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Investigating the Paleoproterozoic glaciations with 3-D climate modeling

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ABSTRACT

It is generally assumed that the Earth's surface was warm during most of its early history but that significant cooling occurred between 2.45 and 2.22 Ga leading to the first global and cyclical glacial epoch. This onset of snowball Earth conditions was coeval with a large pulse of oxygenation that permanently oxygenated the atmosphere and shallow oceans (Great Oxygenation Event, GOE), though it is not known whether one influenced the other or if they were independent events. Hereafter we used a General Circulation climate Model (GCM) to estimate the partial pressures of atmospheric CO_2 (pCO_2) and CH_4 (pCH_4) required to account for the onset of snowball Earth conditions during the Paleoproterozoic. We show that Earth's surface can be maintained in an ice-free state under atmospheric CO_2 concentrations lower than 2.6×10^{-2} bar without invoking the need of high CH_4 concentrations. Assuming that the cooling of the Earth's surface is related to the collapse of atmospheric greenhouse gases, we tested the relevance of different scenarios including (i) the collapse of pCH_4 in response to the GOE and (ii) the drawdown of pCO_2 due to both a decrease in volcanic outgassing rate and an increase in global weathering efficiency. We show that the cyclical character of Paleoproterozoic glaciations is best explained by a long-lasted decrease of pCO_2. To support this scenario, we examine how the long-term carbon cycle and the equilibrium pCO_2 respond to the emplacement of large subaerial basaltic provinces (LIPs) and to a temporary shutdown of volcanism as supported by geologic data. We show that the sink of pCO_2 through silicate weathering is limited by the absence of terrestrial higher plants. In such conditions, the equilibrium pCO_2 remains high enough to preclude the onset of snowball conditions regardless the intensity of the pCH_4 collapse. The combination of an increase in weathering efficiency and a decrease in volcanic outgassing rate can significantly reduce the equilibrium pCO_2, thus favoring the onset of glaciations. Such a buffering of atmospheric CO_2 cannot initiate global glaciations alone. Yet, it remains a required condition for the initiation of a snowball Earth event in response to the collapse of pCH_4, possibly after 2.32 Ga.

1. Introduction

Although the solar constant at the end of the Archean did not exceed 80% of the present day value (Gough, 1981; Sagan and Mullen, 1972), Earth's surface remained unfrozen during most of the Archean and Proterozoic eons allowing the emergence of life (Feulner, 2012; Schopf, 2006). This intriguing situation known as the Faint Young Sun Paradox led to the development of scenarios invoking high atmospheric concentrations of greenhouse gases such as carbon dioxide (Kasting, 1987), methane (Pavlov et al., 2000, 2003), hydrocarbon gases (Haqq-Misra et al., 2008) or by collision absorption of H_2–N_2 (Wordsworth and Pierrehumbert, 2013) to counteract the low brightness of the young Sun and maintain the Earth's surface essentially unfrozen. During the first 3 billions of years of Earth's history, only two glacial periods have been reported: the 2.9 Ga Pongola glacial event recorded in South Africa (Young et al., 1998) and the 2.45–2.22 Ga glaciation characterized by a series of three to four glacial events (Bekker et al., 2003; Eriksson et al., 2011; Young et al., 1998) recorded in Canada (known as the Huronian glaciation; Young, 2002), South Africa

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(Makganyene glaciation; Polteau et al., 2006), USA (Snowy Pass and Marquette Range Supergroups; Bekker et al., 2005; Ojakangas et al., 2001; Sekine et al., 2010) and Australia (Meteorite Bore Member; Williford et al., 2011). The ubiquitous presence at low latitudes of glaciogenic rocks during the Early Paleoproterozoic suggests that at least one of the glacial events would have been global (snowball Earth) (Kopp et al., 2005). The onset of such extreme climatic conditions is usually associated with the collapse of atmospheric CH_4 partial pressure (pCH_4) driven by the Great Oxidation Event (GOE) (e.g., Kopp et al., 2005) and/or the drawdown of atmospheric CO_2 partial pressure (pCO_2) as a result of tectonic and/or volcanic changes (Condie et al., 2009; Evans, 2003; Eyles, 2008; Tajika, 2003, 2007). These scenarios can be tested through the numerical modeling of climate. Since the first studies of the Archean – Paleoproterozoic climate (Kasting, 1987, 1993; Owen et al., 1979), all climatic simulations of this period have been conducted using 1-D Radiative Convective models (RCM).

In the present study, we estimate the pCO_2 and pCH_4 threshold values required for the occurrence of the extreme and cyclical Paleoproterozoic glaciations using a 3-D General Circulation Model (GCM). The use of a 3-D climate model was motivated for two reasons: (i) determining the climate state of the Earth from spatial climatic indicators (e.g. the extension of perennial sea ice) in response to a variety of forcing factors (solar brightness, atmospheric chemical composition, rotation rate, ocean salinity), (ii) simulations of glacial epochs requires to consider feedback mechanisms, essentially the ice-albedo-temperature feedback, and dynamics processes such as heat transport which are poorly represented in 1-D climate models.

Our approach requires the knowledge of the timing and duration of the ice ages with regards to environmental and geologic changes. However, the number, duration and intensity of the different glacial phases associated with the Paleoproterozoic glaciations are still debated (Eriksson et al., 2011; Sekine et al., 2011; Williford et al., 2011) and possible correlations of glaciogenic deposits between different cratons are controversial (Bekker et al., 2005; Hannah et al., 2004; Hilburn et al., 2005; Kopp et al., 2005). We first provide a short review of the constraints on timing, duration and extent of the Paleoproterozoic glaciations, accounting for the scarcity of continuous stratigraphic successions and reliable paleomagnetic constraints. We then calculate climate and latitudinal extent of perennial snow/sea ice as a function of both pCO_2 and pCH_4 using the 3-D GCM FOAM 1.5 (Poulsen, 2003; Poulsen and Jacob, 2004). We finally estimate the impacts of an increase in subaerial basaltic surface and a decrease in volcanic outgassing rate on pCO_2, using simplified carbon laws inferred from the geochemical cycle model COMBINE (Godderis and Joachimski, 2004). Results of climate simulations are used to discuss the different hypotheses accounting for the onset and breakdown of the Paleoproterozoic glaciations, with regards to the conditions required to satisfy the climate–carbon equilibrium.

2. Geologic records of the Paleoproterozoic glaciations

2.1. Ages, occurrences and depositional latitudes of Paleoproterozoic diamictites

The best preserved record of the Paleoproterozoic glacial events is hosted by the Huronian Supergroup in Ontario, Canada. Three glaciogenic diamictites have been described, revealing the onset of three glacial phases between 2.45 and 2.22 Ga as part of the Ramsay Lake, Bruce and Gowganda Formations, respectively (Bekker and Kaufman, 2007; Kopp et al., 2005; Menzies, 2000; Ojakangas, 1988; Sekine et al., 2011; Young and Nesbitt, 1999). Similarly, three successive glaciogenic deposits occur within the Campbell Lake, Vagner and Headquarters Formations of the Snowy Pass Supergroup (Wyoming, USA) and are possibly correlated with the Huronian diamictites (Bekker et al., 2005). Other glacial sediments are recognized as part of the Enchantment Lake Formation (Marquette Range Supergroup, Michigan, USA), recently correlated with the Gowganda Formation (Huronian Supergroup) by the occurrence of a two-stage anomalous negative excursion of carbon isotopes (Sekine et al., 2010). Despite a good stratigraphic record, these glaciogenic units are poorly constrained in latitude (Hilburn et al., 2005). In the ca. 2.4 Ga Eastern Transvaal Supergroup, South Africa, diamictite horizons are known within the Rooihoogte–Duitschland and Upper Timeball Hill Formations (Hannah et al., 2004; Melezhik, 2006). The age of these two units is estimated between 2.41 and 2.32 Ga, and between 2.32 and 2.22 Ga, respectively (Evans et al., 1997; Hannah et al., 2004; Kirschvink et al., 2000; Kopp et al., 2005). The Makganyene diamictite in the Griqualand West Basin, considered as a lateral equivalent of the Upper Timeball Hill diamictite (Bekker et al., 2001; Hannah et al., 2004), is interstratified with the overlying Ongeluk basalts, which yields a depositional latitude of $11^\circ \pm 5^\circ$ (Evans et al., 1997). The Makganyene diamictite is considered as the most reliable evidence for a Paleoproterozoic glacial environment at low latitudes, thus supporting the Snowball Earth Hypothesis (Kopp et al., 2005; Polteau et al., 2006; but for opposite interpretation see Cornell et al., 1996; Eriksson et al., 2011). Radiogenic ages and lithostratigraphic reconstructions suggest that the Makganyene–Upper Timeball Hill and the Rooihoogte–Duitschland diamictites are well correlated with the youngest (Gowganda Fm.) and intermediate (Bruce Fm.) diamictites of the Huronian Supergroup (Bekker et al., 2001, 2005; Hannah et al., 2004; Papineau et al., 2007). However, this interpretation has been disputed by Hilburn et al. (2005) and Eriksson et al. (2011), who proposed that the Makganyene diamictite postdates the Gowganda diamictite. Finally, glaciogenic diamictite of similar age has been described in the Hamersley basin (Meteorite Bore Member, Kungarra Formation), Western Australia (Evans, 2003; Krapez, 1996; Martin, 1999; Williford et al., 2011). Age constraints from the Meteorite Bore Member are provided by the underlying 2.45 Ga Woongarra Rhyolite and the overlying 2.21 Ga Cheela Springs Basalt (Barley et al., 1997). Unfortunately, the low paleolatitude yielded by the Woongarra Rhyolite cannot be extrapolated to the Meteorite Bore Member diamictite as these two units are possibly separated by a significant time gap (Barley et al., 1997). Based on sulfur isotope measurements, Williford et al. (2011) proposed that the Meteorite Bore Member diamictite of the Turee Creek Group may be correlated with the Ramsay Lake diamictite, i.e. the oldest glaciogenic formation of the Huronian Supergroup. Despite a number of arguments against the Snowball Earth hypothesis (Eriksson et al., 2011), glaciogenic diamictites remain a robust paleoclimatic indicator and argue for the succession of severe glaciations between 2.45 and 2.22 Ga. Occurrence of glaciogenic formations at low latitudes ($<30^\circ$) during the Early Paleoproterozoic suggests that the Earth was entirely frozen at that time. Indeed, due to the ice-albedo-temperature positive feedback, spreading of ice sheets and sea ice below subtropical latitudes leads to an extreme cooling that favors the onset of snowball Earth state (Donnadieu et al., 2004). Alternatively, the possibility of maintaining a stable ice line to 10–20° latitude, referred as to the Jormungand state (i.e. a largely ice-covered Earth at the exception of a thin strip of open ocean along the equator), has been suggested by coupled GCM simulations assuming a bare sea ice albedo lower than 0.6 (Abbot et al., 2011). Because of the limited geological data, it remains difficult to determine whether all identified glaciogenic deposits of Paleoproterozoic age are related to snowball Earth state. Nevertheless, such an assumption is at least suited for Makganyene diamictite as proposed by Coetzee et al. (2006) and Kopp et al. (2005). This