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Focus paper

Global glaciations and atmospheric change at ca. 2.3 Ga

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ABSTRACT

This paper compiles lithostratigraphic and geochronological data obtained for the Palaeoproterozoic glacial diamictite-bearing successions, and thereby provides insights into understanding the geological processes causing the Huronian Glaciation Event. The majority of evidence for appearances of this glaciation event can be related to the Kenorland supercontinent breakup, allied to significant atmospheric change, as well as blooms of biogeochemical oxygenic photosynthesis. In this paper, the Huronian Glaciation Event is constrained to have occurred synchronously during 2.29–2.25 Ga, accompanied by dramatic environmental changes characteristic of the Great Oxidation Event which includes the pre-2.3 Ga hydrosphere oxidation and the post-2.3 Ga atmosphere oxygenation.

1. Introduction

The Archaean/Palaeoproterozoic transition witnessed dramatic changes in Earth's history which include several environmental oscillations and the emergence of an aerobic Earth System (e.g., Chen, 1990; Chen and Su, 1998; Bekker et al., 2004, 2010; Bekker and Kaufman, 2007; Frei et al., 2009; Holland, 2009; Konhauser et al., 2009, 2011; Lyons and Reinhard, 2009; Tang et al., 2011, 2012; Young, 2012, 2013; Zhai and Santosh, 2013). One of the earliest significant events known from this transition is the sharp drop of volcanism (Holland, 2002) and temperature resulting in the formation of stably normal sedimentary basins over the world and the rapid onset of global glacial event. Palaeoproterozoic glaciogenic rocks have been known since the beginning of the last century in almost every continent, including North America, Fennoscandia, South Africa, Western Australia, South America, and India (Table 1; Young, 1970, 2002; Hambrey and Harland, 1981; Bekker et al., 2001, 2005, 2006; Ojakangas et al., 2001; Melezhik, 2006; Eriksson et al., 2011; Strand, 2012; and references therein). This is the oldest glaciation known of global significance and has been termed as the "Huronian Glaciation" after the best-studied example from the Huronian Supergroup in Canada (Young, 1970; Miall, 1983; Young et al., 2001). It was followed shortly after the 2450 Ma breakup of the Kenorland/Superia supercontinent (Aspler and Chiarenzelli, 1998; Bekker and Eriksson, 2003; Eyles, 2008) and prevailed at some time between ca. 2.4 (possibly 2.45 Ga) and 2.2 Ga, with up to three possible glacial horizons, couched within a "Snowball Earth model" (Hoffman et al., 1998; Kirschvink et al., 2000) and the "Great Oxidation Event" (GOE). The GOE is widely accepted to have occurred during 2.3–1.8 Ga (Holland, 1994, 2002; Rye and Holland, 1998; Kasting and Siefert, 2002; Farquhar et al., 2010; Tang et al., 2011, 2013; Lai et al., 2012) and recently traced to have begun at some time between 2.4 and 2.3 Ga (e.g., Karhu and Holland, 1996; Bekker et al., 2004; Canfield, 2005; Anbar et al., 2007; Holland, 2009).

The causes and timing of the Huronian Glaciation Event (abbreviated to HGE hereafter), as well as the global extent of ice cover are still controversial (Young, 1991; Evans et al., 1997; Evans, 2003; Kopp et al., 2005). It remains possible that the glaciation was diachronous in different areas, rather than a simultaneous and catastrophic event as implicit within the Snowball Earth model (Eriksson et al., 2011). Thus, this paper compiles and reviews the Palaeoproterozoic glacial records in different cratons, further

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Table 1
Compilation of the reported Palaeoproterozoic diamictite units in the world.

Continent	Name or strata	Geography or locality	Age (Ma)	References
N. America	Gowganda Fm., Cobalt Gp., Huronian SGp.	45°40′–48°40′ N, 79°–85° W; Ontario, Canada	2450 –2217.5	Krogh et al. (1984), Andrews et al. (1986)
N. America	Bruce Fm., Quirke Lake Gp., Huronian SGp.	45°40′–48°40′ N, 79°–85° W; Ontario, Canada	2450 –2217.5	Krogh et al. (1984), Andrews et al. (1986)
N. America	Ramsay Lake Fm., Hough Lake Gp., Huronian SGp.	45°40′–48°40′ N, 79°–85° W; Ontario, Canada	2450 –2217.5	Krogh et al. (1984); Andrews et al. (1986)
N. America	Chibougamau Fm.	49°40′–50°15′ N, 74°40′–73°50′ W; Quebec, Canada	2500–1800	Frakes (1979), Hambrey and Harland (1981)
N. America	Padlei Fm., Hurwitz Gp.	61°–62°30′ N, 95°–99° W; Northwest Territories, Canada	2300–2100	Frakes (1979), Hambrey and Harland (1981)
N. America a	Northern Black Hills	43°50′–44°07′ N, 103°20′–103°45′ W; South Dakota, USA	2559–1870	Dahl et al. (1999)
N. America	Bottle Creek, Singer Peak Fm., Snowy Pass Gp.	Snowy Pass Group, Sierra Madre Mountains, Wyoming, USA	<2450	Frakes (1979), Hambrey and Harland (1981)
N. America	Headquarters Fm., Lower Libby Creek Gr., Snowy Pass SGp.	41°–41°30′ N, 107°15′–106°15′ W, Medicine Bow Mountains, Wyoming, USA	2451–2000	Premo and Van Schmus (1989), Cox et al. (2000)
N. America	Vagner Fm., Deep Lake Gp., Snowy Pass SGp.	41°–41°30′ N, 107°15′–106°15′ W, Medicine Bow Mountains, Wyoming, USA	2451–2000	Premo and Van Schmus (1989), Cox et al. (2000)
N. America	Campbell Lake Fm, Deep Lake Gr., Snowy Pass SGp.	41°–41°30′ N, 107°15′–106°15′ W, Medicine Bow Mountains, Wyoming, USA	<2451 ± 9	Premo and Van Schmus (1989)
N. America	Fem Creek Fm., Chocolay Gp., Marquette Range SGp.	Menominee and Iron River–Crystal Falls Ranges, Amasa Uplift, WI and MI, USA	2302–2115	Bekker et al. (2006), Vallini et al. (2006)
N. America	Enchantment Lake Fm., Chocolay Gp., Marquette Range SGp.	45°49′–46°30′ N, 87°30′–88°05′ W; Marquette Trough, Upper Peninsula Michigan, USA	2288–2131	Bekker et al. (2006), Vallini et al. (2006)
Africa	Witwatersrand SGp.	South Africa	2600–2300	Frakes, 1979; Hambrey and Harland, 1981
Africa	Makganyene Diamictite, Postmasburg Group	28°47′ S, 23°15′ E; Griqualand West Basin, South Africa	2415–2222	Cornell et al. (1996), Gutzmer and Beukes (1998), Bau et al. (1999)
Africa	Boshoek Fm, Lower Pretoria Group, Transvaal SGp.	25°50′ S, 28°25′ E; Transvaal Basin, South Africa	2316–2249	Dorland (2004), Hannah et al. (2004)
Africa	Duitschland Fm, Lower Pretoria Group, Transvaal SGp.	25°50′ S, 28°25′ E; Transvaal Basin, South Africa	2480–2316	Pickard (2003), Hannah et al. (2004)
Australia	Meteorite Bore Mb., Turee Creek Group	22°55′ S, 117° E; Hamersley basin, Western Australia	2209–2449	Barley et al. (1997), Trendall et al. (1998), Pickard (2002)
Antarctica	Widdalen Fm.	71°51′ S, 2°43′ W or 71°05′ S, 2°21′ W	>1700	Frakes (1979), Hambrey and Harland (1981)
Asia	Gangau tillites	79°07′–79°55′ E, 24°20′–24°40′ N; Central India	2600–1850	Frakes (1979), Hambrey and Harland (1981)
Asia	Sanverdam tillites	74°50′–73°10′ E, 15°30′–15°05′ N; South India	2600–2200	Frakes (1979), Hambrey and Harland (1981)
Europe	Sakukan tillites	Baikal, Russia	2640–1950	Melezhik and Fallick (1996), Melezhik et al. (1997b)
Europe	Lammos tillites	68° N, 30° E; Kola Peninsula, Russia	>1900	Melezhik and Fallick (1996), Melezhik et al. (1997b)
Europe	Partanen tillites	Southern Karelia, Russia	2150–1900	Melezhik and Fallick (1996), Melezhik et al. (1997b)
Europe	Sarioli tillites, Karelian Sgp.	Eastern Baltic Shield, Russia	2455–2180	Melezhik and Fallick (1996), Melezhik et al. (1997b)

constrains the time of glaciation and attempts to relate to other secular changes including positive $\delta^{13}C_{carb}$.

2. Geology and timing of typical Palaeoproterozoic glacial records

Archaean plate reconstructions show the assembly of two supercontinents (Aspler and Chiarenzelli, 1998), the Northern Supercontinent (Kenorland/Superia) and the Southern Supercontinent. The former is composed of the North American, Fennoscandian and possibly Siberian shields (Williams et al., 1991). The latter is poorly constrained and likely includes the Kaapvaal, Pilbara, Zimbabwe, São Francisco and Indian cratons (Cheney, 1996; Bleeker, 2003; De Kock et al., 2009a). Both supercontinents experienced protracted breakup driven by inferred mantle plumes and associated intraplate rifting (Aspler and Chiarenzelli, 1998; Bekker and Eriksson, 2003; Zhong et al., 2007; Eyles, 2008). Breakup was shortly followed by the onset of “icehouse” conditions in the Palaeoproterozoic. Hambrey and Harland (1981) documented at least three discrete glacial successions within the Palaeoproterozoic sedimentary record of ~2.45–2.22 Ga (Table 1; Fig. 1A–G). The lowermost glacial record is separated from the continental flood-basalts by a ~2000 m thick, rift-related, siliciclastic succession, and the youngest glaciogenic association is older than 2.22 Ga (Young et al., 2001; Long, 2004).

2.1. North America

In North America, Palaeoproterozoic glaciogenic deposits are present in the Marquette Range Supergroup in Michigan (Fig. 1A), the Huronian Supergroup in Ontario (Fig. 1B), and the Snowy Pass Supergroup in Wyoming (Fig. 1C), as well as in their equivalent successions in northern Quebec and Northwest Territories (Ojakangas, 1988). The best preserved example is from the Huronian Supergroup of Canada (Fig. 1B), which contains three glaciogenic units from the lowermost Ramsey Lake Formation, through Bruce Formation in the middle, and to the uppermost Gowganda Formation, inter-bedded with the shales, carbonate rocks and non-glacial fluvial-deltaic clastic sediments (Fralick and Miall, 1989; Young, 1991; Sekine et al., 2011). The Espanola Formation (Fig. 1B) was ever suggested to be cap carbonates with $\delta^{13}C_{carb}$ values ranging from −4.0‰ to 0.8‰ (Bekker et al., 2005).