Evolution of Earth’s climatic system: Evidence from ice ages, isotopes, and impacts

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ABSTRACT

Multiple glaciations took place near the beginning and end of the Proterozoic Eon. Neoproterozoic (Cryogenian) glacial deposits are more widespread than those of older (Paleoproterozoic) glacial episodes. Paleomagnetic results suggest that most Proterozoic glaciogenic rocks were deposited at low paleolatitudes. Some contain enigmatic evidence of strong seasonal temperature variations, and many formed at sea level. These attributes inspired both the snowball Earth hypothesis and the high obliquity theory, but only the latter explains strong seasonality at low latitudes. The Proterozoic glaciations may have been triggered by drawdown of atmospheric CO_2 during enhanced weathering of elevated supercontinents. Multiple glaciations resulted from a negative feedback loop in the weathering system that ended when the supercontinent broke apart. A radical reorganization of the climatic system took place in the Ediacaran Period. In contrast to previous glaciations, these ice sheets developed in high latitudes and many follow mountain building episodes. During the Ediacaran Period, Earth’s climatic zonation and controls appear to have undergone a radical change that persisted throughout the Phanerozoic Eon. The change may coincide with the world’s greatest negative $\delta^{13}C$ excursion, the Shuram event, here interpreted as the result of a very large marine impact that decreased the obliquity of the ecliptic, causing the Earth’s climatic system to adopt its present configuration. Attendant unprecedented environmental reorganization may have played a crucial role in the emergence of complex life forms.

INTRODUCTION

There is evidence of local glaciation in Archean times (at ca. 2.9 Ga), and several Paleoproterozoic (Huronian) glaciations are recorded in North America, NW Europe, South Africa, Western Australia, and Asia (Young, 1973, 2013; Ojakangas, 1988; Tang

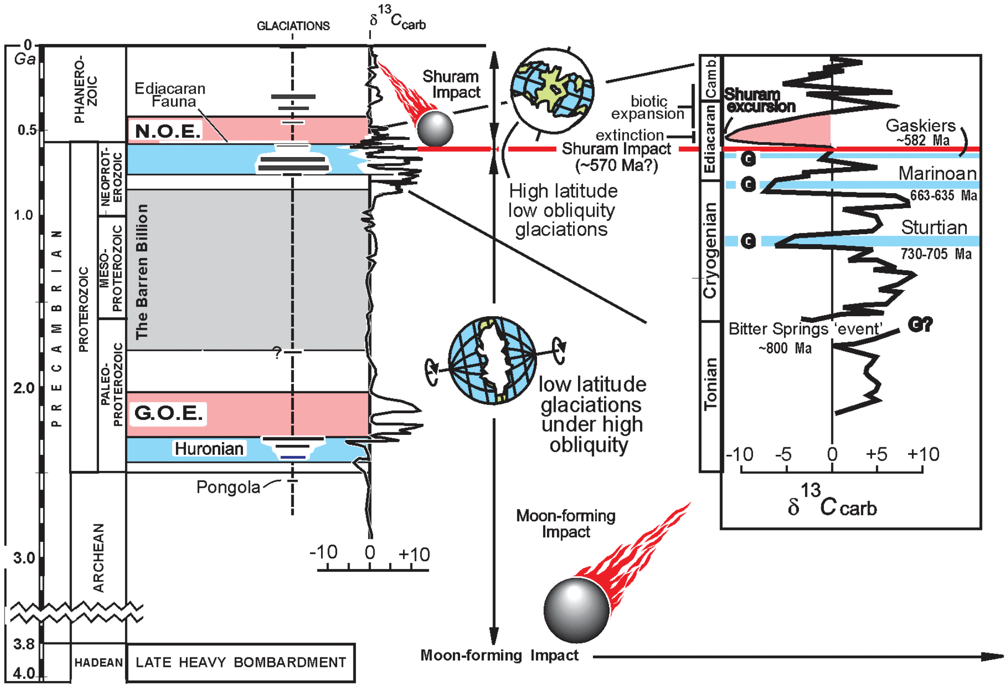

Figure 1. Schematic depiction of some aspects of Earth’s climatic history. Note the two great Proterozoic glacial episodes (at left), each followed by an atmospheric “oxidation event.” The “barren billion” has little evidence of glaciations or iron formations. Two contrasted climatic regimes are depicted in the central part of the diagram. During most of the Proterozoic eon, glaciations appear to have been concentrated in low latitudes, possibly as a result of Earth’s high obliquity (Williams, 2008). A radical change occurred near the beginning of the Phanerozoic eon, when a putative large marine impact brought about a major shift in the orientation of the world’s spin axis, resulting in a new climatic zonation that still exists today. The impact is inferred from the Shuram $\delta^{13}C$ anomaly (right side; modified from fig. 1 of Halverson et al., 2010) and associated stratigraphic and sedimentological evidence. Note that the Shuram anomaly and impact (age after Bowring et al., 2009) is depicted as younger than the Gaskiers glaciation (age after Mason et al., 2013, their fig. 3) but has been considered older by some. See text for full explanation. G.O.E.—great oxidation event; N.O.E.—Neoproterozoic oxidation event; G—glacial episode.

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and Chen, 2013). Among Neoproterozoic glaciations (Fig. 1), the most convincing and widespread are the Sturtian (730–705 Ma) and the Marinoan (663–635 Ma), although geochronological problems remain. Between ca. 2.2 Ga and 730 Ma, there is little evidence of glaciation (but see Williams, 2005). The temporal distribution of Precambrian glacial deposits is shown in Figure 1. Possible relationships to the supercontinental cycle (Fischer, 1984; Worsley et al., 1984; Bleeker, 2004) were discussed by Young (2013). For full documentation of ancient glacial occurrences, see Hambrey and Harland (1981), Eyles (1993), Deynoux et al. (1994), Crowell (1999), Chumakov (2004), Fairchild and Kennedy (2007), and Arnaud et al. (2011).

IDENTIFICATION OF GLACIAL DEPOSITS

Physical criteria for the identification of ancient glacial activity are relatively simple, but few are unequivocal. These include widespread diamictites—conglomerates with a variety of clast types "floating" in a matrix of rock flour (Fig. 2A). A second criterion is the presence of laminated mudstones with scattered "outsize" clasts and "splash-up" structures indicating vertical emplacement, as from floating ice (Fig. 2B). These resemble "varved" deposits formed by annual freeze-thaw cycles in modern proglacial lakes. Other attributes include striations on rock pavements or contemporary sediments and striated, faceted, and "bullet-shaped" clasts. Evidence of ancient permafrost and other periglacial phenomena has also been used, as have geochemical data (Nesbitt and Young, 1982).

Diamictites can form in a variety of depositional and climatic settings (Crowell, 1957; Dott, 1961). Glacial deposits are susceptible to "resedimentation" related to seismic shock or slope failure, obscuring their original glacial character (Schermerhorn, 1974; Eyles and Januszczak, 2007). Many Proterozoic glacial deposits formed in active tectonic settings (Arnaud and Eyles, 2002; Basta et al., 2011; Freitas et al., 2011). Evidence of "resedimentation" does not, however, preclude a glacial origin.

PRECAMBRIAN GLACIAL DEPOSITS IN TIME AND SPACE

The distribution of glaciogenic rocks (Hambrey and Harland, 1981) (Fig. 1, left side) suggests that younger Proterozoic glaciations were more widespread than their older counterparts. This may be due, in part, to growth of continental crust with time, providing a larger substrate for extensive ice sheets and increasing the preservation potential of their deposits.

Glacial deposits present great challenges to geochronologists, but, in some cases, ages can be obtained from interbedded tuffs and lavas, or they may be bracketed between dates from older and younger rocks.

The dearth of glacial deposits in the early part of Earth's history is surprising because of the less radiant young Sun (Sagan and Mullen, 1972; Sackmann and Boothroyd, 2003), but the surface of the early Earth was probably warmed by atmospheric greenhouse gases (notably CO_2). Archean supracrustal rocks attest to the presence of abundant surface water, but glacial deposits are rare. The Paleoproterozoic Huronian Supergroup (2. 45–2.21 Ga) includes three glacial formations (Young, 1970; Melezhik et al., 2013) separated by units formed under milder climatic conditions (Young, 1973; Eyles and Young, 1994). None of these glacial episodes has been precisely dated (Melezhik et al., 2013). Some early attempts at correlating Paleoproterozoic glaciogenic rocks in North America (Young, 1970, 1973), mainly based on lithostratigraphic criteria, are now broadly supported by geochronological data (Aspler et al., 2001; Vallini et al., 2006).

A discussion of individual Neoproterozoic glacial deposits is beyond the scope of this article but see Hambrey and Harland (1981), Arnaud et al. (2011), and Harland (2007). The snowball Earth hypothesis was proposed to explain the wide distribution of Cryogenian glaciations (Kirschvink, 1992; Hoffman et al., 1998), such as the Sturtian and Marinoan. Isotopic ratios of C and O from Neoproterozoic carbonates (e.g., Halverson et al., 2010) have been used to support the concept of sporadic, widespread

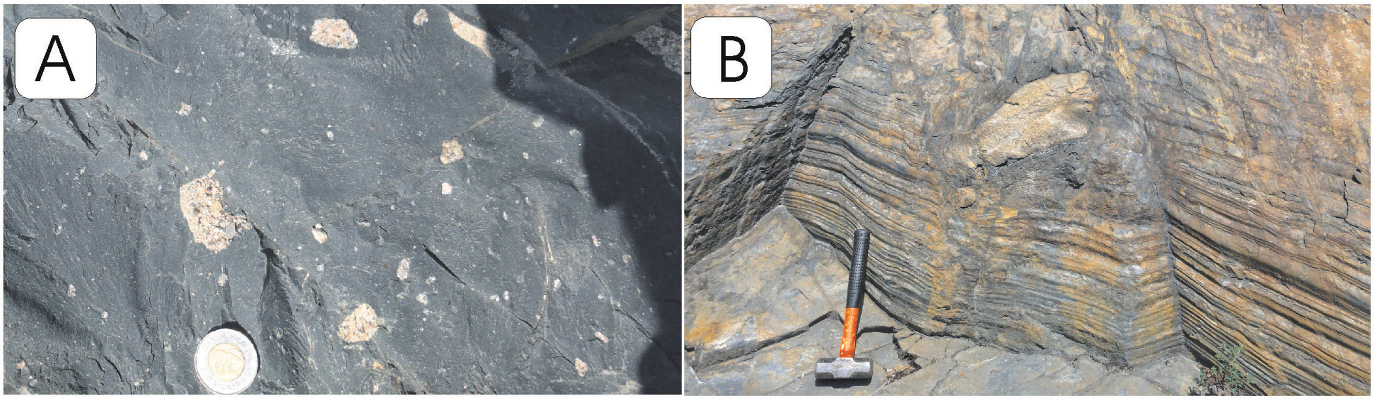

Figure 2. Some field attributes of glacial deposits. (A) Diamictite of the Paleoproterozoic Gowganda Formation, Ontario, Canada. Note that the clasts (mostly granitic) are "floating" in a matrix of crushed rock (rock flour). Coin is 2.8 cm in diameter. (B) Finely bedded mudstones of the Paleoproterozoic Pecors Formation (Huronian) north of Elliot Lake, Ontario, with dropstones that were transported by floating glacier ice. Hammer (head 10 cm long) lies on diamictites of the glaciogenic Ramsey Lake Formation.

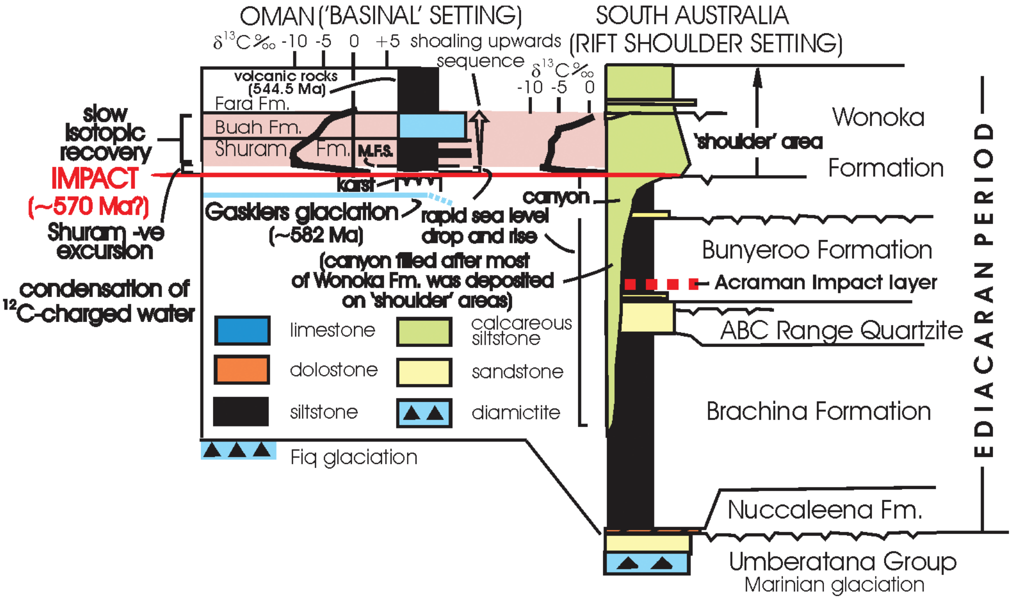

Figure 3. Two representative sections containing the Shuram isotopic anomaly. The Oman section is simplified from Le Guerroué et al. (2006, their fig. 2), and the Wonoka section is after Christie-Blick et al. (1995, their fig. 3). See Le Guerroué et al. (2006) for sources of isotopic profiles. The sections are not to scale, but the Wonoka canyons are up to 1 km deep. The Shuram excursion (age after Bowring et al., 2009) is younger than the Acraman impact layer. The Shuram excursion is shown as younger than the Gaskiers glaciations (Bowring et al., 2007; Macdonald et al., 2013) although some (Le Guerroué et al., 2006; Halverson et al., 2010) have considered the possibility that it may be younger. Much of the fill of the Wonoka canyons occurred after deposition of most of the Wonoka Formation on adjacent "shoulder" areas (Husson et al., 2012). The karst beneath the base of the Shuram Formation is after McCarron (2000). M.F.S.—maximum flooding surface.

glaciations that affected the chemistry of world oceans. Because most Neoproterozoic glacial deposits formed in low paleolatitudes near sea level (Hoffman et al., 1998; Hoffman and Li, 2009, their fig. 7b), it was suggested that Earth's surface was entirely frozen. This conclusion may, however, be invalid if glaciations were concentrated at low latitudes (see following section).

PROBLEMATIC PALEOLATITUDES AND THE OBLIQUITY OF THE ECLIPTIC

Paleomagnetic results led Harland (1964) to suggest that the Varanger (Neoproterozoic) tillites of east Greenland and Norway were deposited between ~4.5°N and 11°N. Neoproterozoic glacial rocks from around the world have subsequently yielded similar low paleolatitudes, and Williams (1975) proposed that the angle between Earth's spin axis and a line perpendicular to its orbital plane (obliquity of the ecliptic) was much greater in the past. If the steeply tilted Earth (obliquity >54°) descended into a cool period, equatorial regions would have been preferentially glaciated and subject to seasonal temperature fluctuations. Annual temperature differences are small in today's tropical regions, but several Proterozoic glacial successions contain "varved" deposits and sand-wedge structures (Williams, 1986, 2008; Williams and Schmidt, 1997).

Phanerozoic glaciers were markedly different. They descended to sea level only at high latitudes (Crowell, 1999; Evans, 2003; Hoffman and Li, 2009). Paleomagnetic and sedimentological data point to a radically different climatic regime throughout most of the Precambrian eon. The proposed high-obliquity state in Earth's early history may have resulted from the huge impact that produced the Moon (Williams, 1998)—but how to explain the present situation? More than 70% of the surface of the solid Earth was ephemeral oceanic crust, so that craters produced by ancient marine impacts would have been destroyed during subduction. Other suggestions for a large obliquity adjustment include mass distribution changes associated with true polar wander (Williams, 2008) and obliquity-oblateness feedback (Williams et al., 1998).

WHY DID "ICE-HOUSE" CONDITIONS OCCUR AT THE BEGINNING AND END OF THE PROTEROZOIC EON?

Numerous suggested causes of glaciations include both extraterrestrial and terrestrial processes. It was proposed by Melezhik (2006) that a "perfect storm," with a convergence of several factors, could have caused Proterozoic glaciations. Perhaps the most compelling explanation of long-term fluctuations in surface temperatures is variation in atmospheric CO_2, which has been linked (Young, 2013) to the supercontinental cycle (Fischer, 1984; Worsley et al., 1984; Nance and Murphy, 2013).

Phanerozoic glaciations do not appear to be related to supercontinent formation but may have been triggered by increased weathering during orogenic episodes at various stages in the supercontinental cycle. Low ambient Phanerozoic CO_2 levels would have made Earth susceptible to glaciation.

EVIDENCE FROM STABLE ISOTOPES AND THE SHURAM EXCURSION

Some strong fluctuations in carbon isotopic ratios in Cryogenian carbonate rocks coincide with glacial episodes (Halverson et al., 2005, 2010) (Fig. 1). Carbonate rocks of the Ediacaran period (635–542 Ma) contain evidence of the world's deepest negative

$\delta^{13}C_{carb}$ excursion—the Shuram event—named from the type area in Oman. Unless otherwise indicated, $\delta^{13}C$ refers to $\delta^{13}C_{carb}$. In contrast to the Cryogenian isotopic anomalies, the Shuram excursion is believed by some (e.g., Le Guerroué et al., 2006) to lack any glacial influence (but see McGee et al., 2013). The Shuram anomaly has been identified in South Australia in the Wonoka Formation, parts of which are preserved in deep (>1 km) subaerially excavated canyons (von der Borch et al., 1989) (Fig. 3). The anomaly is also known from North America (Verdel et al., 2011), China, India, Siberia, Scandinavia, Namibia, Brazil, and Uruguay (Gaucher et al., 2004). It is widely believed to represent changes in the chemistry of world oceans (Le Guerroué, 2010) rather than secondary (diagenetic) modifications. Deep paleo-canyons have been described from a number of places, including South Australia, California (Clapham and Corsetti, 2005), and Uruguay (Gaucher et al., 2004), some possibly representing significant sea-level changes. The isotopic curves typically show an extremely abrupt drop in $\delta^{13}C$ values (Fig. 3). In California, the drop begins in the widespread Johnnie oolite, but the lowest values (<−10‰) occur in thin limestone beds representing a maximum flooding surface (Bergmann et al., 2011, their fig. 9), as in Oman (Le Guerroué et al., 2006, their figs. 2 and 6; Verdel et al., 2011, their fig. 15) (Figs. 3 and 4) and northwestern Canada (Macdonald et al., 2013).

The Shuram anomaly has defied explanation (Grotzinger et al., 2011; Verdel et al., 2011; Tahata et al., 2013; Bjerrum and Canfield, 2011). None of several theories for formation of the Wonoka canyons (Coats, 1964; von der Borch et al., 1989; Dyson, 2003; Williams and Gostin, 2000) provides an explanation for the contemporary widespread isotopic anomaly.

The Shuram excursion has been attributed by some to oxidation of a large amount of organic carbon in world oceans, both dissolved organic carbon and suspended particulate organic material (see Rothman et al., 2003; Fike et al., 2006; Halverson et al., 2010) (Fig. 1).

AN IMPACT ORIGIN FOR THE SHURAM EXCURSION?

It is here proposed that the Shuram event may be the result of a large impact that occurred in the deep ocean. Such an impact, among other things, would have caused abrupt lowering of sea level by removal of significant volumes of sea water (and its dissolved and particulate carbon), giant tsunamis, and elevated temperatures (van den Bergh, 1989). Such violent events could have contributed to formation of deep subaerial canyons in appropriate locations. The canyons would have been initiated at the time of impact and eroded by flooding of continents followed by return of huge volumes of water to the oceans. The time involved is unknown, but canyon formation was probably relatively rapid. An "isotopic conglomerate test" by Husson et al. (2012) showed that filling of the Wonoka canyons took place after deposition of most of the eponymous formation on adjacent "shoulder" areas of the Adelaide Rift Complex.

Rocky impact debris would have been less voluminous than in a terrestrial impact. Widespread breccias and diamictites were described by Boggiani et al. (2010) and McGee et al. (2013) from Ediacaran successions in Brazil and elsewhere, associated with rocks displaying a negative $\delta^{13}C$ signal identified as a Shuram equivalent. Timing of the initiation of the Shuram event is poorly documented, as is its relationship to the Gaskiers glaciation. Le Guerroué et al. (2006) thought that the Gaskiers glaciation occurred during the recovery period following the nadir of the isotopic excursion, but others (Bowring et al., 2007, 2009; Tahata et al., 2013; Macdonald et al., 2013, their fig. 13) considered the glaciations to be older than the Shuram event, as depicted in Figures 1 and 3 herein. Some paleolatitudes for the Gaskiers glaciation are quite high, but the majority are relatively low (<60°), and glaciations extended into tropical latitudes, like those of the Cryogenian (Hoffman and Li, 2009). Some of the problems regarding the age of the Gaskiers glaciation (and the wide range of its paleolatitudes) may be due to the gathering, under the same umbrella, of results from several Ediacaran glaciations (both older and younger than the Shuram event) (Hebert et al., 2010).

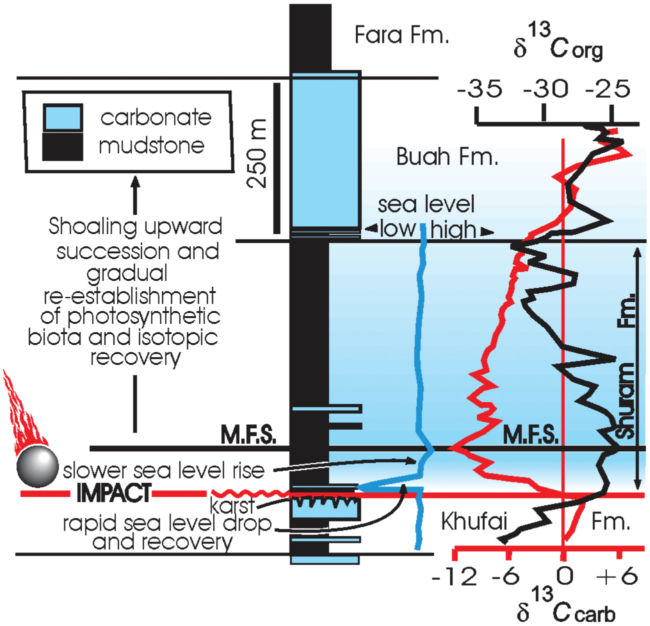

Figure 4. Simplified stratigraphic column from Jabal Akhdar in northern Oman (after Le Guerroué et al., 2006, their fig. 2), together with $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ curves from Fike et al. (2006, their fig. 1). An abrupt sea-level drop and subsequent rise are inferred from canyon incision elsewhere (see Fig. 3) and karst development in the Oman area. This was followed by slower sea-level rise due to condensation of vaporized sea water. The return of ^{12}C-charged water is thought to have brought about the Shuram isotopic anomaly. A shoaling-upward succession then records a slow return to "normal" isotopic values. Note the unusual antithetic relationship between the two isotopic parameters in the Shuram Formation. See text for discussion. M.F.S.—maximum flooding surface (after Le Guerroué et al., 2006, their fig. 2).

The abrupt negative $\delta^{13}C$ excursion may be explained by rapid introduction of large amounts of light carbon to the ocean, caused by oxidation and remineralization of much of the ocean's organic carbon content during an impact event (Fig. 4). Recovery from the light carbon-charged ocean may have involved gradual re-establishment of oceanic photosynthetic microorganisms. The unusual antithetic relationship between the $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ curves in the Shuram Formation (Fig. 4) and equivalents in southern China (Xiao et al., 2012, their fig. 8) is not understood but may indicate a common driver–recrudescence of a shallow marine ^{12}C-sequestering biota. More $\delta^{13}C_{org}$ data are needed from sections around the world. Development of a negative $\delta^{18}O$ anomaly during the

Shuram $\delta^{13}C_{carb}$ excursion (Tahata et al., 2013, their figs. 1 and 7) in several locations suggests that both occurred during a period of general global warming.

Environmental changes related to Neoproterozoic glaciations are commonly cited as stimuli for metazoan evolution, but extinctions, followed by proliferation and increasing sophistication of the Ediacaran fauna, accompanied the Shuram event in several parts of the world (Le Guerroué et al., 2006, their fig. 6; Fike et al., 2006; Grey and Calver, 2007; McFadden et al., 2008, their fig. 1; Macdonald et al., 2013, their fig. 13), so that the proposed giant impact could have been a significant catalyst for these events.

In summary, evidence that the Shuram isotopic excursion may be related to an impact event includes the following:

1. The unusual character of the isotopic excursion, involving an abrupt drop in $\delta^{13}C_{carb}$ values, followed by a smooth and gradual recovery. Unlike the onset of a glaciation, an impact is instantaneous, but its effects can be manifested for a long time afterward.
2. The global nature of the anomaly precludes most explanations that involve secondary processes (such as diagenetic modification), which are generally only locally expressed.
3. Association of the onset of the anomaly with a dramatic fall in sea level, manifested in such settings as rift margins (e.g., Flinders Ranges), by incision of deep canyons. A large marine impact would temporarily displace huge volumes of sea water onto the continents and into the atmosphere.
4. Some sections (e.g., Brazil, western USA, Uruguay) contain coarse sedimentary breccias that could be products of tsunamis and impact-related storms.
5. Many successions that contain isotopic evidence of the Shuram event were storm-dominated.
6. The nadir of the isotopic excursion coincides with a maximum flooding surface (MFS), followed by gradual return to "normal" $\delta^{13}C_{carb}$ values. The opposite sea-level history would be expected if the excursion were related to a glaciation. The MFS could represent relatively rapid return of water to the oceans, first from flooded continents, then from the atmosphere—the latter introducing light carbon (dissolved organic carbon and particulate organic carbon) that was oxidized in the atmosphere following the impact and subsequently incorporated into carbonates. "Normalization" of oceanic carbon isotopic composition resulted from recovery of a ^{12}C-secreting, photosynthesizing biota in the shallow oceans.
7. In some areas (e.g., Oman and southern China), the negative $\delta^{13}C_{carb}$ anomaly is accompanied by a "mirror image" positive $\delta^{13}C_{org}$ anomaly, whereas covariance is typical of most perturbations in ocean chemistry.
8. Unlike two large Cryogenian $\delta^{13}C_{carb}$ anomalies, there is no definitive association with glaciation. This could be explained by glaciation being located elsewhere, but the excursion is the deepest known, and therefore difficult to explain by local ice sheets.

CONCLUSIONS

Most Proterozoic glaciogenic rocks appear to have been deposited at low paleolatitudes. The present climatic model does not adequately explain this or the evidence of strong seasonal temperature fluctuations in tropical regions. The snowball Earth hypothesis remains equivocal. The great Proterozoic glaciations followed periods of supercontinentality when weathering of collisional orogens and buoyant, thickened continental lithosphere resulted in drawdown of atmospheric CO_2. Between the Marinoan glaciation and the beginning of the Phanerozoic eon, Earth's climatic system appears to have undergone a radical change, for Phanerozoic glaciations took place at high latitudes. This dramatic change may be accommodated by a large reduction in the obliquity of the ecliptic. The previously unexplained Shuram isotopic excursion, together with excavation of deep subaerial canyons and deposition of breccias and diamictites, are considered to be the "smoking gun" for a cryptic, large oceanic impact. There is no compelling evidence that the Shuram excursion is related to, or affected by, glaciation, so that the important biological innovations of the Ediacaran period, commonly attributed to the "snowball Earth," may be allied to massive environmental perturbations accompanying the proposed oceanic impact. If the impact origin for the Shuram anomaly is correct, its widespread effects and "instantaneous" nature would provide one of the most useful and precise time markers in the geological record.

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