A note on two occurrences of inferred microbial mat features preserved in the c. 2.1 Ga Magaliesberg Formation (Pretoria Group, Transvaal Supergroup) sandstones, near Pretoria, South Africa

Pieter Bosch
Council for Geoscience, Private Bag X112, Pretoria 0001
e-mail: pbosch@geoscience.org.za

Patrick Eriksson
Department of Geology, University of Pretoria, Pretoria 0002
e-mail: pat.Eriksson@up.ac.za

© 2008 September Geological Society of South Africa

ABSTRACT

A complex variety of casts of sand cracks occurs at two study areas near Pretoria, within mature, thin sandstone beds of the c. 2.1 Ga Magaliesberg Formation (Pretoria Group, Transvaal Supergroup). This formation is ascribed to deposition within the littoral, sandy portions of a low-energy epeiric sea, then covering much of the Transvaal preservational basin. Reticulate networks of these sand crack casts (which equate to petee ridges) and lesser vermiform geometries, the latter commonly associated with ripple troughs (cf. Manchuriophycus), reflect a degree of cohesiveness which is difficult to envisage in sands unless there were either thin muddy interbeds between sandy strata, or the sandy beds were bound by microbial mats growing in their upper portions. In the absence of any observed mudstone interbeds, a genetic role for microbial mats can be supported. Several of these inferred microbially-induced sand cracks appear to have "healed", presumably having become overgrown by re-establishment of a new mat following partial desiccation of an earlier one. Associated "oncolites", found at one of the sites, confirm this general model of microbially-mediated "sand-cracking" having taken place. Such microbial mat features appear to be relatively widespread within the Magaliesberg Formation, most likely reflecting the shallow epeiric marine palaeoenvironment which would have favoured their preservation.
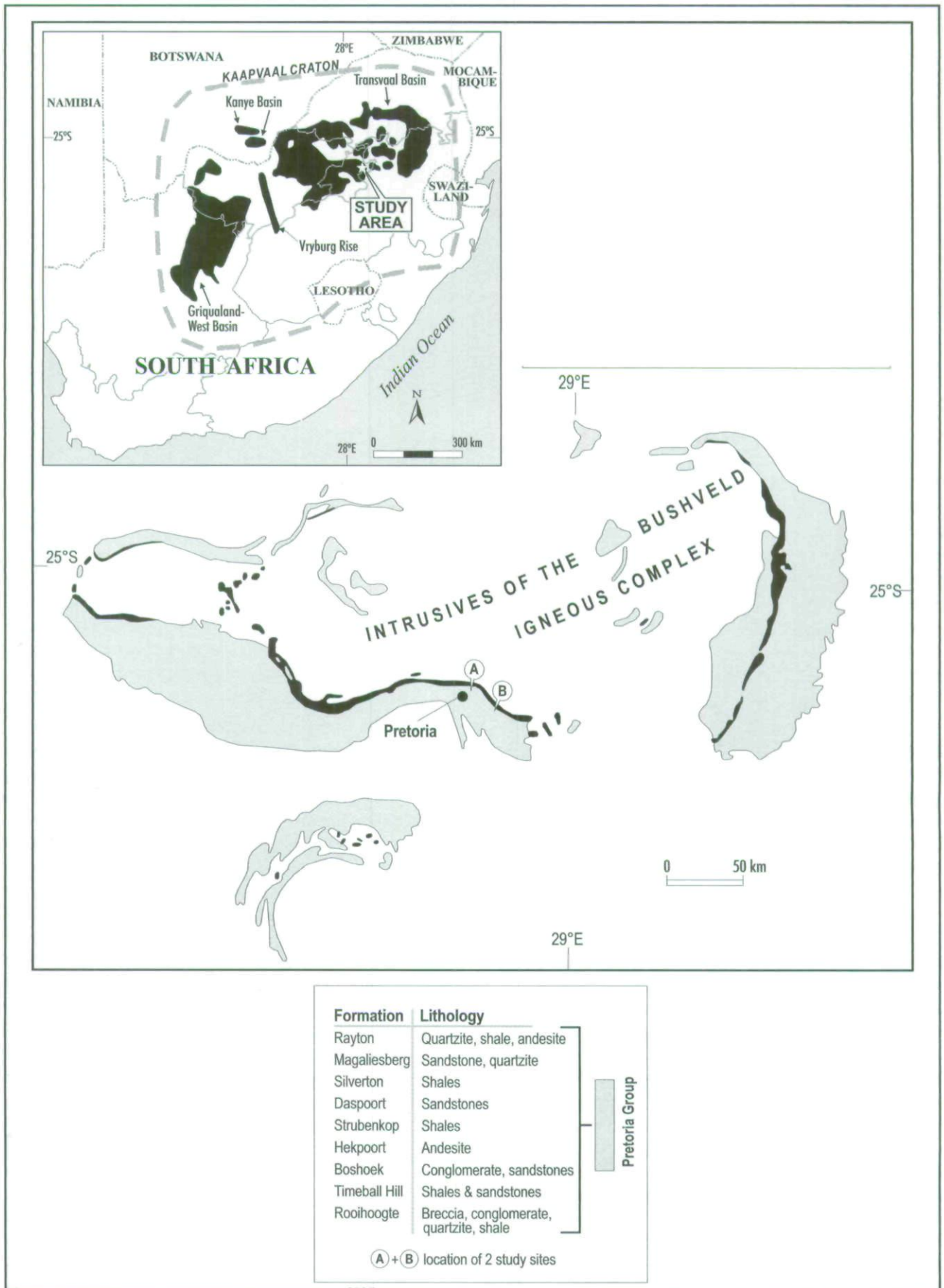
Introduction

Before the advent of grazing metazoans approximately coincident with the Neoproterozoic-Phanerozoic boundary, microbial mats would have been prolific on Earth and probably colonised most sedimentary surfaces, clastic and chemical, where their requirements in water/moisture, light and nutrition could be met (e.g., Schieber, 2004). Microbial features (cf. stromatolites) from carbonate rock-forming palaeo-environments are well known, but microbial mat features preserved within the clastic sedimentary record are much less so. A relatively large number of clastic sedimentary features directly or indirectly indicative of the presence of such mats is identified from the Precambrian rock record (e.g., Schieber, 1998; Gerdes et al., 1994, 2000; Gehling, 1999; Hagadorn et al., 1999; Sarkar et al., 2004; Schieber et al., 2007). Noffke et al. (2001) term these features the "microbially-induced sedimentary structures" ("MISS") and propose a classification thereof as an addendum to the well-known scheme of Pettijohn and Potter (1964). Schieber (2004) relates these microbially-influenced sedimentary structures to a genetic continuum from mat growth, through mat metabolism and mat destruction, to mat decay and diagenesis, within either sandstones or mudrocks. It should be emphasized that these mat-related features are sedimentary structures sensu stricto, that they may form from several

microbial genetic influences, and that analogous features may also form by non-biogenic means or through a mixture of physical-chemical and microbial influences (e.g., Schieber et al., 2007).

Recent work by Noffke et al. (2003; 2006a and b) has indicated that the "MISS" occur back as far as 3.2 Ga in the rock record, with the oldest known examples being South African at this stage: c. 3.2 Ga Moodies Group of the Barberton greenstone belt; c. 2.9 Ga Witwatersrand and Pongola Supergroups. They are often almost endemic to Precambrian epeiric marine coastal and intertidal (and even supratidal) facies, but also spread from deeper subtidal examples right through to palaeodesert mat-related features (e.g., Eriksson et al., 2000). While many workers find that mat-induced structures are not very facies-specific (reviewed in Schieber et al., 2007), Noffke et al. (2006a) use "MISS" to interpret shallow marine siliciclastic environments, and more specifically regression-transgression turning points (see their Figure 6 especially). The latter simplistic application is disputed by Catuneanu (2007) who argues in favour not only of a wider palaeoenvironmental distribution, but more specifically for mats having had a more complex effect on sequence architecture, systems tract preservation and sedimentation rates.

This paper examines inferred mat-related features from outcrops at two new study sites in the shallow marine sandstones of the Magaliesberg Formation

Formation	Lithology
Rayton	Quartzite, shale, andesite
Magaliesberg	Sandstone, quartzite
Silverton	Shales
Daspoort	Sandstones
Strubenkop	Shales
Hekpoort	Andesite
Boshoek	Conglomerate, sandstones
Timeball Hill	Shales & sandstones
Rooihoogte	Breccia, conglomerate, quartzite, shale

Pretoria Group

(A) + (B) location of 2 study sites

Figure 1. Geological map showing the locality of the two field sites: **(A)** – where casts of various sand cracks and "oncolites" were found on Baviaanspoort 330 JR; and **(B)** – where vermiform and reticulate sand cracks were found on Rietvlei 518 JR. The legend is also a stratigraphic column for the Pretoria Group in the Gauteng area; the Magaliesberg Formation is highlighted in black within the Pretoria Group symbol. Rayton Formation not shown on map.

(Pretoria Group, Transvaal Supergroup) in South Africa. The only previous study was at a quarry site in these rocks, where samples were no longer *in situ*. The current paper thus examines these mat-related structures within their preserved geological context, adds several additional biogenic structures to the previous study, and makes a contribution to the examination of these features in South Africa, where documentations of such MISS assemblages are as yet, few and far between, in one of the world's best Precambrian rock records.

General geology

The Magaliesberg Formation forms part of the *c.* 2.67 to 2.1 Ga Transvaal Supergroup within the Transvaal basin, one of three related preservational basins on the Kaapvaal craton (Eriksson *et al.*, 2001). The Transvaal basin-fill comprises basal "protobasinal" rocks (Wolkberg, Godwan and other Groups), followed by the Black Reef Formation, Chuniespoort Group and the uppermost Pretoria Group. The Pretoria Group in the central part of the Transvaal basin (Gauteng area) is subdivided into the basal Rooihoogte Formation, followed upwards by the Timeball Hill, Boshoek, Hekpoort, Strubenkop, Daspoort, Silverton, Magaliesberg and Rayton Formations (SACS, 1980; Eriksson *et al.*, 2001) (Figure 1). Pretoria Group sedimentation is ascribed to two cycles of rifting and

subsequent thermal subsidence, with the Magaliesberg Formation being deposited late in the second episode of thermal subsidence, in an intracratonic sag basin (Eriksson *et al.*, 2001).

The Magaliesberg Formation is characterized by a succession of fine- to coarse-grained, horizontally stratified and cross-bedded quartzose sandstones, with abundant ripple marks (Van der Neut, 1990). In the vicinity of Pretoria the formation is up to 300 m thick and locally contains minor, thin (a few dm) mudrock beds (Visser, 1969; Eriksson *et al.*, 1995). Three architectural elements (*cf.* Miall, 1985) are identified in the Magaliesberg: (1) medium- to coarse-grained sandstone sheets; (2) fine- to medium-grained sandstone sheets; and (3) mudrock elements. Both arenaceous elements are dominated by horizontal lamination and planar cross-bedding, with subordinate trough cross-bedding, channel-fills, wave ripple marks, minor double-crested and flat-topped ripples and desiccated mudrock partings (Eriksson *et al.*, 1995). This *c.* 2.1 Ga formation is ascribed to deposition through a combination of ephemeral braid-delta systems (architectural element #1 above, with unimodal palae-ocurrent trends) which debouched onto high-energy peritidal flats (element #2 above, with bi- to polymodal palaeocurrent modes), situated around the margins of a shallow epeiric sea then occupying the Transvaal basin (Eriksson *et al.*, 2002), where reworking through small

Figure 2. Upper sandstone bedding surface showing simple pattern of linear casts of sand cracks, with some second-order cracks within the larger features. Note also, poorly preserved ripple marks, manifested by dark coatings in the troughs. Baviaanspoort 330 JR.

Figure 3. Dense network of reticulate casts of sand cracks on a sandstone upper bedding surface at Baviaanspoort 330 JR. Note that some of the crack casts are linear and semi-parallel, and that second-order features appear to be less regular in their geometry.

Figure 4. Casts of sand cracks, up to 10 mm wide, forming an angular mosaic on a Magaliesberg sandstone upper bed surface at Baviaanspoort 330 JR. The casts are up to 2 cm above the bed surface.

Figure 5. Branching and sinuous casts of sand cracks that exhibit a second-order ridge within the first-order ridges; the former presumably formed after the latter, and it is thought that further desiccation following "healing" of the first-order cracks resulted in those of the second order, which the again became filled with sediment. Baviaanspoort 330 JR.

waves and macro-tidal action occurred (Eriksson *et al.*, 1995). The subordinate mudrock element suggests either abandonment of braid-delta channels, or uppermost tidal flat sedimentation.

The Magaliesberg (and other Transvaal basin rocks) formed the floor to the Bushveld Complex and as a result it has locally undergone intense contact metamorphism, producing hornfels and quartzite or quartzitic sandstone from the original sedimentary rocks. Further deformation of the Transvaal Supergroup rocks was caused by open interference folds (Eriksson *et al.*, 1998) and faulting (Bumby *et al.*, 1998). The dip of the bedding of the Magaliesberg Formation and other Transvaal strata is mostly towards the location of the centrally-situated Bushveld Complex.

Previous work on Magaliesberg Formation mat-related features
A localised study by Parizot *et al.* (2005) at a glass sand quarry about 50 km east of Pretoria was hampered by ongoing quarrying activities; many of the structures were thus observed on large loose blocks of sandstone rather than *in-situ* on upper bedding plane surfaces. These authors reported the presence of several structures supporting cyanobacterial mats in the Magaliesberg palaeoenvironment: cracked sand layers, ripple-crest cracks, petee ridges, "elephant skin textures", wrinkle structures and *Manchuriophycus*

(sinuous sand cracks in ripple troughs, originally given a trace fossil name). The ubiquitous ripple marks on most Magaliesberg sandstone bed surfaces were used by Parizot *et al.* (2005) to apply the Tanner (1967; 1971) formulae for estimating wave height and water depth within the depositional basin. Water depth estimates were between 30 and 40 cm and wave heights about 10 cm; minimum epeiric tidal ranges of about 112 cm were also indicated from these data (Parizot *et al.*, 2005). The present paper examines the Magaliesberg Formation over a wider area to try and establish how widespread the inferred microbial mat features may be.

Description of inferred microbial mat-related structures from this study
Very good exposures of crack-like features, vermiform structures and circular imprints resembling concretions or, possibly, oncolites occur on sand sheet surfaces within the uppermost beds of the Magaliesberg Formation at two localities: (1) north of Pretoria, on the farm Baviaanspoort 330 JR (shown as "A" on Figure 1); (2) the farm Rietvlei 518 JR (shown as "B" on Figure 1), east of Pretoria.

At both sites, the "sand cracks" (*cf.*, Schieber, 1998; Schieber *et al.*, 2007) occur on or partially within upper bedding surfaces and are highly variable in size, pattern and extent (Figures 2 to 7). The inferred sand cracks are manifested by the presence of linear, semi-circular,

Figure 6. Ripple marked sandstone upper bedding surface with casts of sand cracks superimposed thereon. Note that these casts are both semi-parallel to the ripple crests, yet also cut across them. Baviaanspoort 330 JR.

Figure 7. Vermiform casts of sand cracks found along the troughs of bifurcating, symmetrical ripples, on a sandstone bedding surface within the Magaliesberg Formation, at Rietvlei 518 JR. Note that some of the sinuous casts may branch locally, while others are much shorter, tapering and even have spindle-like forms. These structures are identified as equivalent to *Manchuriophycus* (see text).

curved or polygonal patterns or casts of slightly lighter coloured quartzitic sandstone to that typical of the local Magaliesberg Formation outcrops (Figures. 2 to 7). The individual cracks generally occur as casts, and are either embedded within, partially embedded within and partially elevated above, or only occur upon the surrounding bedding plane. These features occur from a few millimetres of depth within the bedding planes to two centimetres above the surrounding bedding plane. Normally, the wider the cast, the higher is the vertical thickness above the bedding plane. The casts within the sediment are u-shaped. This contrasts with the typically v-shaped profiles of mudcracks, and the lack of such v-shaped geometries has been confirmed by thin section work on many Magaliesberg sand crack samples (see also, Parizot et al., 2005).

These features resemble cracks that formed in sands and then became filled, or "healed". They vary from single isolated casts, far apart, that might locally cross-cut each other (Figure 2) to much denser networks (Figure 3). Some of the latter contain second-order cracks within larger features, and yet others form a network of closely spaced first- and second-order casts (Figure 3). Some of the first-order casts appear to be linear and semi-parallel over tens of centimetres (Figure 3), while others form branching and curved, healed crack-like patterns (Figure 5). The sand casts are highly variable in width, from a few millimetres (Figure 3) to 10 cm (Figure 4). Some of the structures show a central, secondary ridge within the larger ridge or cast (Figure 5). The sand-filled casts often cut across or run parallel to the axes of associated ripple marks (Figure 6).

At Rietvlei 518 JR, a different pattern of sand cast occurs, which shows a close relationship with ripple marks, where the casts occur as connected or disconnected, curved spindles or rods along the troughs of the ripple marks, resembling worm burrows (Figure 7). These casts form very shallow moulds, up to 2 mm deep, on the bedding surfaces and protrude up to 3 mm above the bedding surface. In plan they curve, branch, taper and may also be longitudinal, and sometimes they overlap partially. Two separate bedding surfaces containing these structures, and overlying each other with approximately 10 cm of sandstone in between, have been found at Rietvlei 518 JR. At the same locality, casts of sandstone cracks similar to those at Derdepoort 326 JR were found on a bedding surface a few centimetres below the surfaces containing the vermiform casts. On this bedding surface two distinct orders of filled sand cracks may be seen (Figure 8), namely very large casts and relatively smaller casts. The large casts form an angular blocky pattern of which the individual filled cracks are up to 3 cm wide and 1 cm above the bedding surface (Figure 8). The smaller casts are found within the larger casts and are polygonal, only a few mm wide, hardly protrude above the bedding surface, and apparently occupy very shallow moulds.

Imprints of round structures of relatively constant size, 7 to 8 mm in diameter, were also found on a bedding surface in close proximity to the sand cracks on Derdepoort 326 (Figure 9). These structures display concentric rings and some of them appear to be twinned (Figure 9). One of these circular structures shows a disruption of the concentric rings from the outside, from near the rim of the structure towards the centre (arrowed in Figure 9).

Discussion

Sedimentary structures which were previously interpreted as possible desiccation cracks were noted by Visser (1969) and Van der Neut (1990) in the mature Magaliesberg Formation sandstones, but their origin was not explained satisfactorily. An origin as mudcracks, with the muddy layer having been removed through erosion and/or weathering prior to deposition of the second, overlying sandstone layer, has thus commonly been assumed for these Magaliesberg structures. The large variety in size, shape and density of the "desiccation" structures, their positive relief and their occurrence on relatively mature sandstone beds can not be explained satisfactory by ordinary mudcracks or desiccation cracks, and special conditions must have existed for their formation. Sand on its own does not possess enough cohesiveness to crack, unless it contains a significant proportion of clay minerals or is bound by a microbial mat growing on its upper surface (e.g., Schieber, 1998). It is this factor, as well as the lack of amalgamation of successive mature sandstone beds within a thick arenaceous succession, that suggest a possible role for microbial mats in the formation of what are essentially "sand cracks". Thin sections across such cracks and the bedding planes separating non-amalgamated sandstone beds (cf., Bottjer and Hagadorn, 2007; Eriksson et al., 2007a) confirm the absence of clays associated with the Magaliesberg sand cracks (e.g., Parizot et al., 2005).

In a recent atlas of all the known microbial mat-related features within the clastic sedimentary record (Schieber et al., 2007), several different types of sand cracks are described. These features fall within the mat destruction group of mat-related sandstone features, according to the Schieber (1998; see also Eriksson et al., 2007b) classification scheme. Leaf- or spindle-shaped cracks are known, which appear to reflect incipient tears in a microbial mat; these may connect up to form triradiate cracks, which can also form in that geometry on their own; polygonal or reticulate crack patterns form once enough cracks join up; more complex patterns include sinuously curved to sinusoidal geometries and even Figures-of-eight patterns (Eriksson et al., 2007a).

Once these various cracks have occurred within the mat growing upon a sandy substrate, they may penetrate into the underlying sand, with the mat providing the necessary cohesion. These sand cracks can either themselves become filled later by secondary sands, or the cracks in the living mats can be filled by later sand

from above, forming positive features – in the latter case, the composition or texture of the filling sand will differ from that of the underlying bed (*cf.* Eriksson *et al.*, 2007a). However, such cracks in living mats can also be filled from below, by sand driven into the cracks by pressure from overlying water or newly deposited (sandy) beds, or even due to tidally mediated water level changes (Schieber *et al.*, 2007). Such filled cracks would then stand out as positive features on the underlying sand bed surface – these positive ridges are often termed "petee" ridges (see, however, discussion below on the precise usage of this term). Alternatively, the growing microbial mats may either expand or gas from decaying sub-mat organic matter may cause similar bulges in the living mat surface – unconsolidated, pressurised sand may fill in these sub-mat hollows, forming "petees" (*sensu stricto*) with a geometry of sinuous to polygonal surface ridge patterns (Gehling, 1999). The discrimination of such petees from those filled from above generally requires detailed thin section studies. The Magaliesberg petee ridges appear to have been formed by unconsolidated sand moving into the cracks from below, as indicated by thin section studies (see also, Parizot *et al.*, 2005a). In some cases, negative sand cracks preserved in ancient sandstone beds pass laterally into positive petees, reinforcing a genetic relationship between such cracks and petees (*e.g.*, Eriksson *et al.*, 2007a).

The word "petees", introduced by Gavish *et al.* (1985), was used to denote tepee-like structures in modern mats, whose positive wrinkling was ascribed to wind or gravity deformation of the partially loose mats growing on sandy substrates. Later, Reineck *et al.* (1990) interpreted petees as biologically modified overthrust structures, formed due to subsurface gas concentrations, or surficial wind or water friction which deformed the growing mats' upper surfaces. These two original definitions restricted the term petee (*sensu stricto*) to closed and rounded positive features in the mats themselves. A possible association of petees (*sensu lato*) with cracked mat surfaces was noted by Gehling (1999, 2000). Schieber (2004) similarly expanded the original definition, describing crack-related positive features as "petee ridges", related to rupturing of the mat surfaces, and he described polygonal and network-like ridge complexes. Once a first-order set of petee ridges had formed through mat rupture, second-order ridges could easily result from partial desiccation of first-order mat fragments, providing patterns similar to those observed in the Magaliesberg Formation (Figures 3 and 8). According to Shinn (1983) the difference in the sizes of the cracks in microbial mats is not well understood but it is probably related to the length of exposure and the thickness of the mats.

The presence of secondary filled cracks (Figure 5) or ridges within older cracks suggests that some of the original cracks were healed or filled in by sand and the process must have repeated itself by further desiccation, cracking and healing. Analogous features

have been noted by several previous workers on microbial mat structures within the sandy sedimentary record, notably by E. Bouougri and H. Porada (pers. comm., 2006); they note a continuum from curled crack margins to flipped-over mat edges to rolled up (*cf.* "roll-ups'; see also Eriksson *et al.*, 2000) mat fragments and eroded mat chips (*e.g.*, Bouougri and Porada, 2002). Renewed mat growth can overgrow existing mat cracks, a feature termed "overgrown upturned margins" by Bouougri and Porada (pers. comm., 2006); this could explain those observed in the Magaliesberg also (*cf.*, Figure 5).

Vermiform curved markings, similar to those on Rietvlei 518 JR, have been described by Hofmann (1967) as *Rhysonetron*, a dubious pseudofossil from the 2500-2130 Ma Bar River Formation, Cobalt Group in Canada. *Rhysonetron* structures have also been described from Proterozoic quartzites in northeastern Finland by Laurma and Piispanen (1967). A biologic or fossil origin was initially favoured by Hofmann, (1967) for these structures, based on on the presence of well-developed corrugations, clean separation of the spindles from the matrix, the elliptical or circular cross-sections, paucity of mud, and overlap of some of the structures. However, Hofmann (1971) argues that the corrugations are found in a distinct shrinkage crack pattern and therefore concludes that the structures are a sedimentary-diagenetic structure, resulting from shrinkage crack-filling and modified by compaction and injection processes, and impressed into the substrate and superstrate, accompanied by removal of a pelitic layer. The inferred sandy littoral palaeoenvironment with well-sorted, clean sandstone beds and the absence of interbedded pelitic sedimentary rocks at the top of the Magaliesberg Formation, and the absence of corrugated structures in the spindles in the study area, makes a similar process less likely. A more viable option for the formation of the vermiform pseudofossils of the Magaliesberg Formation is similar to that proposed by Donaldson (1967), who studied modern flat algal mats subjected to subaerial desiccation and witnessed the formation of hollows and tunnel-like ridges in flat, paper-thin coatings of such mats. In plan these "tunnels" appear as distinct linear, curved, and sinuous ridges, between 3 and 15 mm high and/or wide, that commonly branch and taper and disappear over short distances. Donaldson (1967) mentions that these structures are often aligned, mostly hollow and filled by sediment during subsequent periods of sedimentation. Desiccation polygons of various sizes formed on the desiccated microbial mats studied by Donaldson (1967) and he noticed marginal rolling up of the mats along the edges of the polygons. Infill of sediment along these may form cylindrical or curved sand casts. Donaldson (1967) also mentions that these algal mats may completely decay subsequent to burial, leaving only the structures they served to create as a record of their former presence. The sinuous forms found in the Magaliesberg Formation on Rietvlei 518 JR can be

Figure 8. Casts of large sand cracks containing much smaller second-order features between the larger polygons, Rietvlei 518 JR.
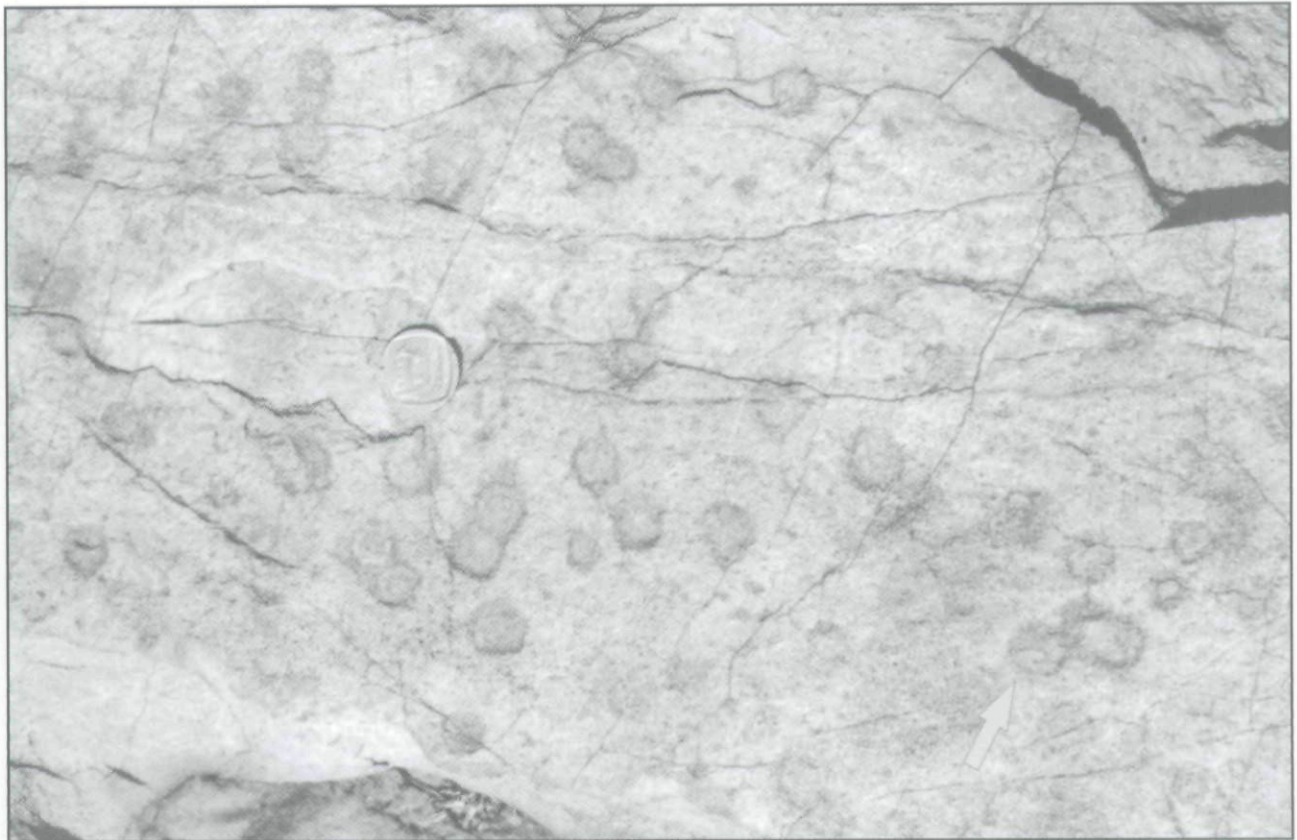
Figure 9. Circular imprints on a sandstone bedding surface of the Magaliesberg Formation at Baviaanspoort 330 JR. Some of the circular features are twinned, and they also show an internal concentric structure, except for the arrowed example, where the concentric rings are disrupted.

equated with *Manchuriophycus* (*cf. Rhysonetron* – note that this is a pseudofossil appellation in both cases), which is a special type of microbial shrinkage crack, normally developed within the thicker mats that occur within the troughs between ripples (Schieber *et al.*, 2007); this is why they are found directly associated with that part of preserved ripple marks, as in the case also of the Magaliesberg examples discussed here (see Figure 7).

The circular imprints within the Magaliesberg Formation on Baviaanspoort 330 JR (Figure 9) might at first glance be explained as concretions, but this explanation is not satisfactory to explain all the observed features. An interpretation as "oncolites" (oncolites are normally carbonate sediment entrapment features), however, satisfies many of the described features. According to Pettijohn (1975) oncolites are nearly spheroidal in shape and are commonly between 1 and 2 cm in diameter. A most characteristic feature of oncolites is their quasiconcentric internal structure of which the laminations vary somewhat in thickness and regularity (Pettijohn, 1975). According to Pettijohn (op. cit.), micro-unconformities might exist and these would be expressed as interruptions in growth. Such an irregular growth form might well be displayed in one of the circular features in Figures 9. The formation of oncolites is attributed to entrapment of carbonate detritus by a microbial mat, and growth takes place on the sides and upper surface of the resultant positive features (Pettijohn, 1975). The presence of the twinned circular features in Figures 9 may be explained by separate clastic "oncolites" initially adjacent to each other that grew, joined and eventually shared a mutual outer rim. Entrapment of clastic sediment by a microbial mat is postulated here as a possible explanation of these structures in the Magaliesberg Formation. Alternatively, they may reflect fluid escape features in unconsolidated sands, preserved through the medium of mat-related cohesiveness (S. Sarkar, 2007, personal communications).

The combination of ripple marks, inferred "oncolites" and various forms of microbial mat-related desiccation cracks suggests that these beds of the Magaliesberg Formation were formed in a very shallow water environment that was subjected to aerial exposure and desiccation. Microbial mat features ("MISS") are best preserved in the upper portion of intertidal and supratidal settings (*e.g.*, Noffke *et al.*, 2006a). Oncolites *sensu stricto* generally form in relatively more saline lacustrine environments (Dean and Fouch, 1983); their possible occurrence within the largely analogous clastic shoreline settings of the large epeiric Magaliesberg sea, subject to low wave energy, is compatible with this general viewpoint.

Conclusion

The occurrence of microbial mat-related features in the Magaliesberg Formation, first noted at a single locality by Parizot *et al.* (2005), thus appears to be relatively widespread within this unit; further research is needed to establish whether these were pervasive features during deposition of the Magaliesberg epeiric marine tidally dominated coastline. The rhythmic alternation of water levels inherent in such settings can explain desiccation of microbial mats growing on the sandy substrates formed within the palaeoenvironment, and shifting loci of deposition were probably also related to braided fluvial inputs, through the medium of braid-deltas.

It would have been necessary for abandonment of such mat surfaces to have taken place, once they had cracked and filled to form petee ridges, *Manchuriophycus* cracks etc., for some weeks (G. Gerdes, 2006, personal communication), as continuous sedimentation does not allow the development and preservation of these features (Schieber *et al.*, 2007). The possibility that such mat-related features preferentially form and are preserved in shallow littoral and tidal settings rests partly on their common observation in such settings today, and the preferential preservation of epeiric marine shoreline deposits in contrast to their more distal equivalents, as such epicontinental seas retreated off emerging continents within the Neoarchaean and Palaeo-proterozoic (see discussion by Catuneanu, 2007).

References

Bottjer, D. and Hagadorn, J.W. (2007). Mat growth features. *In*: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann and O. Catuneanu (Editors), Atlas of Microbial Mat features preserved within the Siliciclastic Rock Record. *Elsevier Atlases in Geology 2, Elsevier, Amsterdam, the Netherlands*, in press.

Bouougri, E. and Porada, H. (2002). Mat-related sedimentary structures in Neoproterozoic peritidal passive margin deposits of the West African craton (Anti-Atlas, Morocco). *Sedimentary Geology*, **153**, 85-106.

Bumby, A.J., Eriksson, P.G. and Van der Merwe, R. (1998). Compressive deformation of the floor rocks to the Bushveld Complex (South Africa): evidence from the Rustenburg Fault Zone. *Journal of African Earth Sciences*, **27**, 307-330.

Catuneanu, O. (2007). Sequence stratigraphic context of microbial mat features. *In*: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann and O. Catuneanu (Editors), Atlas of Microbial Mat features preserved within the Siliciclastic Rock Record. *Elsevier Atlases in Geology 2, Elsevier, Amsterdam, the Netherlands*, in press.

Dean, W.E. and Fouch, T.D. (1983). Lacustrine Environment. *In*: P.A. Scholle, D.G. Bebout and C.H. Moore (Editors), Carbonate Depositional Environments. *American Association of Petroleum Geologists, Tulsa, Oklahoma, United States of America*, 99-130.

Donaldson, J.A. (1967). Precambrian vermiform structures; a new interpretation. *Canadian Journal of Earth Science*, **4/6**, 1273-1276.

Eriksson, P.G., Reczko, B.F.F., Boshoff, A.J., Schreiber, U.M., Van der Neut, M. and Snyman, C.P. (1995). Architectural elements from Lower Proterozoic braid-delta and high-energy tidal flat deposits in the Magaliesberg Formation, Transvaal Supergroup, South Africa. *Sedimentary Geology*, **97**, 99-117.

Eriksson, P.G., Van der Merwe, R. and Bumby, A.J. (1998).The Palaeoproterozoic Woodlands Formation of eastern Botswana – northwestern South Africa: lithostratigraphy and relationship with Transvaal basin inversion structures. *Journal of African Earth Sciences*, **27/3-4**, 349-358.

Eriksson, P.G., Simpson, E.L., Eriksson, K.A., Bumby, A.J., Steyn, G.L. and Sarkar, S. (2000). Muddy roll-up structures in siliciclastic interdune beds of the c. 1.8 Ga Waterberg Group, South Africa. *Palaios*, **15**, 177-183.

Eriksson, P.G., Altermann, W., Catuneanu, O, van der Merwe, R. and Bumby, A.J. (2001). Major influences on the evolution of the 2.67 – 2.1 Ga Transvaal basin, Kaapvaal craton. *Sedimentary Geology*, **141-142**, 205-231.

Eriksson, P.G., Altermann, W., Eberhardt, L., Ahrend-Heidbrinck, S. and Bumby, A.J. (2002). Palaeoproterozoic epeiric sea palaeoenvironments: the Silverton Formation (Pretoria Group, Transvaal Supergroup), South Africa. *In*: W. Altermann and P.L. Corcoran (Editors), Precambrian Sedimentary Environments: a modern approach to ancient depositional systems. *Special Publication 33, International Association of Sedimentologists, Blackwell, Oxford, United Kingdom*, 351-367.

Eriksson, P.G., Porada, H., Banerjee, S., Bouougri, E., Sarkar, S. and Bumby, A.J. (2007a). Mat destruction features. *In*: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann and O. Catuneanu (Editors), Atlas of Microbial Mat features preserved within the Siliciclastic Rock Record. *Elsevier Atlases in Geology 2, Elsevier, Amsterdam, the Netherlands*, in press.

Eriksson, P.G., Schieber, J., Bouougri, E., Gerdes, G., Porada, H., Banerjee, S., Bose, P.K. and Sarkar, S. (2007b). Classification of structures left by microbial mats in their host sediments. *In*: J. Schieber, P.K. Bose, P.G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann and O. Catuneanu (Editors), Atlas of Microbial Mat features preserved within the Siliciclastic Rock Record. *Elsevier Atlases in Geology 2, Elsevier, Amsterdam, the Netherlands*, in press.

Gavish, E., Krumbein, W.E. and Halevy, J. (1985). Geomorphology, mineralogy and groundwater chemistry as factors of the hydrodynamic system of the Gavish Sabkha. *In*: G.M. Friedman and W.E. Krumbein (Editors), Hypersaline Ecosystems: the Gavish Sabkha. *Springer, Berlin, Germany*, 186-217.

Gehling, J.G. (1999). Microbial mats in terminal Proterozoic siliciclastics: Ediacaran death masks. *Palaios*, **14**, 40-57.

Gehling, J.G. (2000). Environmental interpretation and a sequence stratigraphic framework for the terminal Proterozoic Ediacara Member within the Rawnsley Quartzite, south Australia. *Precambrian Research*, **100**, 65-95.

Gerdes, G., Krumbein, W.E. and Reineck, H.-E. (1994). Microbial mats as architects of sedimentary surface structures. *In*: W.E Krumbein, D.M. Paterson and L.J. Stal (Editors), Biostabilization of Sediments. *Bibliotheks- und Informationssystem, Universität Oldenburg, Oldenburg, Germany*, 165-182.

Gerdes, G., Klenke, T. and Noffke, N. (2000). Microbial signatures in peritidal siliciclastic sediments: a catalogue. *Sedimentology*, **47**, 279-308.

Hagadorn, J.W., Pfluger, F. and Bottjer, D.J. (1999). Unexplored microbial worlds. *Palaios*, **14**, 1-2.

Hofmann, H.J. (1967). Precambrian Fossils (?) near Elliot Lake, Ontario. *Science*, **157/3774**, 500-504.

Hofmann, H.J. (1971). Precambrian fossils, pseudofossils, and problematica in Canada. *Bulletin, Geological Survey of Canada*, **189**, 146pp.

Lauerma, R and Piispanen, R. (1967). Worm-shaped casts in Precambrian quartzite from Kuusamo, northeastern Finland. *Bulletin de la Commission Géologique de Finlande*, **229**, 189-197.

Miall, A.D. (1985). Architectural-element analysis; a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews*, **22**, 261-308.

Noffke, N., Gerdes, G., Klenke, T. and Krumbein, W.E. (2001). Microbially induced sedimentary structures – a new category within the classification of primary sedimentary structures. *Journal of Sedimentary Research*, **A71**, 649-656.

Noffke, N., Hazen, R. and Nhleko, N. (2003). Earth's earliest microbial mats in a siliciclastic marine environment (2.9 Ga Mozaan Group, South Africa). *Geology*, **31**, 673-676.

Noffke, N., Beukes, N. and Hazen, R. (2006a). Spatial and temporal distribution of microbially induced sedimentary structures: a case study from siliciclastic storm deposits of the 2.9 Ga old Witwatersrand Supergroup, South Africa. *Precambrian Research*, **146**, 35-44.

Noffke, N., Eriksson, K.A., Hazen, R.M. and Simpson, E.L. (2006b). A new window into Early Archean life: microbial mats in Earth's oldest siliciclastic deposits (3.2 Ga Moodies Group, South Africa). *Geology*, **34**, 253-256.

Parizot, M., Eriksson, P.G., Aifa, T., Sarkar, S., Banerjee, S., Catuneanu, O., Altermann, W., Bumby, A.J., Bordy, E.M., Rooy, J.L. and Boshoff, A.J. (2005). Suspected microbial mat-related crack-like sedimentary structures in the Palaeoproterozoic Magaliesberg Formation sandstones, South Africa. *Precambrian Research*, **138**, 274-296.

Pettijohn, E.J. (1975). Sedimentary Rocks, 3rd Edition. *Harper, New York, United States of America*, 628pp.

Pettijohn, F.J. and Potter, P.E. (1964). Atlas and Glossary of Primary Sedimentary Structures. *Springer, Berlin, Germany*, 370pp.

Reineck, H.-E., Gerdes, G., Claes, M., Dunajtschik, K., Riege, H. and Krumbein, W.E. (1990). Microbial modification of sedimentary surface structures. *In*: D. Heling, P. Rothe, U. Förstner and P. Stoffers (Editors), Sediments and Environmental Geochemistry. *Springer, Berlin, Germany*, 254-276.

Sarkar, S., Banerjee, S. and Eriksson, P.G. (2004). Microbial mat features in sandstones illustrated. *In*: P.G. Eriksson, W. Altermann, D.R. Nelson, W.U. Mueller, O, Catuneanu (Editors), The Precambrian Earth: Tempos and Events. *Developments in Precambrian Geology 12, Elsevier, Amsterdam*, 673-675.

Schieber, J. (1998). Possible indicators of microbial mat deposits in shales and sandstones: examples from the Mid-Proterozoic Belt Supergroup, Montana, USA. *Sedimentary Geology*, **120**, 105-124.

Schieber, J. (2004). Microbial mats in the siliciclastic rock record: a summary of the diagnostic features. *In*: P.G. Eriksson, W. Altermann, D.R. Nelson, W.U. Mueller and O. Catuneanu (Editors), The Precambrian Earth: Tempos and Events. *Developments in Precambrian Geology 12, Elsevier, Amsterdam, the Netherlands*, 663-673.

Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W. and Catuneanu, O. (Editors) (2007). Atlas of Microbial Mat features preserved within the Siliciclastic Rock Record. *Elsevier Atlases in Geology 2, Elsevier, Amsterdam, the Netherlands*, in press.

Shinn, E.A. (1983). Tidal Flat Environment. *In*: Scholle, P.A, Bebout, D.G and Moore, C.H. (Editors), Carbonate Depositional Environments. *American Association of Petroleum Geologists, Tulsa, Oklahoma, United States of America*, 172-210.

South African Committee for Stratigraphy (SACS), (1980). Stratigraphy of South Africa. Part 1. Lithostratigraphy of the Republic of South Africa, South

West Africa/Namibia, and the Republics of Bophuthatswana, Transkei, and Venda (L.E. Kent, compiler). *Handbook, Geological Survey of South Africa* **8**, 690pp.

Tanner, W.F. (1967). Ripple mark indices and their uses. *Sedimentology,* **9**, 89-104.

Tanner, W.F. (1971). Numerical estimates of ancient waves, water depths and fetch. *Sedimentology,* **16**, 71-88.

Van der Neut, M. (1990). Afsettingstoestande van die Pretoria Groep gesteentes in the Pretoria-Bronkhorstspruit-Delmas gebied. *Unpublished MSc thesis, University of Pretoria, South Africa,* 233pp.

Visser, J.N.J. (1969). 'n Sedimentologiese Studie van die Serie Pretoria in Transvaal. *Unpublished PhD thesis, University of the Orange Free State, South Africa,* 263pp.

Editorial Handling: Adam Bumby