Geoscience Frontiers 4 (2013) 247–261

Contents lists available at SciVerse ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Review

Precambrian supercontinents, glaciations, atmospheric oxygenation, metazoan evolution and an impact that may have changed the second half of Earth history

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ARTICLE INFO

Article history:
Received 11 May 2012
Received in revised form
16 July 2012
Accepted 25 July 2012
Available online 9 August 2012

Keywords:
Proterozoic supercontinents
Glaciations
Impacts
Oxygenation
Metazoa

ABSTRACT

In more than 4 Ga of geological evolution, the Earth has twice gone through extreme climatic perturbations, when extensive glaciations occurred, together with alternating warm periods which were accompanied by atmospheric oxygenation. The younger of these two episodes of climatic oscillation preceded the Cambrian “explosion” of metazoan life forms, but similar extreme climatic conditions existed between about 2.4 and 2.2 Ga. Over long time periods, changing solar luminosity and mantle temperatures have played important roles in regulating Earth’s climate but both periods of climatic upheaval are associated with supercontinents. Enhanced weathering on the orogenically and thermally buoyed supercontinents would have stripped CO_2 from the atmosphere, initiating a cooling trend that resulted in continental glaciation. Ice cover prevented weathering so that CO_2 built up once more, causing collapse of the ice sheets and ushering in a warm climatic episode. This negative feedback loop provides a plausible explanation for multiple glaciations of the Early and Late Proterozoic, and their intimate association with sedimentary rocks formed in warm climates. Between each glacial cycle nutrients were flushed into world oceans, stimulating photosynthetic activity and causing oxygenation of the atmosphere. Accommodation for many ancient glacial deposits was provided by rifting but escape from the climatic cycle was predicated on break-up of the supercontinent, when flooded continental margins had a moderating influence on weathering. The geochemistry of Neoproterozoic cap carbonates carries a strong hydrothermal signal, suggesting that they precipitated from deep sea waters, overturned and spilled onto continental shelves at the termination of glaciations. Paleoproterozoic (Huronian) carbonates of the Espanola Formation were probably formed as a result of ponding and evaporation in a hydrothermally influenced, restricted rift setting. Why did metazoan evolution not take off after the Great Oxidation Event of the Paleoproterozoic? The answer may lie in the huge scar left by the ~2023 Ma Vredefort impact in South Africa, and in the worldwide organic carbon-rich deposits of the Shunga Event, attesting to the near-extirpation of life and possible radical alteration of the course of Earth history.

1. Introduction

Because it was probably lost to space during the Late Heavy Bombardment (~3.9 Ga), the nature of the early atmosphere is unknown but it was likely rich in H_2 and He. It is widely believed that much of the secondary atmosphere was derived from de-gassing of the Earth’s interior so that it is also likely that the early atmosphere was anoxic. Free oxygen is believed to have resulted from photodissociation of water and, more importantly, as a by-product of photosynthetic activity. Oxygen played a crucial role in the evolution of life, both in the opening up of new, highly efficient metabolic pathways and in permitting colonization of shallow waters and land surfaces under the protective cover of the ozone layer (Fischer, 1965). The questions addressed in this paper relate to when and how the Earth’s atmosphere changed, its tectonic controls and attendant palaeoclimatic and biological events.

The idea of “continental drift” was first entertained in the 17th century but it was not until quite recently, following documentation of sea floor spreading by Lawrence Morley, and Vine and Matthews (1963), that plate tectonics was widely accepted. An important paper

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Peer-review under responsibility of China University of Geosciences (Beijing).

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http://dx.doi.org/10.1016/j.gsf.2012.07.003

by Wilson (1966) suggested that the Atlantic Ocean had opened twice, introducing the concept of a supercontinental cycle and its possible role in effecting great climatic perturbations in both Phanerozoic (Fischer, 1984; Worsley et al., 1984) and Proterozoic times (Worsley et al., 1986, 1994; Young, 1991; Bleeker, 2004; Eyles, 2008).

It is widely (but not universally) believed that the transition to an oxygenic atmosphere took place in early Paleoproterozoic times (Cloud, 1968; Roscoe, 1973; Holland, 1999). Roscoe (1973) studied the Huronian Supergroup (~2.45–2.2 Ga) and drew attention to unusual Fe-depleted paleosols, detrital pyrite and uraninite in mineralogically mature fluvial deposits, and an upward transition from drab to red subaerially-deposited sedimentary rocks. These observations placed important constraints on when free oxygen appeared in the atmosphere. Supporting evidence has subsequently been gathered from Paleoproterozoic rocks in many parts of the world and the change in atmospheric composition has come to be known as the Great Oxidation Event (Karhu and Holland, 1996; Bekker et al., 2004) or Lomagundi-Sarioli Event (Melezhik et al., 2005). It was accompanied by strong positive excursions in $\delta^{13}C_{carb}$ (Fig. 1). Since ^{12}C is commonly sequestered by photosynthetic organisms, marked increases in $\delta^{13}C$ values in seawater (which are thought to be captured in precipitates such as carbonates) are taken to indicate periods of enhanced photosynthetic activity and rapid sedimentation, causing removal of ^{12}C from the carbon cycle.

2. Rodinia and the Neoproterozoic climatic cycles

Following the Grenville collisional orogeny and formation of the supercontinent Rodinia, the Earth entered a long period of climatic upheaval. Glacial deposits are extremely widespread (Mawson, 1949; Harland, 1964; Kaufman et al., 1997) and there are significant perturbations in the $\delta^{13}C_{carb}$ curve (Fig. 1). For a recent compilation of Neoproterozoic glacial deposits see Arnaud et al. (2011). The great Neoproterozoic glaciations inspired the phrase, “snowball Earth” (Kirschvink, 1992; Hoffman et al., 1998), which sparked lively discussions regarding its severity. Whatever the outcome of the on-going debate, there can be little doubt that most of today’s continents carry evidence of several late Neoproterozoic glacial episodes whose deposits, like those of the first two Paleoproterozoic (Huronian) glaciations, were commonly preserved in rift settings (Young, 1985; Young and Nesbitt, 1985; Eyles and Januszczak, 2004). Both great Proterozoic glacial episodes were initiated following formation of supercontinents (Fig. 2), and introduced extended periods of extreme climatic oscillation. For a recent discussion as to how climates and the evolution of life might have been influenced by the amalgamation and break-up of supercontinents see Santosh (2010).

3. Termination of the Neoproterozoic glaciations

3.1. Cap carbonates

The name “cap carbonate” refers to thin (~3–20 m) buff or pink dolostones and limestones that overlie glacial deposits. They commonly display fine bedding or lamination. Many contain evidence of stromatolitic activity, in the form of broad domes with irregular tube structures oriented approximately normal to regional bedding, regardless of the attitude of the stromatolitic laminations. Most occurrences display a remarkably consistent set of structures including brecciated and veined (sheet-cracked) zones, usually near

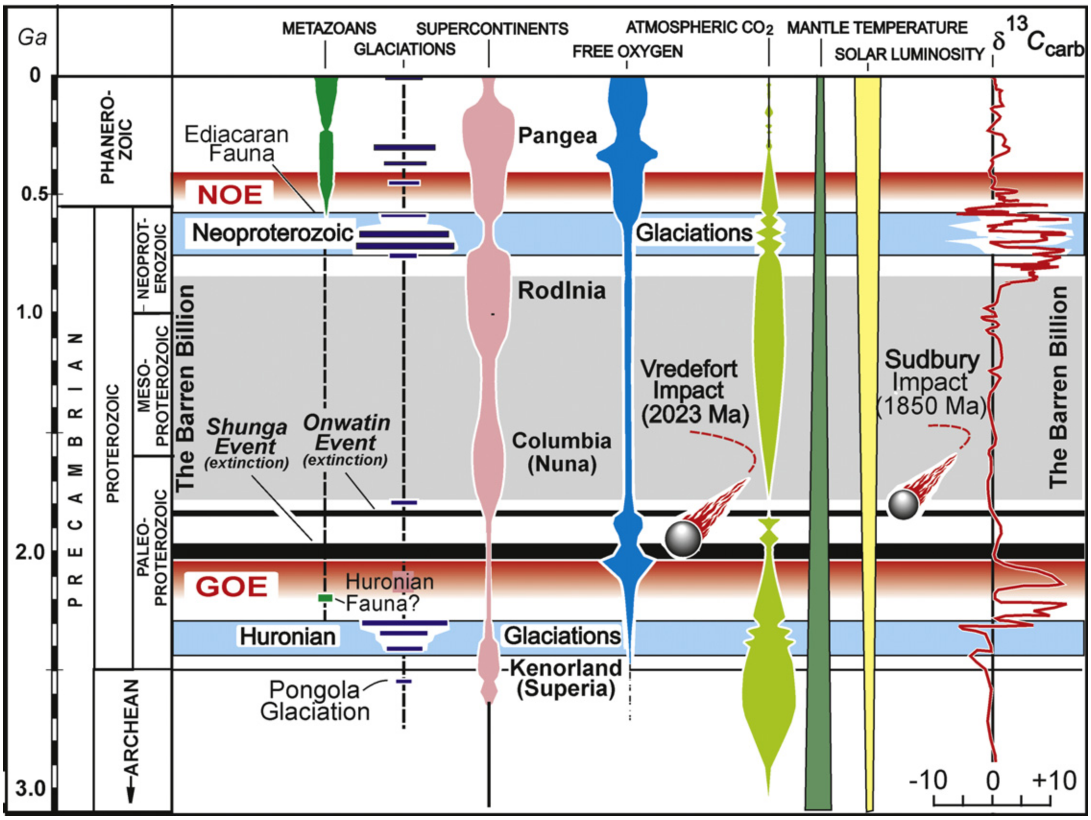

Figure 1. Schematic representation of events discussed in the text. Apart from the right hand column (after Kah et al., 2004; Halverson et al., 2005; Melezhik et al., 2005), the depicted changes are qualitative. Two Precambrian periods of multiple glaciations were followed by accumulation of atmospheric oxygen. Note the two massive impact events that occurred after the Great Oxidation Event (GOE) and caused global extinctions, resulting in accumulation of carbonaceous deposits of the Shunga and Onwatin events. NOE is the Neoproterozoic Oxidation Event (Och and Shields-Zhou, 2011).