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Correlation of Paleoproterozoic glaciations based on U–Pb zircon ages for tuff beds in the Transvaal and Huronian Supergroups

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ABSTRACT

The rise in atmospheric oxygen between 2.45 and 2.2 Ga has been linked to the demise of a methane-rich atmosphere and the onset of multiple glaciations, culminating in a possible Snowball Earth. The glacial deposits represent possible global marker horizons, however, their correlation is uncertain because key sedimentary successions are undated, hampering paleoenvironmental reconstructions. Three potentially global glaciations have been proposed based on the correlation of glacial deposits in southern Africa with those in North America. However, it has also been suggested that there were four glaciations and that the youngest was a Snowball Earth event recorded only in South African successions. In situ U–Pb zircon ages for tuffs in southern African and North American successions establish the existence of four glaciations between 2.45 and 2.22 Ga. Geochronological and stratigraphic data demonstrate that the three oldest glaciations predate ∼2.31 Ga and that the final glaciation, which is only recognized in South Africa, occurred between 2.26 and 2.22 Ga. The new age-calibrated correlations show that a rise in atmospheric oxygen inferred from sulfur isotope data occurred between the second and third glaciations. At 2.31 Ga, the first marine sulfate evaporites were deposited contemporaneously with ^{13}C-enriched carbonates, indicating a direct link between perturbations of the carbon and sulfur cycles and rising atmospheric oxygen. The appearance of "red beds" and oxidized palesols after the third glaciation signals a major increase in atmospheric oxygen levels, which culminated with the fourth glaciation between 2.26 and 2.22 Ga, after which the atmosphere remained irreversibly oxygenated.

1. Introduction

The early Paleoproterozoic (2.5–2.1 Ga) was a period of major environmental changes, marked by the transition from an anoxic to an oxic world (Bekker et al., 2004; Canfield, 2005; Farquhar et al., 2000; Holland, 2002; 2006). Large swings in atmospheric oxygen levels were accompanied by multiple glaciations and deposition of marine carbonates with highly positive carbon isotope values (e.g., the 2.22–2.06 Ga Lomagundi Event), indicating a high burial rate of organic carbon and release of free oxygen in surface environments (Bekker et al., 2001; Karhu and Holland, 1996). The rise in atmospheric oxygen is broadly constrained between ∼2.45 Ga, the maximum age of the youngest rocks with strong mass-independent fractionation (MIF) of sulfur isotopes (Boolgeeda Iron Formation and the lower part of the Turee Creek Formation, Western Australia; Williford et al., 2011), and ∼2.32 Ga, the age of the oldest rocks without an MIF signal (Rooihoogte and Timeball Hill formations, South Africa; Bekker et al., 2004; Hannah et al., 2004). Glacial deposits are recorded in sedimentary successions across the world at this time (2.45–2.22 Ga) and are regarded as potential marker beds that can be used to correlate stratigraphic units from separate cratons.

Three stratigraphically discrete glacial horizons are preserved in the Huronian Supergroup, Canada (Figs. 1 and 2). The glacial diamictites are constrained in age between 2450 +25/−10 Ma, the age of volcanic rocks in underlying units (Krogh et al., 1984), and 2217 ± 1.6 Ma, the age of cross-cutting Nipissing dolerite dykes (Andrews et al., 1986). The youngest of the Huronian glacial deposits, the Gowganda Formation, has been correlated with a single glacial diamictite in the Marquette Range Supergroup, Michigan, USA (Bekker et al., 2006).

In contrast, the Transvaal Supergroup in southern Africa, which is preserved in three separate structural basins that were once part of the same depositional basin, includes only two *bona fide* glacial deposits, although evidence for a third glaciation has been discussed (Coetzee, 2001; Eriksson et al., 1993; Fig. 2). The oldest is in the basal Duitschland Formation in the eastern Transvaal structural basin. The youngest, the Rietfonteindam diamictite in the uppermost part of the Timeball Hill Formation, has most often been interpreted to correlate with the Makganyene diamictite in the Griqualand West structural basin (Coetzee, 2001; Coetzee et al., 2006;

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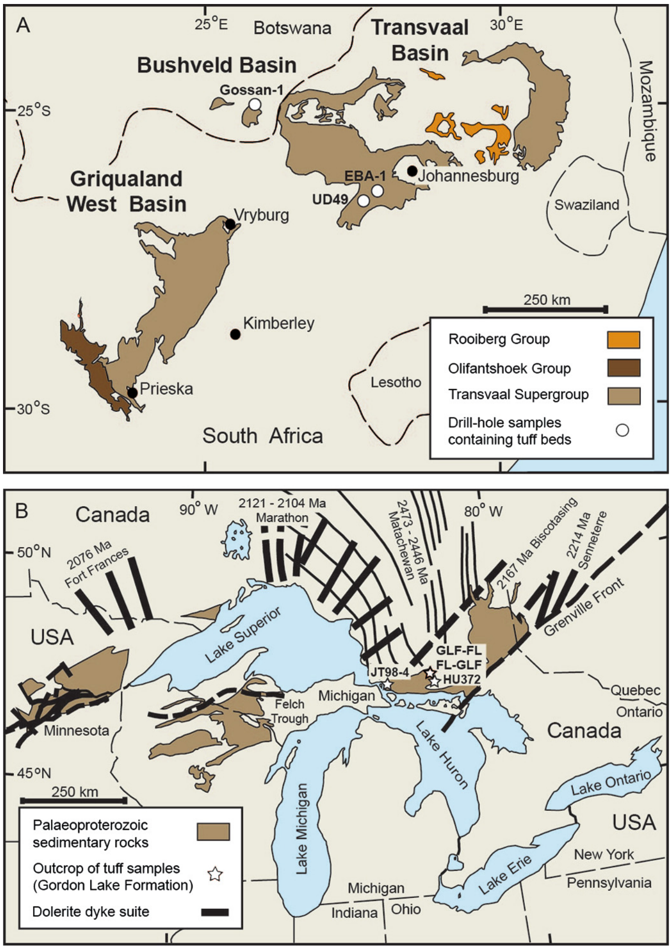

Fig. 1. A. Geological map showing the main outcrop areas of the Transvaal Supergroup in southern Africa and the sampled drill-holes (UD49, EBA1 and Gossan-1). B. Map showing the distribution of the Huronian Supergroup and other Paleoproterozoic successions in the Great Lakes area. Samples of tuffaceous mudrock were collected from three outcrop localities (HU372, GLF-FL/FL-GLF and JT98-4).

Eriksson et al., 1993; Evans et al., 1997; Visser, 1971, 1981). A thin diamictite in the basal Rooihoogte Formation is locally preserved and has also been interpreted to be glacial in origin (Coetzee, 2001).

Re–Os dating of early diagenetic pyrite from the upper Rooihoogte and lower Timeball Hill Formations yielded an age of 2316 ± 7 Ma (Hannah et al., 2004), representing a minimum age for their deposition. The Rooihoogte and Timeball Hill Formations unconformably overlie the Duitschland Formation (Cheney and Winter, 1995), which is not dated but must be significantly younger than 2480 ± 6 Ma, the age of a tuff in the unconformably underlying Penge Iron Formation (Fig. 2). A single diamictite in the Ditlhojana Shale from the Bushveld structural basin, which is an extension of the Transvaal structural basin into Botswana (Fig. 2), is considered to be lithostratigraphically correlative with the glacial deposit in the uppermost part of the Timeball Hill Formation in the Transvaal structural basin (Eriksson et al., 1993).

There are no direct age constraints for the Ditlhojana diamictite, but quartzites underlying the correlative diamictite of the Tlaameng Formation in the Kanye structural basin ∼50 km west of the Bushveld structural basin in Botswana contain a population of detrital zircons with U–Pb SHRIMP age of 2250 +14/−15 Ma (Mapeo et al., 2006), indicating that the last glacial event in southern Africa must be younger ∼2250 Ma. Considering that this diamictite has been correlated with the Rietfonteindam diamictite in the Timeball Hill Formation dated by the Re–Os method at 2316 ± 7 Ma, there are three alternatives to consider: (1) the Re–Os age is incorrect; (2) the inferred correlation is not valid; and (3) there is a major time gap within the Timeball Hill Formation between the basal part dated by the Re–Os method, and the Rietfonteindam diamictite at the top.

The Ongeluk flood basalts that overlie the Makganyene diamictite with a low-angle erosional unconformity (Altermann and Halbich, 1991) have been correlated with the Hekpoort volcanic rocks and Ditlhojana Volcanics (Eriksson et al., 1993; Key, 1983; Fig. 2). The ages of the Ongeluk and Hekpoort volcanic units are interpreted to be 2222 ± 13 Ma (Pb/Pb whole-rock isochron), and 2193 ± 71 Ma (Rb–Sr whole-rock isochron; Cornell et al., 1996; Walraven et al., 1990), respectively. The Ongeluk volcanics were erupted at latitude 11 ± 5° (Evans et al., 1997; Kirschvink et al., 2000) and, based on correlation with the Hekpoort Formation (Cornell et al., 1996), the underlying Makganyene and upper Timeball Hill diamictites are inferred to record a Snowball Earth glaciation (Kopp et al., 2005).

Alternative correlations have been made based on detrital zircon age distributions and a Pb/Pb age for the Mooidraai Dolomite (∼2.39 Ga; Bau et al., 1999; Fairey et al., 2013). For instance, Moore et al. (2012) correlate the Makganyene diamictite with the diamictite at the base of the Duitschland Formation, whereas Hoffman (in press) suggests that the Makganyene diamictite is missing along a sequence boundary in the middle of the Duitschland Formation. If either of these interpretations is correct, low-latitude Snowball Earth-like glaciation and transition to oxygenated atmosphere and ocean occurred before ∼2.32 Ga rather than at ∼2.22 Ga as previously inferred (Evans et al., 1997; Kopp et al., 2005).

The total number of Paleoproterozoic glaciations, their precise ages and their correlations thus remain unclear because key sedimentary successions are undated (Bekker et al., 2004; Pavlov et al., 2000). Correlation of the upper two glacial deposits of the Huronian Supergroup with the two glacial deposits in South Africa (Bekker et al., 2004, 2005, 2006) implies only three glaciations in the Paleoproterozoic. However, others have argued that there were four glaciations and the youngest glaciation in South Africa recorded in the upper Timeball Hill and Makganyene Formations is not recorded in the Huronian Supergroup (Kopp et al., 2005). It was further suggested that only the fourth glaciation, apparently preserved only in South Africa, was a Snowball Earth event and that it was triggered by the emergence of cyanobacteria and subsequent irreversible oxidation of the atmosphere and ocean (Kopp et al., 2005). Constraints on the age of these glacial horizons thus play a critical role in reconstructing the sequence of environmental changes in the early Paleoproterozoic, including changes in the carbon and sulfur cycles and surface oxidation.

2. Material and methods

In order to constrain the timing of the glaciations and possible correlations between these basins, we searched for and identified tuffaceous beds in the Timeball Hill Formation (and its lateral equivalent in the Bushveld structural basin, Botswana) in southern Africa and in the Gordon Lake Formation, Huronian Supergroup, Canada (Figs. 1 and 2).

2.1. Timeball Hill Formation

The Timeball Hill Formation comprises two upward coarsening sequences: the lower unit grades from carbonaceous shale and siltstone into sandstone and oolitic ironstone marking the sequence boundary, whereas the upper unit passes from shale and siltstone into glacial diamictite and conglomerate (Coetzee, 2001;