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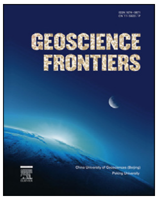

Focus Paper

Shuram–Wonoka carbon isotope excursion: Ediacaran revolution in the world ocean's meridional overturning circulation

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ABSTRACT

The late Ediacaran Shuram–Wonoka excursion, with $\delta^{13}C_{carb}$ values as low as −12‰ (PDB) in marine-shelf deposits and spanning up to 10 Myr, is the deepest and most protracted $\delta^{13}C_{carb}$ negative anomaly recognised in Earth history. The excursion formed on at least four continents in low (≤32°) palaeolatitudes, and in China is associated with a major phosphogenic event. Global and intrabasinal correlation, magnetostratigraphy, isotope conglomerate tests and further geochemical data are consistent with a primary or syn-depositional origin for the excursion. Continental-margin phosphorites are generated by oceanic upwelling driven by surface winds, and $\delta^{13}C_{carb}$ negative anomalies are explicable by oceanic upwelling of ^{13}C-depleted deep oceanic waters, arguing that a feature common to these exceptional Ediacaran events was unprecedented perturbation of the world ocean. These events occurred during the transition from an alien Proterozoic world marked by low-palaeolatitude glaciation near sea level and strong seasonality to the familiar Phanerozoic Earth with circum-polar glaciation and temperate climate, suggesting that the Shuram–Wonoka excursion is related to this profound change in Earth's climate system. Of various hypotheses for Proterozoic low-palaeolatitude glaciation, only the high obliquity (>54°) hypothesis, which posits secular decrease in obliquity to near the present-day value (23.5°) during the Ediacaran, predicts an unparalleled revolution in the Ediacaran world ocean. The obliquity controls the sense of the world ocean's meridional overturning circulation, which today is driven by the sinking of cold, dense water at the poles and upwelling driven by zonal surface winds. When the decreasing obliquity passed the critical value of 54° during the Ediacaran the meridional temperature gradient reversed, with the equator becoming warmer than the poles and Hadley low-latitude (<30°–35°) atmospheric zonal circulation reversing. This reversal of the temperature gradient is unique to the Ediacaran Period and caused reversal of the oceanic meridional overturning circulation, with upwelling of anoxic, ^{13}C-depleted deep oceanic waters producing a deeply negative and protracted $\delta^{13}C_{carb}$ signature on late Ediacaran marine-shelf deposits.

1. Introduction

The Ediacaran Period (~635–541 Ma) is a key interval in Earth history, marking the transition from an alien world with unicellular life and glaciation near sea level in low latitudes, with accompanying strong seasonality, to the familiar world of complex animal life, circum-polar glaciation and temperate climate (Williams, 2008; Eriksson et al., 2013; Williams et al., 2016). The Ediacaran is renowned for the proliferation and demise of the Ediacara biota, astonishing fossils that 'are now generally regarded as a "failed experiment" in the revolution that changed the world from Proterozoic to Phanerozoic' (Young, 2017, p. 5).

This interval is remarkable also for the late Ediacaran carbon isotope anomaly, herein termed the Shuram–Wonoka excursion (SWE), with early $\delta^{13}C_{carb}$ values as low as −12‰ (PDB) and continuing below the mantle value of about −6‰ for marine-shelf successions several hundred metres thick, thus constituting the deepest and most protracted $\delta^{13}C$ excursion known in Earth history (Fike et al., 2006; Le Guerroué, 2010; Grotzinger et al., 2011). The SWE is of global extent, comparable excursions having been identified in Ediacaran strata on at least four continents. It was first

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recognised in the Wonoka Formation in South Australia by Jansyn (1990) and further documented by Ayliffe (1992), Urlwin (1992), Pell et al. (1993), Urlwin et al. (1993) and Calver (2000). There the SWE spans all but the uppermost 150–200 m of the 700 ± 100 m-thick Wonoka mixed calcareous–siliciclastic and locally phosphatic marine-shelf succession (Haines, 1988), although the full declining arm of the SWE is not preserved (Husson et al., 2012, 2015a). Adjacent deep (1 km) palaeocanyons were eroded and filled in Wonoka times (Forbes and Preiss, 1987). The SWE is also displayed in the Shuram Formation of the Huqf Supergroup in Oman (Burns and Matter, 1993; Le Guerroué et al., 2006a), the Johnnie Formation in southwestern USA (Corsetti and Kaufman, 2003; Bergmann et al., 2011; Verdel et al., 2011), the Gametrail Formation, northwestern Canada (Macdonald et al., 2013), and the Doushantuo Formation in the Nanhua basin, South China (Jiang et al., 2007; Zhu et al., 2007). In China the SWE is associated with 'one of the largest phosphogenic events in Earth's history' (Cui et al., 2016, p. 134), with the Doushantuo Formation containing globally significant economic phosphorite deposits (Li, 1986). Other δ^{13}C negative anomalies potentially correlative with the SWE occur in the Nama Group, Namibia (Workman et al., 2002), the Dalradian Supergroup, Scotland (Prave et al., 2009), the Scandinavian Caledonides (Melezhik et al., 2008), the Krol Group, India (Kaufman et al., 2006), Ediacaran carbonates, southeastern Siberia (Melezhik et al., 2009) and the Clemente Formation, northwestern Mexico (Loyd et al., 2012). A common albeit variable feature of the SWE is a covariation between $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$. Husson et al. (2015a) found that the correlation ranges from strong (r^2 values up to 0.88) for individual sections in the Wonoka Formation, to moderate ($r^2 = 0.36$) for combined Wonoka data for all sections with $\delta^{13}C_{carb} < -5‰$, and weak ($r^2 = 0.12$) for strata in southwestern USA.

Proposed causes of such a deeply negative and durable carbon isotope excursion invoke either primary/syn-depositional or authigenic/diagenetic processes (Grotzinger et al., 2011). Because the SWE immediately preceded the advent of the Ediacara biota of complex animal life, some have argued that the excursion is linked to a pervasive oxygenation of the world ocean that stimulated metazoan evolution (e.g. Fike et al., 2006; McFadden et al., 2008).

Grotzinger et al. (2011, p. 290) concluded that the 'Ediacaran enigma' of the SWE 'presents a tough problem, and one that is ripe for fresh approaches and ideas.' In that spirit, we argue that the SWE resulted from oceanic turmoil associated with reversal of the world ocean's meridional overturning circulation and atmospheric zonal winds in response to a threshold or tipping-point being reached during the Ediacaran with secular change in Earth's meridional temperature gradient.

2. Shuram–Wonoka excursion

2.1. Form, age and duration

The SWE typically is asymmetric (Fig. 1). Combined data for the Shuram, Wonoka, Doushantuo and Johnnie formations show a rapid decline to the most negative δ^{13}C values of around −12‰, 'followed by a slow recovery to less negative and eventually positive values' (Grotzinger et al., 2011, p. 287). In the Wonoka Formation (Fig. 2), the nadir of δ^{13}C values (−12‰ to −10‰) is reached in the stratigraphically lowest carbonates, with positive values of between +2‰ and +5‰ attained near the top of the formation (Husson et al., 2012, 2015a).

The age of the SWE is constrained by data for the Ediacaran succession of the Wilpena Group in the Adelaide Geosyncline, South Australia (Fig. 2), and global correlations. The Wilpena Group disconformably to unconformably overlies the terminal Cryogenian, glaciogenic Elatina Formation (Williams et al., 2008, 2011; Schmidt et al., 2009), whose age is taken as ~635 Ma through correlation with the Ghaub glaciation in Namibia, dated at 635 ± 1.2 Ma (Hoffmann et al., 2004), the Nantuo glaciation in China, dated at between 636 ± 4.9 and 635.2 ± 0.6 Ma (Condon et al., 2005; Zhang et al., 2008), and the Cottons Breccia in Tasmania, dated at 636.41 ± 0.45 Ma (Calver et al., 2013). The 400–700 m-thick Bunyeroo Formation, comprising mostly red shale and siltstone deposited in a low-energy marine-shelf setting, has ice-rafted detritus near its base (Gostin et al., 2010, 2011) that may be correlated with the Gaskiers glaciation in North America, dated at between 579.88 ± 0.44 Ma and 579.63 ± 0.15 Ma (Pu et al., 2016). Such correlation accords with the time-scale of Walter et al. (2000), based on global chemostratigraphy, indicating an age of ~580 Ma for the Bunyeroo Formation.

The Wonoka Formation overlies the Bunyeroo Formation with no evidence of significant erosional contact, and a serial, arcuate tubular fossil, *Palaeopascichnus*, the oldest identifiable form of the Ediacara biota in South Australia, occurs near the top of the Wonoka (Haines, 2000; Gehling and Droser, 2012). A U–Pb zircon date of 556 ± 24 Ma for the 225 m-thick Bonney Sandstone possibly records penecontemporaneous volcanism and provides a maximum age for the overlying fossiliferous beds near the base of the 413 m-thick Rawnsley Quartzite (Forbes and Preiss, 1987; Preiss, 2000). The Ediacara Member of the lower Rawnsley Quartzite hosts the famous Ediacara biota, whose taxa are closely comparable with those of the 'White Sea Association' in Russia (Grazhdankin, 2004; Narbonne, 2005). The White Sea Association is confined to the Belomorian Regional Stage, the age of which is constrained by a U–Pb zircon date of 558 ± 1 Ma for a tuff at its base and a U–Pb

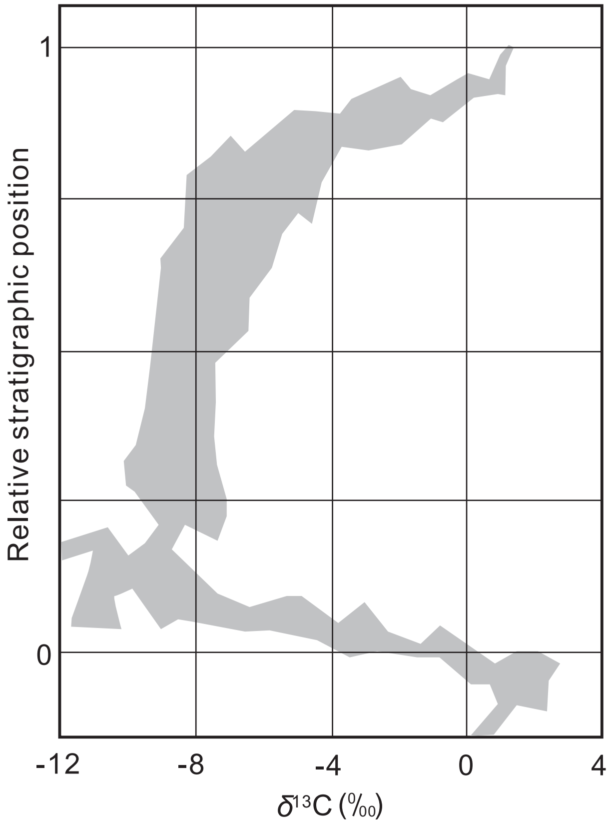

Figure 1. Generalised swath covering some 290 $\delta^{13}C_{carb}$ values (excluding eight outliers) for the Shuram, Wonoka, Doushantuo and Johnnie formations, showing the magnitude and asymmetry of the SWE. Based on Grotzinger et al. (2011).

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