act 1997** through a Management Order, whereby the interests of the Reserves are vested in the Minister for Mines and Petroleum, for management by the Executive Director of the Geological Survey of Western Australia (Executive Director GSWA, the most senior state government geologist) on behalf of the State Government.

The Reserves include one or more sites of such outstanding scientific and educational value that their importance is recognized nationally and internationally. Reserve status provides a management process for preventing inappropriate activities such as un-necessary destructive sampling or any other form of ground disturbance that could reduce or destroy geoscientific value. Anyone intending to enter a State Geoheritage Reserve, for whatever purpose, must first submit an application to the Executive Director GSWA to visit or to undertake research. Access will normally be granted to parties wishing only to view and photograph features within the reserves, but camping on the reserves, and driving off established roads and tracks is not permitted. There must be no collecting from a Reserve (including collection from scree material) without prior approval (via the issue of a collecting permit) from the Executive Director GSWA.

Additional information, including procedures required to apply for entry permits, is available in Grey et al. (2010), available online (http://geodocs.doir.wa.gov.au/search.jsp?cabinetId=1101&Combined=N10M).

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* For reference to the WA State legislation, the reader should search on the WA Government website <http://www/dmp.wa.gov.au> using the word 'legislation'.

Appendix 2

State Geoheritage Reserves — proposal to visit or carry out research

Reserve to be visited:

Date of proposal:

Dates of proposed visit:

Main purpose of visit:

Contact details:

Name of Principal Researcher or Tour Leader:

Address:

Other contact details:

Email:

Fax:

Phone:

Names and contact details of other members of the party:

Attach a visit or research proposal that provides the following information:

- *Background to the proposed research*
- *Coordinates of sample-site polygons*
- *Sampling strategy*
- *Related material in Australian or other collections*
- *Sample treatment*
- *Sample export arrangements*
- *Sample repository*
- *Outcomes of Research Project*

RECORD 2011/10

STATE GEOHERITAGE RESERVE R50149 (TRENDALL RESERVE), NORTH POLE, PILBARA CRATION, WESTERN AUSTRALIA — GEOLOGY AND EVIDENCE FOR EARLY ARCHEAN LIFE

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