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Research paper

Environmental upheavals of the Ediacaran period and the Cambrian "explosion" of animal life

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ABSTRACT

The second half of the Ediacaran period began with a large impact – the Acraman impact in South Australia, which was accompanied by a negative $\delta^{13}C_{carb}$ anomaly and an extinction-radiation event involving acritarchs. A few million years later (~570 Ma?) there was a second, deeper and longer-lived world-wide $\delta^{13}C_{carb}$ anomaly (the Shuram anomaly) which coincides with extinction of the acanthomorphic acritarchs. Wide distribution of the Shuram event is exemplified by stratigraphic sections from South Australia, Oman, southern California and South China. The widespread anomaly has been tentatively attributed to a marine impact. During recovery from the Shuram event the enigmatic Ediacaran biota achieved its zenith, only to be extirpated and replaced by a polyphyletic assemblage of shelly animals in what is known as the Cambrian "explosion". This extinction-radiation cycle was preceded by glaciation, another $\delta^{13}C_{carb}$ excursion and the highest $^{87}Sr/^{86}Sr$ values known from marine carbonates. These high Sr ratios have been linked to weathering of extensive tracts of continental crust that were elevated during amalgamation of the supercontinent Gondwana. Introduction of essential nutrients to the oceans would have promoted biological production of oxygen and provided P and Ca for the important skeletonization that characterizes the Cambrian "explosion" and caused a quantum leap in the preservation potential of animal remains. Turbulent events of the last 50 million years of Precambrian time include three glaciations, two large impacts and a massive orogenic episode. These dramatic environmental upheavals are held responsible for three consecutive extinction-radiation cycles that culminated in the appearance of a diverse array of shelly fossils. Various lines of evidence suggest that the metazoans have deep roots so that they too may have been subjected to the environmental pressures of the late Ediacaran period clearly illustrated by acritarchs and the Ediacaran biota but the long-lived diversity of the metazoan population was "suddenly" revealed by the acquisition of biomineralization.

1. Introduction

Despite being the last-named period of the geological time scale (Knoll et al., 2006) the Ediacaran, between about 635 and 542 Ma, was perhaps the most important in Earth history. During the latter half of the Ediacaran period, the brief span of time between about 580 and 541 Ma, the Earth may have been completely changed. The atmosphere and oceans were oxygenated to a higher degree than previously and there were dramatic changes in the biological world that culminated in the so-called "Cambrian explosion" with the appearance of large, complex life forms whose ancestors remain shrouded in mystery but whose descendants went on to populate the planet. The Ediacaran was a pivotal period in the evolution of Earth and its biota. These events are widely recognised but there is little agreement concerning their precise timing or understanding of their root cause or causes. Many of the radical environmental and biotic changes may have been affected (effected?) by two large impacts – the well-documented terrestrial Acraman impact in South Australia (Gostin et al., 1986; Williams, 1986; Williams and Gostin, 2005) and the much more speculative Shuram impact proposed by Young (2013).

Many important environmental and biological events have been attributed to the great glaciations that gripped the Earth in the Cryogenian period (e.g. Hoffman et al., 1998; Hoffman, 2009) but the Ediacaran rock record lacks evidence of glaciations of comparable magnitude to the older Sturtian and Marinoan events of the

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Cryogenian period. Paleomagnetic results from glacial deposits suggest that, during the Ediacaran period there was a radical change from low to high paleolatitudes for deposits from sea-going continental ice sheets.

The change from low to high paleolatitudes appears to have taken place at about 570 Ma when glaciations may have adopted their modern circum-polar distribution. Paleomagnetic data also indicate anomalous behaviour of the Earth's geodynamic system during the Ediacaran period, including unusually rapid displacement of lithospheric plates, possible oscillatory plate movements and evidence of inertial interchange-related true polar wander (Levashova et al., 2014 and references therein). Unprecedented environmental changes may have been the catalyst for extinctions and remarkable biological changes including the dramatic proliferation and demise of two successive assemblages of acritarchs, the evolution and extirpation of the Ediacaran biota and the appearance of the ancestors of modern metazoans. Another unusual aspect of the Ediacaran is the occurrence of the world's largest negative $\delta^{13}C_{carb}$ (hereafter $\delta^{13}C$) anomaly, known as the Shuram-Wonoka anomaly. This exceptionally deep $\delta^{13}C$ excursion was first discovered in the Wonoka Formation in South Australia (Jansyn, 1990; Pell et al., 1993; Urlwin et al., 1993) and was later documented in the Shuram Formation in the Sultanate of Oman (Burns and Matter, 1993) and in the Siberian Aldan Shield (Pokrovsky and Gertsev, 1993). These findings attracted considerable attention (e.g. Melezhik et al., 2005; Le Guerroué et al., 2006; Le Gerroué, 2010) and the deep isotopic excursion is now known throughout the world as the Shuram anomaly. The Shuram anomaly, unlike those associated with the Sturtian and Marinoan glaciations, does not appear to be related to widespread paleoclimatic changes. Over the last several decades evidence has accumulated in support of the existence, in sedimentary rocks belonging to what is now known as the latter part of the Ediacaran period, of a diverse and advanced biota, including early metazoans. Thus there is convergence, around the later part of the Ediacaran period, of several unusual events (Fig. 1) including aspects of isotopic geochemistry of the oceans, an apparent change in the distribution of the Earth's climatic zones, poorly understood anomalous geophysical phenomena, and unprecedented biological changes. The idea that some of these events might be related to the ca. 580 Ma Acraman impact in South Australia was introduced by Grey et al. (2003), Grey and Calver (2007) and Gostin et al. (2011), supported by the discovery of changes in organic chemistry across the Acraman ejecta layer (McKirdy et al., 2006). In an effort to explain the world's largest $\delta^{13}C$ anomaly and associated physical and biological phenomena, a slightly younger (ca. 570 Ma?) large marine impact was proposed by Young (2013). The purpose of this contribution is to more fully explore the possible geological and biological consequences of the well documented Acraman impact and the more speculative marine impact thought to have been responsible for the Shuram anomaly.

2. The Acraman impact

At about the same time as the Acraman impact crater was discovered in the Gawler Ranges of South Australia (Gostin et al., 1986; Williams, 1986, 1987) anomalous occurrences of relatively large volcanic clasts were noted in the fine-grained Bunyeroo Formation in the northern part of the Flinders Ranges in the Adelaide "Geosyncline", Fold Belt or Rift Complex (ARC) (Preiss et al., 2011 and references therein), about 300 km to the east of the impact site (Gostin et al., 1986). In an attempt to obtain the age of the Bunyeroo Formation, some of the volcanic fragments were dated but the ages were disappointingly old (about 1.6 Ga) compared to the anticipated age of the host Bunyeroo Formation (Gostin et al., 1986). Through detailed sedimentological and geochemical studies (Gostin et al., 1989) it was discovered that the volcanic fragments were derived from the Gawler Ranges (site of the Acraman impact), and weak Ir anomalies in the host sediments suggested that the rocks carried an extra-terrestrial chemical signal. Eventually the blanket of impact ejecta was extended to the Officer Basin about 540 km to the NW (Gostin et al., 2010). The age of the Acraman impact is not precisely known but it is thought to be about 580 Ma, which is close to the age of the Gaskiers glaciation in Newfoundland. It was suggested by Hebert et al. (2010, Fig. 1) and Narbonne et al. (2012, Fig. 18.6) that there is a negative $\delta^{13}C$ anomaly associated with the Gaskiers glaciation and Gostin et al. (2010) reported what they interpreted as ice-rafted debris both above and below the Acraman impact layer in the ARC and Officer Basin to the west. Younger glacial deposits of the Fauquier glaciation in Virginia (USA) were considered by Hebert et al. (2010) to be about 570 Ma, apparently associated with a weak $\delta^{13}C$ anomaly. It was also noted by Hebert et al. (2010, p.408) that $\delta^{13}C$ values as low as $-9‰$ are present in limestones beneath the Fauquier Formation. They commented that these were similar to the low values associated with the Shuram anomaly elsewhere, which was considered by them to be older. As discussed later (see Section 5) the Fauquier glacial deposits may be of approximately the same age as (or slightly younger than) the Shuram event.

3. Possible biological consequences of the Acraman impact

Rocks of the Ediacaran period are rich in organic remains, including both microfossils such as acritarchs and the enigmatic structures known as the "Ediacaran biota", although use of this name has recently come under critical scrutiny (MacGabhann, 2014). The micro-organisms (acritarchs) are of diverse origin and taxonomic affinity but many are thought to be resting cysts of chlorophyta (green algae). In the Ediacaran period they show remarkable changes in abundance, complexity and diversity so that some authors have used them in attempts to set up biozones (e.g. Grey et al., 2003; Grey and Calver, 2007; Willman, 2007; McFadden et al., 2008; Liu et al., 2014) that may eventually be used to establish global correlations comparable to those of the Phanerozoic.

A significant change from small smooth spherical acritarchs (leiospheres) to larger forms with complex ornamentation (acanthomorphic acritarchs) was reported by Grey et al. (2003) in Ediacaran rocks of the Officer Basin in Australia. They noted that the change to acanthomorphic forms and their diversification occurred about 50 m above the ejecta layer attributed to the Acraman impact and speculated that the marked change in acritarch morphology, size and diversity might be related to environmental upheavals associated with the impact event. The changes in the palynoflora coincide with a short negative $\delta^{13}C$ anomaly based on data from Calver (2000).

The Three Gorges area of South China contains a well preserved succession of Ediacaran rocks that have also yielded remarkable acritarch assemblages (McFadden et al., 2008; Liu et al., 2014). Within the Doushantuo Formation, which is between about 635 and 551 Ma there are three important negative $\delta^{13}C$ excursions, EN1 to EN3. The first is considered to have developed in response to the widespread Marinoan glaciation. The second (EN2) probably corresponds to that associated with the less widespread Gaskiers glaciation, which is thought to be about the same age as the Acraman impact so that its origin could also be linked to that event. As noted by Gostin et al. (2010), ice-rafted debris is associated with the ejecta blanket of the Acraman impact in the ARC and Officer Basin. In southern China, as was the case in Australia, the sedimentary succession above the negative $\delta^{13}C$ anomaly (EN2) shows a remarkable diversification of acanthomorphic acritarchs (McFadden et al., 2008). In spite of problems associated with environmental and