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Evidence for 2.0 Ga continental microbial mats in a paleodesert setting

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ABSTRACT

Early evolved microbial communities characterized the initial biological invasion of Precambrian continental landscapes. In modern arid settings, microbial mats and biological soil crusts are well-developed and stabilize sediment. The Paleoproterozoic Makgabeng Formation in South Africa is one of the oldest and best preserved, dryland systems on Earth. Six types of microbial mat-related structures are now recognized within these depositional systems. This paper presents three newly discovered structures that include tufted microbial mat, biological soil crusts, and gas-escape features, in addition to three previously documented structures that include roll up features, sand cracks, and wrinkled features. These discoveries demonstrate that microbial communities were well-established and inhabited diverse continental settings by 2.0 Ga, approximately 200 million years after the onset of the Great Oxidation Event.

1. Introduction

Microbial mat communities played a critical role in the initial biological invasion of Precambrian continental landscapes (Campbell, 1979; Buick, 1992; Prave, 2002; Battistuzzi et al., 2004; Retallack, 2008; Beraldi-Campesi et al., 2009; Beraldi-Campesi and Garcia-Pichel, 2011; Finkelstein et al., 2010; Noffke, 2010; Sheldon, 2012). Stable isotope and/or major element geochemistry gleaned from paleosols and marine sediments have been cited as proxy evidence of initial biological expansion of microbes onto continents in the Archean (Kenny and Knauth, 1992; Gutzmer and Beukes, 1998; Watanabe et al., 2000; Retallack, 2001; Stüeken et al., 2012). During the Archean, this ecospace exploitation led to the initial appearance of the mature quartz sandstones generated partially (in addition to an aggressive paleo-atmosphere) by microbial binding that enhanced in situ weathering (Dott, 2003). Although the exact timing is uncertain, initial terrestrial mat and crust development appear to have occurred after the onset of the prokaryotic radiation (Labandeira, 2005). Phylogenic analysis is congruent with these estimates that colonization of continents transpired between ~2.8 and 3.1 Ga (Battistuzzi et al., 2004).

This study describes the variety of microbially induced sedimentary structures (MISS; Noffke et al., 1996) and biological soil crust (BSC) features in the ~2.0 Ga (new age constraint), Makgabeng Formation, South Africa (Fig. 1) and documents their morphological varieties in continental environments. These MISS and BSC structures signal the presence of a robust and thriving Paleoproterozoic continental microbial ecosystem, approximately 200 million years after the Great Oxidation Event (e.g., Holland, 2002, 2006).

2. Geologic setting

The Waterberg Group ranges from approximately 2.06–1.88 Ga based on new mapping and radiometric age constraints; these age constraints are significantly older than previously thought (SACS, 1980; Jansen, 1982; Walraven and Hattingh, 1993; Bumby, 2000; Bumby et al., 2001, 2004; Eglington and Armstrong, 2004; Hanson et al., 2004; Dorland et al., 2006). The Main Waterberg Basin, part of the Kaapvaal Craton, is bounded to the north by the Limpopo Mobile Belt as exemplified by the Palala Shear Zone (Fig. 1; Light, 1982; Roering et al., 1992; Kröner et al., 1999) and to the south by the Thabazimbi-Murchison lineament (Kröner et al., 1999). The Limpopo Belt has an extended and complex tectonic history with numerous periods of fault reactivation that acted as a northern source for pulses of sediment entering and filling the Waterberg Basin (Bumby, 2000; Bumby et al., 2001, 2004). Regional

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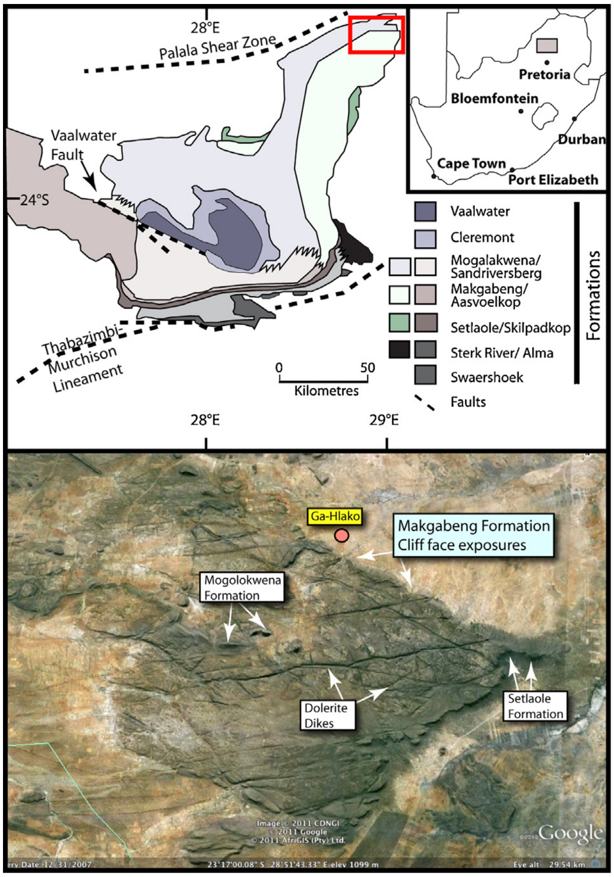

Fig. 1. (A) Locality map of the Main Waterberg Basin in northern South Africa. The northern boundary of the basin is delineated by the Palala Shear Zone and the southern boundary by the Thabazimbi-Murchison Lineament. (B) Google Earth map view of the Makgabeng plateau. Note the location of the cliff exposure and the dip slope to the southwest.

paleocurrent analysis in the northern part of the Waterberg basin supports a consistent source from the Limpopo Belt for the time span of the Waterberg Group fluvial systems (Callaghan et al., 1991; Bumby, 2000; Bumby et al., 2001, 2004; Eriksson et al., 2006, 2008).

Within the Main Waterberg Basin, the Waterberg Group is subdivided into eleven formations that vary vertically and laterally in lithology (Fig. 2; Eriksson et al., 2006). In the northern part of the Main Waterberg Basin the Makgabeng Formation conformably overlies the Setlaole Formation and in turn is disconformably overlain by the Mogalakwena Formation (Fig. 2; SACS, 1980; Jansen, 1982; Bumby, 2000). The Setlaole Formation consists of feldspathic sandstones and conglomerates (with minor volcanic ash layers) that record southward-draining braided fluvial systems shed off the reactivated Limpopo Belt (Fig. 2; Callaghan et al., 1991; Bumby, 2000; Bumby et al., 2001). The contact between the Setlaole and Makgabeng Formations is not well exposed in the study area. Polymictic conglomerates and feldspathic to lithic sandstones characterize the younger Mogalakwena Formation and these reflect the presence of braided stream systems with unusually high stream gradients, also sourced from the reactivated Limpopo Belt (Eriksson et al., 2006, 2008).

The Makgabeng Formation crops out along a series of cliff faces, ~15 km long, as well as dip slope exposures on the concomitant plateau in the northern part of the main basin (Fig. 1; Bumby, 2000; Eriksson et al., 2008) where the Makgabeng Formation reaches a maximum thickness of ~800 m. Here, the upper strata of the Makgabeng Formation are best exposed. The Makgabeng Formation is composed predominately of fine- to medium-grained, quartz-rich sandstone (Callaghan et al., 1991; Eriksson and Cheney, 1992; Bumby, 2000; Eriksson et al., 2000; Simpson et al., 2002, 2004). Along the plateau and the cliff face, strata dip approximately southwest at less than 5°. Metamorphism of the Makgabeng Formation strata was minimal and is mainly linked to a series of cross-cutting, post-Bushveld-age doleritic dikes (Hanson et al., 2004) and shallow-burial metamorphism. The dikes are expressed as a series of linear topographic lows on the plateau (Fig. 1). Hydrothermal metamorphism and soft-sediment deformation of the Makgabeng Formation strata are restricted to the proximity of these dikes.

The Makgabeng Formation quartz sandstones are one of the oldest eolian erg deposits preserved on Earth (Eriksson and Cheney, 1992; Eriksson and Simpson, 1998; Simpson et al., 2002, 2004; Eriksson et al., 2013). Associated with the preserved dune deposits are interdune, saline pan/playa, and minor fluvial environments (Fig. 3; Meinster and Tickell, 1975; Callaghan et al., 1991; Bumby, 2000; Simpson et al., 2002, 2004). Within the eolian deposits, specifically the interdune setting, mudstone roll-up structures have been previously documented (Eriksson et al., 2000, 2007; Porada and Eriksson, 2009). Other types of sedimentary features that are attributable to the binding of microbial mats have been recognized (Eriksson et al., 2007; Porada and Eriksson, 2009). The upper strata of the Makabeng Formation are best exposed within the cliff face and on the dip slopes of the plateau (Meinster and Tickell, 1975; Callaghan et al., 1991; Bumby, 2000; Eriksson et al., 2000; Simpson et al., 2002, 2004; Heness et al., 2012). This work was restricted to the uppermost ~75 m of strata (Fig. 4).

3. Paleoenvironments

The facies composing the upper strata of the Makgabeng Formation record the impact of climate variation on the Paleoproterozic dune field system (Eriksson et al., 2013; Heness et al., 2012). Within this upper portion of the Makgabeng Formation, lower and upper erg deposits are separated by a laterally extensive playa deposit (Figs. 3A and 4 and Table 1; Bumby, 2000; Heness et al., 2012). Variable size sets of eolian cross-strata compose the lower erg deposits (Table 1). Wet interdune deposits of the lower erg increase in abundance, thickness, and lateral extent approaching the overlying medial playa strata (Figs. 3B and 4; Eriksson et al., 2000; Heness et al., 2012). The transition from the lower erg to the overlying playa deposit is abrupt, and the stratal surface at the base of the playa has up to ~50 cm of relief (Fig. 3C). The playa facies varies greatly in grain size, from mudstone to coarse-grained sandstone (Simpson et al., 2004, 2012). Climatic amelioration at variable time scales is reflected in the vertical variation of the facies stacking patterns. The upper erg deposit consists of larger-scale cross-bed sets (Table 1). In the main portion of the upper erg deposit interdune deposits are very thin, less than a centimeter thick, to absent (Fig. 3D). Near the top of the upper erg deposit, playa and interfingering sand-dominated ephemeral fluvial facies reflect an increase in precipitation (Fig. 4; Bumby, 2000; Heness et al., 2012). Also, near the top of the upper erg deposit, dune facies with interbedded massive sandstone facies, more prevalent and better developed below the contact with the overlying Mogalakwena Formation, attest to climatic amelioration that led to cessation of erg development (Fig. 4).

4. Microscopic mat features: establishing biogenicity

Noffke (2009) developed six criteria to determine the biogenicity of sedimentary features found in Precambrian strata. Although the criteria were developed for marine strata, the benchmarks are mostly applicable to Precambrian continental strata as well. Noffke's (2009) criteria necessary to assign biogenicity to features