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Possible evidence for episodic epeiric marine and fluvial sedimentation (and implications for palaeoclimatic conditions), c. 2.3–1.8 Ga, Kaapvaal craton, South Africa

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ABSTRACT

The debate on Palaeoproterozoic atmospheric composition, climate, and the timing and nature of the postulated “great oxidation event” (possibly at c. 2.3 Ga) remain matters of debate within Precambrian geology. This paper contributes to the debate through examination of physical sedimentary structures preserved within two separate groups of sedimentary deposits, from the central and northern portions of the Kaapvaal craton, South Africa. Within the c. 2.3–2.1 Ga Pretoria Group, study of epeiric marine sandstones and mudrocks (Magaliesberg and Silverton Formations, c. 2.1 Ga) suggests that fluvial input was predominant over low energy reworking by waves, winds and tides. This together with extensive evidence for microbial mat growth within the littoral sandstones of the Magaliesberg Formation, points to strongly episodic sedimentation by both marine and fluvial processes. Within two younger basins, belonging to the c. 2.05–1.8 Ga Waterberg Group, anomalously high palaeoslopes (calculated according to standard palaeohydrological methods), combined with direct field evidence for sediment gravity-flows and sheetflood deposition within an overall braided fluvial setting, again suggest episodic sedimentation. Strongly episodic sedimentation can most easily be reconciled with a greenhouse palaeoclimate, at least for that part of Kaapvaal at that time. Taken together, these data sets point to the postulate that the generally accepted change from a Palaeoproterozoic greenhouse through a “great oxidation event” (c. 2.3 Ga?) to less extreme climatic conditions, may have been gradational and even “diachronous” across the Earth's cratons at that time.

1. Introduction

The history of Earth's early atmosphere, hydrosphere, and biosphere, from Hadean through Proterozoic time, is one of geology's enduring puzzles. The main controls on the chemistry of the Archaean oceans were probably reactions with hot igneous rocks (including vigorous hydrothermal inputs), sea floor weathering, and additions of new juvenile water, with minor input from fluvial systems (e.g., Lambert, 1982). Oxygen isotope studies (Lambert, 1982; see also, Kasting and Howard, 2006; Kasting and Ono, 2006) from Archaean sediments suggested that fluids were isotopically similar to modern seawater, and that Archaean hydrospheric temperatures reached up to 70 °C. However, these early oceans may not have been so warm (Shields and Kasting, 2007; Van den Boorn et al., 2007 for contrasting views). Lecuyer et al. (1996) determined that the hydrogen isotope composition of Palaeoproterozoic seawater was similar to the modern value and that subduction and ridge processes that control the global water cycle have not changed significantly since the Palaeoproterozoic. From the Neoarchaean to c. 2.0 Ga, major changes occurred in Earth history, particularly in plate tectonic regimes, supercontinental events, heat flow in the mantle and sea surface temperatures, palaeo-atmospheric (e.g., Kasting and Siefert, 2002; Catling et al., 2001; Kasting, 2005) and palaeo-oceanic compositions (Strauss, 2002; Condie, 2004; Eriksson et al., 2004a). This paper aims to contribute relevant field data pertinent to this debate for the c. 2.3–1.8 Ga period, from the Kaapvaal craton, South Africa.

Estimation of early Precambrian palaeo-atmospheric and palaeo-hydrospheric compositions is both difficult and hotly debated. The debate is premised on the same set of geological, palaeontological and biogeochemical data, much of it equivocal (e.g., Ohmoto, 2004). Ohmoto's (2004) review discusses two essentially mutually exclusive models: (1) the “CWHK” (Cloud, 1968; Walker, 1977; Holland, 2002; Kasting and Siefert, 2002) model, with an early reducing atmosphere, minor rise of oxygen at c. 3.0–2.8 Ga, and a major rise at c. 2.0 Ga; (2) the “DO” (Dimroth and Kimberley, 1976; Lasaga and Ohmoto, 2002) model, with a single rise in atmospheric oxygen and oxygenated oceans soon after c. 4.0 Ga (Ohmoto, 2004). However, most researchers agree that a complex interaction of crustal, atmospheric,

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oceanic and biological influences was responsible for Precambrian surficial processes and controlled their possible change over time (e.g., Lindsay and Brasier, 2002; Eriksson et al., 2004a; Tice and Lowe, 2004; Lowe and Tice, 2007).

In the "CWHK" model, the earliest known major carbonate platform successions (e.g., the 2.65–2.5 Ga Malmani and Campbellrand Subgroups, Transvaal Supergroup, Kaapvaal craton) acted as sinks for the extremely high levels of CO_2 in the Archaean atmosphere (e.g., Falkowski and Raven, 1997). However, high levels of CO_2 would result in oceans with low pH and very high concentrations of HCO_3 compared with CO_3. The precipitation of carbonate from such acidic seawater, where supersaturation would be difficult to achieve, would become problematic, quite apart from overcoming the natural kinetic barriers to carbonate precipitation in seawater (Wright and Altermann, 2000; Wright and Oren, 2005). Gandin et al. (2005) and Gandin and Wright (2007) use field, petrographic and stable isotopic evidence from the Campbellrand carbonates to propose significant changes in near-shore surface ocean chemistry at ~2.5 Ga, linked to microbial colonization of new, vast shallow-water marine environments, and associated biogeochemical processes including carbonate precipitation. Such transgressive epeiric marine events are in turn linked to crustal growth rates, tectonic regimes etc. (e.g., Eriksson et al., 2006a). Banded iron formations, like those of the Asbesheuwels and Koegas Subgroups and Penge and Hotazel Formations overlying the Transvaal carbonates, are interpreted as indicating growth in the oxygen content of the upper/shallower parts of the oceans where Fe^{2+}, transported in seawater from deeper anoxic ocean basins, was oxidized and precipitated during photosynthesis (Cloud, 1973; Kasting, 1987; see, however, Trendall, 2002; Trendall and Blockley, 2004) beneath a still mainly anoxic atmosphere. This period supposedly lasted from 2.5 to at least 2.2 Ga.

The existence of biogenic pyrite in the Campbellrand carbonates (Gandin et al., 2005; Kamber and Whitehouse, 2006) demonstrates that SO_4 was present in the shallow ocean, periodically (episodically?) consumed by sulphate-reducing bacteria (SRB) to leave S+Fe-poor shallow seas. This is supported by work on fluid inclusions (Kesler et al., 2006) and contradicts the assertions of others who maintain that SO_4 levels at that time were very low, and related to low oxygen levels (e.g., Canfield et al., 2000; Habicht et al., 2002). The claim that SO_4^{2-} is likely to have established itself as a mobile and ubiquitous constituent of the upper ocean at the time when oxygen became a prominent constituent of the atmosphere (cf., the "great oxidation event", at c. 2.3–1.8 Ga; e.g., Holland, 2002; see discussion in Ohmoto, 2004), and that this abundant sulphate was accompanied by the proliferation of SRB, is challenged by Wright and Wacey (2004) and Gandin et al. (2005); they report empirical evidence for the recognition of microbial sulphate-reduction in Archaean rocks. Supporting evidence for the relatively early oxygenation of shallow seas is provided by Brocks et al. (1999; however, see Brocks et al., 2003 who refute the earlier interpretation) who present biomarkers from 2.7 Ga containing molecular signatures of eukaryote metabolism. Summons et al. (1999) showed that the 2-methylhopanes found in sediments derive from 2-Me-bacteriohopanepolyols, membrane lipids synthesized in large quantities only by cyanobacteria. Therefore, the extraction of 2-methylhopanes from 2700 Ma rocks by Brocks et al. (1999) provides independent evidence for the antiquity of cyanobacteria and strongly indicates a still earlier origin (by at least 2.9 Ga; Noffke et al., 2008). The sequential zoning of sulphur-isotopes seen in microanalysis of single Archaean pyrite nodules allowed Kakegawa (2000) to demonstrate their biogenic origin related to bacterial sulphate reduction. Eigenbrode and Freeman (2003) have also reported S-isotope data ($\Delta^{33}S$ and $\delta^{34}S$ values) consistent with active microbial sulphate reduction in shallow-water facies of the ~2.6 Ga Carawine Dolomite.

Despite alternate, more uniformitarian views such as those discussed above, a majority school of thought still argues in favour of a major change in palaeo-atmospheric and -oceanic conditions, with a "great oxidation event" postulated at c. 2.3 Ga (e.g., Karhu and Holland, 1996). Lowe and Tice (2007) stress an apparently great similarity in the character of c. 3.5–3.2 Ga, 2.7–2.4 Ga and Neoproterozoic tectonic, environmental and biological cycles. They argue in favour of the two earlier cycles having been characterized by elevated surface temperatures (c. >60 °C), developed in tandem with a greenhouse atmosphere, and with high levels of CO_2 and CH_4 (but with $CH_4 \ll CO_2$). These two cycles were separated by a period when early craton development and concomitant crustal weathering led to collapse of the preceding greenhouse condition, with cooler (even glacial) palaeoclimatic conditions, and methane/carbon dioxide ratios close to 1. Analogous collapse of the second greenhouse cycle after c. 2.4 Ga is envisaged to have been followed by cooling once more, encompassing also the c. 2.4–2.2 Ga global glaciation, and eventually permanent oxygenation of the atmosphere (Lowe and Tice, 2007).

Most of the models of Archaean-Palaeoproterozoic oceanic and atmospheric evolution rely on essentially geochemical data for their formulation (e.g., $\delta^{18}O$ composition of cherts, Knauth and Lowe, 2003; silicon isotopic compositions of cherts, Robert and Chaussidon, 2006; mineral and sedimentary petrographic studies, examination of palaeosols, redox-sensitive sedimentary lithologies, Lowe and Tice, 2007; $\delta^{13}C$ isotopic values, Schidlowski et al., 1983; Rye and Holland, 1998; Lindsay and Brasier, 2002). Chemical data from such ancient rocks are always open to equivocal interpretations, particularly with the influence of deformation, metamorphism, and diagenesis within sedimentary strata which are seldom fully closed chemical systems.

In this paper we attempt to contribute to the debate on early Precambrian oceanic and atmospheric evolution by an alternative approach of presenting and interpreting physical data from the clastic sedimentary record of the Kaapvaal craton within the Transvaal and Waterberg basins from c. 2.3 Ga to about 1.8 Ga. We examine the nature of the sedimentary systems making up the vast fluvial braidplains and the large epeiric marine basins they fed, and argue in support of a model that envisages strongly episodic sedimentation systems predominating on the Kaapvaal craton over several hundred million years.

2. Geological background

The Kaapvaal craton (Fig. 1) most likely evolved through the amalgamation of a mosaic of subdomains to form a nucleus by c. 3.1 Ga, followed by accretion of composite terranes from both north and west at c. 3.0–2.7 Ga (De Wit et al., 1992), contemporaneous with development of Earth's oldest known large sedimentary basin, the c. 3.0–2.8 Ga Witwatersrand depository (Robb and Meyer, 1995). The high-grade Limpopo terrane was amalgamated with the Kaapvaal craton between 2.95 and 2.69 Ga (De Wit et al., 1992; however, a younger age for this orogenesis is currently vigorously debated — e.g., McCourt and Armstrong, 1998; Bumby and Van der Merwe, 2004). The c. 2.7 Ga Ventersdorp Supergroup mantle plume (e.g., Eriksson et al., 2002) and that inferred for the 2058±0.8 Ga (Buick et al., 2001) Bushveld Complex essentially bracket evolution of the c. 2658–2050 Ma Transvaal basin (Fig. 1), through a combination of extensional and thermal subsidence (Eriksson et al., 2001). Within both Witwatersrand and Transvaal basins, extensive epeiric seaways developed, from which shallow marine sedimentary successions were preserved (Eriksson et al., 2005). Within the Transvaal basin-fill, three major shallow seaway events are documented: the lowermost one comprised a carbonate-BIF platform, and the stratigraphically higher Timeball Hill and Daspoort–Silverton–Magaliesberg were clastic seaways (Fig. 2). The latter two are discussed in this paper. Intrusion of the Bushveld layered mafic complex was followed soon after by formation of two essentially fluvial basins belonging to the c. 2.0–1.9 Ga Waterberg Group (Fig. 1) (e.g., Callaghan et al., 1991).