Estudios Geológicos
julio-diciembre 2019, 75(2), e114
ISSN-L: 0367-0449
https://doi.org/10.3989/egeol.43605.569

Sulfur cycle imbalance and environmental change during the Ediacaran Period

Desequilibrio del ciclo del azufre y cambio ambiental durante el Período Ediacárico

G.A. Shields[1], B.J.W. Mills[2]

[1]Department of Earth Sciences, University College London, Gower Place, London, WC1E 6BT, UK. Email: g.shields@ucl.ac.uk; ORCID ID: https://orcid.org/0000-0002-7828-3966
[2]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK. ORCID ID: https://orcid.org/0000-0002-9141-0931

ABSTRACT

A different approach is proposed here to solve the problem of negative $\delta^{13}C$ excursions during the Ediacaran, by viewing them in terms of a linked carbon-sulfur-oxygen system, whereby changes in oxidant dynamics caused an excess of organic carbon oxidation over burial, resulting in a smaller DOM reservoir. The amount of oxidant required to achieve a deep negative carbon isotope excursion through net organic carbon oxidation may reasonably result from basin-scale evaporite dissolution.

Keywords: Carbon isotopes; Sulfur isotopes; Biogeochemical balance; Ediacaran.

RESUMEN

Se propone aquí un enfoque diferente para resolver el problema de las excursiones quimioestratigráficas negativas durante el Ediacárico, considerándolas en términos de un sistema vinculado de carbono-sulfuro-oxígeno, en el que los cambios en la dinámica de los oxidantes causarían un exceso de oxidación de carbono orgánico sobre el enterramiento, lo que resultaría en un depósito menor de DOM. La cantidad de oxidante requerida para lograr una excursión isotópica de carbono negativa a través de la oxidación de carbono orgánico neto puede resultar razonablemente de la disolución de evaporitaa a escala de cuenca.

Palabras clave: Isótopos de carbono; Isótopos de azufre; Balance biogeoquímico; Ediacárico.

Introduction

The Ediacaran Period (ca. 635-540 Ma) marks a turning point in Earth history when groups of morphologically complex multicellular eukaryotes, including algae and animals, attained ecological dominance, irrevocably changing Earth System dynamics (Lenton *et al*., 2014). These biological radiations took place after two prolonged episodes of global glaciation during the Cryogenian Period (ca.715-660 and ca. 650-635 Ma), and were accompanied by further short-lived (ca.580 Ma

---

Recibido el 20 de mayo de 2019; Aceptado el 1 de julio de 2019; Publicado online el 28 de noviembre de 2019

Citation / Cómo citar este artículo: Shields G.A. & Mills B.J.W. (2019). Sulfur cycle imbalance and environmental change during the Ediacaran Period. Estudios Geológicos 75(2): e114. https://doi.org/10.3989/egeol.43605.569.

and ca.550 Ma) regional ice ages, interspersed with warmer intervals (Condon *et al*., 2005; Pu *et al*., 2016; Le Heron *et al*., 2019). The world's oceans also became episodically more oxygenated during the Ediacaran with the extent of oxygenated seafloor reaching near-modern levels at times by the early Cambrian (Chen *et al*., 2015). Both climate and oxygenation are regulated by Earth's long-term carbon cycle, and so perhaps unsurprisingly this interval is characterised by extreme carbon isotope instability (Kaufman *et al*., 1997). Since its discovery over 30 years ago (Burns & Matter, 1993; Calver, 2000), the uniquely high amplitude of the Shuram $\delta^{13}C$ anomaly has led some to question conventional interpretations of carbonate carbon isotopes (Melezhik *et al*., 2005; Schrag *et al*., 2011). However, its pivotal position beneath fossil evidence for the first biomineralising, bioturbating and bilaterian animals encourages us to venture a more satisfying, parsimonious explanation for the Shuram anomaly, one that ties together carbon cycle perturbations with life's evolution.

Conventional carbon isotope mass balance is based on the principle that the isotopic composition of carbon input via outgassing and weathering, and that of sedimentary carbon outputs are equal on time scales of $>10^5$ years (Garrels & Lerman, 1984). This $\delta^{13}C$ value is considered to be unchanging at -5‰: the average composition of crustal carbon. Because organic matter is depleted in ^{13}C, and carbonate rocks precipitate in isotopic equilibrium with ambient dissolved inorganic carbon (DIC), the mean $\delta^{13}C$ value of carbonate rocks and fossils can be used to determine the proportion that sedimentary organic matter makes up of the total sedimentary carbon sink. This proportion is generally referred to as f_{org}, which has varied over Earth history between 0.1 and 0.3 (Krissansen-Totton *et al*., 2015). Using a conventional mass balance approach, extreme negative anomalies can only be explained by negative rates of organic burial. This is particularly true of the late Ediacaran Shuram excursion when $\delta^{13}C$ remained below -8‰ for at least ~10 Myr (Condon *et al*., 2005; Gong *et al*., 2017). In order to address this quandary, it was proposed that the pool of dissolved organic matter (DOM) in the Proterozoic ocean was much larger than today, and that negative excursions represent non-steady-state remineralisation of that pool (Rothman *et al*., 2003). However, later numerical treatments of this model pointed out that the Earth system cannot remain out of oxygen (and carbon) balance for such a long period of time (Bristow & Kennedy, 2008). In other words, there is insufficient oxidant even in the modern atmosphere and oceans to remineralize enough organic matter to drive a -8‰ $\delta^{13}C$ excursion for several million years. As a result, many authors have interpreted extreme negative anomalies as diagenetic artefacts, biased sampling of authigenic cements or as purely regional phenomena (Bristow & Kennedy, 2008; Derry, 2010; Grotzinger & Fike, 2011; Schrag *et al*., 2013; Li *et al*., 2017; Shi *et al*., 2018). However, such arguments appeal to an inexplicable sampling bias, whereby globally correlative isotopic signatures are presumed to be unrepresentative of the global carbonate sink.

Here we take a different approach to the problem of negative $\delta^{13}C$ excursions by viewing them in terms of a linked carbon-sulfur-oxygen system, whereby changes in oxidant dynamics caused an excess of organic carbon oxidation over burial, resulting in a smaller DOM reservoir. For steady state to be maintained throughout a negative $\delta^{13}C$ excursion, shrinkage of the DOM pool would need to match surplus oxidant production for the duration of the anomaly. If we consider plausible $\delta^{13}C$ values of -10‰ and -35‰ for deposited carbonates and kerogen (globally averaged carbon sinks), respectively, and -30‰ and -5‰ for the DOM reservoir and crustal carbon (globally averaged carbon sources), respectively (Lu *et al*., 2013; Krissansen-Totton *et al*., 2015; Lee *et al*., 2015), then organic carbon oxidation would need to increase over the background rate by approximately a factor of three. In other words, and following conventional C-isotope mass balance [$\delta^{13}C_{carb} = (\delta^{13}C_{carb\text{-}org}) . f_{org} + \delta^{13}C_{input}$ at steady state], when $f_{org} = 0.1$, $\delta^{13}C_{input} = -12.5$‰ and $f_{DOM} = 0.3$, whereby f_{DOM} is the proportion that marine organic matter oxidation contributes to the overall carbon flux. The oxidant imbalance ($f_{DOM} = 0.3$) would have needed three times as much oxygen as could have been supplied by organic burial ($f_{org} = 0.1$) alone, and so requires a contribution from other sources, most likely pyrite burial.

Although bacterial sulfate reduction coupled with pyrite burial releases on a mole-for-mole basis almost twice as much oxygen as organic burial , it is generally assumed that the oxygen released by

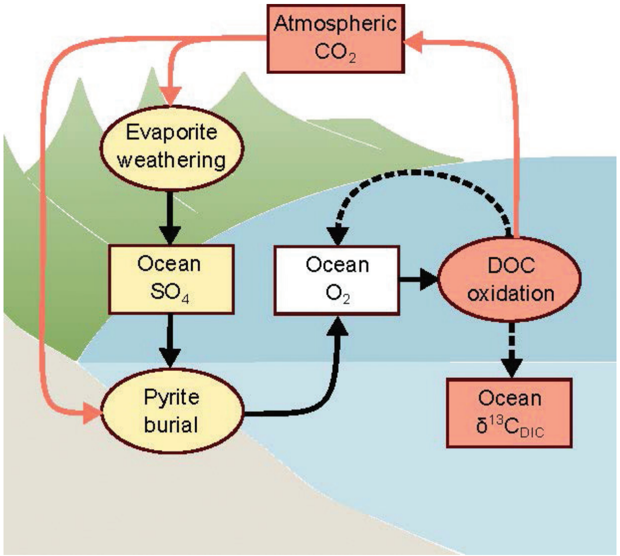

Figure 1.—Feedback diagram illustrating the effects of evaporite weathering on ocean oxygenation and $\delta^{13}C$. Boxes show quantities, ovals show processes, whilst yellow indicates sulfur cycle and red indicates carbon cycle. An evaporite dissolution event results in a large flux of sulfate to the ocean, permitting high rates of pyrite burial, which increases atmospheric and ocean O_2. As the deep ocean becomes oxygenated, depletion of the dissolved organic carbon (DOC) reservoir represents a negative feedback on ocean oxygenation and drives ocean $\delta^{13}C$ to negative values. Red arrows show potential for positive feedback: DOC oxidation increases atmospheric CO_2, leading to higher surface temperature and greater rates of precipitation and runoff, which fuels further evaporite dissolution and nutrient delivery. Solid arrows show positive effects and dashed arrows show negative effects.

pyrite burial is approximately matched by the oxygen consumed during pyrite weathering. However, most riverine sulfate derives from the weathering of evaporites (Burke *et al*., 2018), rates of which due to the sporadic and regional nature of evaporite deposits, will vary considerably over time (Wortmann & Paytan, 2012). During parts of the Proterozoic, when oceans were both iron-rich and anoxic, and so prone to sulfate reducing conditions (euxinia) at productive margins, one might realistically suppose that the amount of oxidising power transferred from rock sulfate to the surface environment would also have varied considerably, particularly during times when no basin-scale evaporite deposits were forming. We refer to this as 'sulfur cycle imbalance', meaning that the oxidant required to oxidise pyrite S was not balanced by the oxidant released by pyrite S burial and/or that the SO_4 flux to the ocean from evaporite weathering was not balanced by evaporite deposition (on timescales over which the long-term carbon and oxygen cycles must be in balance).

By writing a simple steady state mass-balance for the surface carbon cycle we can map the broad relationship between the evaporite sulfate input rate, net DOM oxidation and $\delta^{13}C$ composition of the ocean-atmosphere system. These calculations show that an evaporite weathering flux of around 1.1 x 10^3 mol S yr^{-1} (around 10 times the modern flux, as proposed for the dissolution event during the early Cenozoic could sustain a carbon isotope excursion of between -10‰ and -15‰, depending on the proportion of the riverine sulfate flux that is eventually buried as pyrite. Thus, the amount of oxidant required to achieve a deep negative carbon isotope excursion through net organic carbon oxidation may reasonably result from basin-scale evaporite dissolution.

Sulfur cycle imbalance during the Ediacaran

The second half of the Tonian Period (ca. 830-770 Ma) witnessed the largest evaporite depositional event of pre-Ediacaran time during the break-up of the supercontinent Rodinia (Evans, 2006; Turner & Bekker, 2016; Schmid, 2017). Estimates for the current preserved volume of Tonian evaporites range from 375,000 km^3 to 912,400 km^3, which places Tonian deposits among the largest basin-scale evaporite deposits ever (Evans, 2006; Prince *et al*., 2019). They include: the Centralian Superbasin, Australia (683,000 km^3); Amundsen and Mackenzie-Ogilvie basins, Canada (193,000 km^2); Adelaide fold belt, South Australia (100,000 km^2); Duruchaus basin, Namibia (30,000 km^2); and the Central African copperbelt (50,000 km^2). Despite diverse geodynamic settings, these Tonian evaporite basins underwent inversion during middle to late Ediacaran time, mostly after ca. 570 Ma, and broadly coincident with the 'Pan-African orogeny' or 'Transgondwanan supermountain' events (Campbell & Squire, 2010). Specifically, Centralian evaporites were exhumed by deformation associated with the Kuunga Orogen; Amundsen-Mackenzie-Ogilvie evaporites were exhumed on a passive margin; South Australian evaporites were exhumed during development of a raised volcanic rift margin; Duruchaus was exhumed by early Damaride accretion of terranes onto an active margin; and the Copperbelt was exhumed by intrusion of an anorogenic large igneous province. Subsequent erosion means that initial volumes must have been substantially higher. The high sulfate mineral content of these evaporite deposits (Fakhraee *et al*., 2019) and relatively unchanging seawater $\delta^{34}S$ values (Strauss, 1993) are consistent with the build-up of a large marine sulfate reservoir during the early Neoproterozoic . Sulfur cycle imbalance (excess sulfate weathering over deposition, coupled with excess pyrite deposition over weathering) is likely to have continued until massive evaporite deposition began in the 'Palaeotethyan' realm after c.550 Ma (Schroder *et al*., 2004), at which point the imbalance seems likely to have been reversed.

Environmental effects of sulfur cycle imbalance

This evaporite dissolution / DOM oxidation scenario appears to be the most parsimonious solution to the Shuram C-isotope conundrum in that it predicts the extent of oxic seafloor to increase towards the end of the excursion (Chen *et al*., 2015; Kendall *et al*., 2015), while maintaining high sulfate concentrations, which is in line with geochemical studies (Shi *et al*., 2018). Net oxidation of organic carbon (via pyrite burial) should cause a substantial rise in atmospheric CO_2 concentration, leading to global warming and enhanced continental weathering, with the potential to drive further evaporite dissolution and therefore sustain oxidant delivery.

Although our model fits best the late Ediacaran Shuram anomaly, sulfur cycle imbalance may have also played a role in other carbon isotope excursions. The interval of major carbon cycle disruption from ca.770 Ma until ca.550 Ma was a time of little or no basin-scale evaporite deposition (Guilbaud *et al*., 2015), suggesting that, as in the Cenozoic, the sulfate weathering-deposition cycle was not in steady-state. However, unlike the Cenozoic, the low atmospheric oxygen and anoxic deep ocean of the Neoproterozoic allowed evaporite-derived oxidizing power to be effectively transmitted into a negative $\delta^{13}C$ signal. Such imbalance, potentially driven by weathering events and related positive feedbacks, may be particularly relevant to the ending and immediate aftermath of 'Snowball Earth' glaciations, which are marked by euxinia and anomalously high levels of pyrite deposition (Sahoo *et al*., 2012; Lang *et al*., 2018).

The existence of a series of negative carbon isotope excursions during much of the Neoproterozoic Era indicates that the DOM pool underwent dynamic size changes throughout this time and served as a buffer against oxygenation and climate change, but only when the pool was sufficiently large. The absence of a large DOM buffer in the ocean, climate and oxygen levels would have been rendered more vulnerable to change. There are tantalising hints that this may have been the case after c.550 Ma (Tostevin *et al*., 2019), and that the ocean redox balance remained sensitively balanced throughout the Ediacaran-Cambrian transition interval (He *et al*., 2019). If exhaustion of the DOM pool occurred during the Shuram anomaly, it is plausible to suppose that the subsequent expansion of aerobic Ediacaran fauna was an opportunistic radiation in response to a transient oxidant surplus.

ACKNOWLEDGEMENTS

This work was supported by the NERC-NSFC programme 'Biosphere Evolution, Transitions and Resilience' through grant NE/P013643/1 to G.A.S., by grant NE/R010129/1 to G.A.S. and B.J.W.M., a University of Leeds Academic Fellowship to B.J.W.M and a Leverhulme Research Fellowship to G.A.S.

References

Bristow, T.F. & Kennedy, M.J. (2008). Carbon isotope excursions and the oxidant budget of the Ediacaran atmosphere and ocean. Geology, 36: 863–866. https://doi.org/10.1130/G24968A.1

Burke, A.; Present, T.M.; Paris, G.; Rae, E.C.M.; Sandilands, B.H.; Gaillardet, J.; Peucker-Ehrenbrink, B.; Fischer, W.W.; McClelland, J.W.; Spencer, R.G.M.; Voss, B.M. & Adkins, J.F. (2018). Sulfur isotopes in rivers: Insights into global weathering budgets, pyrite oxidation, and the modern sulfur cycle. Earth and Planetary Sciences Letters, 496: 168–177. https://doi.org/10.1016/j.epsl.2018.05.022

Burns, S.J. & Matter, A. (1993). Carbon isotopic record of the latest Proterozoic from Oman. Eclogae Geologica Helvetiae, 86: 595–607.

Calver, C.R. (2000). Isotope stratigraphy of the Ediacarian (Neoproterozoic III) of the Adelaide Rift Complex, Australia, and the overprint of water column stratification. Precambrian Research, 100: 121–150. https://doi.org/10.1016/S0301-9268(99)00072-8

Campbell, I.H. & Squire, R.J. (2010). The mountains that triggered the Late Neoproterozoic increase in oxygen: The Second Great Oxidation Event. Geochimica et Cosmochimica Acta, 74: 4187–4206. https://doi.org/10.1016/j.gca.2010.04.064

Chen, X.; Ling, H.-F.; Vance, D.; Shields-Zhou, G.A.; Zhu, M.; Poulton, S.W.; Och, L.M.; Jiang, S.-Y.; Li, D.; Cremonese, L. & Archer, C. (2015). Rise to modern levels of ocean oxygenation coincided with the Cambrian radiation of animals. Nature Communications, 6: 1–7. https://doi.org/10.1038/ncomms8142

Condon, D.; Zhu, M.; Bowring, S.; Wang, W.; Yang, A. & Jin, Y. (2005). U-Pb ages from the neoproterozoic Doushantuo Formation, China. Science, 308: 95–98. https://doi.org/10.1126/science.1107765

Derry, L.A. (2010). A burial diagenesis origin for the Ediacaran Shuram-Wonoka carbon isotope anomaly. Earth and Planetary Science Letters, 294: 152–162. https://doi.org/10.1016/j.epsl.2010.03.022

Evans, D.A.D. (2006). Proterozoic low orbital obliquity and axial-dipolar geomagnetic field from evaporite palaeolatitudes. Nature, 444: 51–55. https://doi.org/10.1038/nature05203

Fakhraee, M.; Hancisse, O.; Canfield, D.E.; Crowe, S.A. & Katsev, S. (2019). Proterozoic seawater sulfate scarcity and the evolution of ocean-atmosphere chemistry. Nature Geoscience, 12: 375–380. https://doi.org/10.1038/s41561-019-0351-5

Garrels, R.M. & Lerman, A. (1984). Coupling of the sedimentary sulfur and carbon cycles - an improved model. American Journal of Science, 284: 989–1007. https://doi.org/10.2475/ajs.284.9.989

Gong, Z.; Kodama, K.P. & Li, Y.X. (2017). Rock magnetic cyclostratigraphy of the Doushantuo Formation, South China and its implications for the duration of the Shuram carbon isotope excursion. Precambrian Research, 289: 62–74. https://doi.org/10.1016/j.precamres.2016.12.002

Grotzinger, J.P.; Fike, D.A. & Fischer, W.W. (2011). Enigmatic origin of the largest-known carbon isotope excursion in Earth's history. Nature Geoscience, 4: 285–292. https://doi.org/10.1038/ngeo1138

Guilbaud, R.; Poulton, S.W.; Butterfield, N.J.; Zhu, M. & Shields-Zhou, G.A. (2015). A global transition to ferruginous conditions in the early Neoproterozoic oceans. Nature Geoscience, 8:466–470. https://doi.org/10.1038/ngeo2434

He, T.; Zhu, M.; Mills, B.J.W.; Wynn, P.M.; Zhuravlev, A.Y.; Tostevin, R.; Strandmann, P.A.E.P. Von, Yang, A.; Poulton, S.W. & Shields, G.A. (2019). Possible links between extreme oxygen perturbations and the Cambrian radiation of animals. Nature Geoscience, 12: 468–474. https://doi.org/10.1038/s41561-019-0357-z

Kaufman, A.J.; Knoll, A.H. & Narbonne, G.M. (1997). Isotopes, ice ages, and terminal Proterozoic earth history. Proceedings of the National Academy of Sciences USA, 94: 6600–6605. https://doi.org/10.1073/pnas.94.13.6600

Kendall, B.; Komiya, T.; Lyons, T.W.; Bates, S.M.; Gordon, G.W.; Romaniello, S.J.; Jiang, G.; Creaser, R.A.; Xiao, S.; McFadden, K.; Sawaki, Y.; Tahata, M.; Shu, D.; Han, J.; Li, Y.; Chu, X. & Anbar, A.D. (2015). Uranium and molybdenum isotope evidence for an episode of widespread ocean oxygenation during the late ediacaran period. Geochimica et Cosmochimica Acta, 156: 173–193. https://doi.org/10.1016/j.gca.2015.02.025

Krissansen-Totton, J.; Buick, R. & Catling, D.C. (2015). A statistical analysis of the carbon isotope record from the Archean to phanerozoic and implications for the rise of oxygen. American Journal of Science, 315: 275–316. https://doi.org/10.2475/04.2015.01

Lang, X.; Shen, B.; Peng, Y.; Xiao, S.; Zhou, C.; Bao, H.; Kaufman, A.J.; Huang, K.; Crockford, P.W. & Liu, Y. (2018). Transient marine euxinia at the end of the terminal Cryogenian glaciation. Nature Communications, 9: 3019. https://doi.org/10.1038/s41467-018-05423-x

Le Heron, D.P.; Vandyk, T.M.; Kuang, H.; Liu, Y.; Chen, X.; Wang, Y.; Yang, Z.; Scharfenberg, L.; Davies, B. & Shields, G. (2019). Bird ' s-eye view of an Ediacaran subglacial landscape, 47: 1–5. https://doi.org/10.1130/G46285.1

Lee, C.; Love, G.D.; Fischer, W.W.; Grotzinger, J.P. & Halverson, G.P. (2015). Marine organic matter cycling during the Ediacaran Shuram excursion. Geology, 43: 1103–1106. https://doi.org/10.1130/G37236.1

Lenton, T.M.; Boyle, R.A.; Poulton, S.W.; Shields-Zhou, G.A. & Butterfield, N.J. (2014). Co-evolution of eukaryotes and ocean oxygenation in the Neoproterozoic era. Nature Geoscience, 7: 257–265. https://doi.org/10.1038/ngeo2108

Li, C.; Hardisty, D.S.; Luo, G.; Huang, J.; Algeo, T.J.; Cheng, M.; Shi, W.; An, Z.; Tong, J.; Xie, S.; Jiao, N. & Lyons, T.W. (2017). Uncovering the spatial heterogeneity of Ediacaran carbon cycling. Geobiology, 15: 211–224. https://doi.org/10.1111/gbi.12222

Lu, M.; Zhu, M.; Zhang, J.; Shields-Zhou, G.; Li, G.; Zhao, F.; Zhao, X. & Zhao, M. (2013). The DOUNCE event at the top of the Ediacaran Doushantuo Formation, South China: Broad stratigraphic occurrence and non-diagenetic origin. Precambrian Research, 225: 86–109. https://doi.org/10.1016/j.precamres.2011.10.018

Melezhik, V.; Fallick, A.E. & Pokrovsky, B.G. (2005). Enigmatic nature of thick sedimentary carbonates depleted in 13C beyond the canonical mantle value: The challenges to our understanding of the terrestrial carbon cycle. Precambrian Research, 137: 131–165. https://doi.org/10.1016/j.precamres.2005.03.010

Prince, J.K.G.; Rainbird, R.H. & Wing, B.A. (2019). Evaporite deposition in the mid-Neoproterozoic as a driver for changes in seawater chemistry and the biogeochemical cycle of sulfur. Geology, 47 (4): 375–379. https://doi.org/10.1130/G45464.1

Pu, J.P.; Bowring, S.A.; Ramezani, J.; Myrow, P.; Raub, T.D.; Landing, E.; Mills, A.; Hodgin, E. & Macdonald, F.A. (2016). Dodging snowballs: Geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. Geology, 44 (11): 955–958. https://doi.org/10.1130/G38284.1

Rothman, D.H.; Hayes, J.M. & Summons, R.E. (2003). Dynamics of the Neoproterozoic carbon cycle. Proceedings of the National Academy of Sciences USA, 100: 8124–8129. https://doi.org/10.1073/pnas.0832439100

Sahoo, S.K.; Planavsky, N.J.; Kendall, B.; Wang, X.; Shi, X.; Scott, C.; Anbar, A.D.; Lyons, T.W. & Jiang, G. (2012). Ocean oxygenation in the wake of the Marinoan glaciation. Nature, 489: 546–549. https://doi.org/10.1038/nature11445

Schmid, S. (2017). Neoproterozoic evaporites and their role in carbon isotope chemostratigraphy (Amadeus Basin, Australia). Precambrian Research, 290: 16–31. https://doi.org/10.1016/j.precamres.2016.12.004

Schrag, D.P.; Higgins, J.A.; Macdonald, F.A. & Johnston, D.T. (2013). Authigenic carbonate and the history of the global carbon cycle. Science 339: 540–543, https://doi.org/10.1126/science.1229578

Schroder, S.; Schreiber, B.C.; Amthor, J.E. & Matter, A. (2004). Stratigraphy and environmental conditions of the terminal Neoproterozoic-Cambrian Period in Oman: evidence from sulfur isotopes. Journal of the Geological Society of London, 161: 489–499. https://doi.org/10.1144/0016-764902-062

Shi, W.; Li, C.; Luo, G.; Huang, J.; Algeo, T.J.; Jin, C.; Zhang, Z. & Cheng, M. (2018). Sulfur isotope evidence for transient marine-shelf oxidation during the Ediacaran Shuram Excursion. Geology, 46: 267–270. https://doi.org/10.1130/G39663.1

Strauss, H. (1993). The sulfur isotopic record of Precambrian sulfates: new data and a critical evaluation of the existing record. Precambrian Research, 63(34): 225–246. https://doi.org/10.1016/0301-9268(93)90035-Z

Tostevin, R.; Clarkson, M.O.; Gangl, S.; Shields, G.A.; Wood, R.A.; Bowyer, F.; Penny, A.M. & Stirling, C.H. (2019). Uranium isotope evidence for an expansion of anoxia in terminal Ediacaran oceans. Earth and Planetary Science Letters, 506: 104–112. https://doi.org/10.1016/j.epsl.2018.10.045

Turner, E.C. & Bekker, A. (2016). Thick sulfate evaporite accumulations marking a mid-neoproterozoic oxygenation event (ten stone formation, Northwest territories, Canada). Bulletin of the Geological Society of America, 128(1-2): 203–222. https://doi.org/10.1130/B31268.1

Wortmann, U.G. & Paytan, A. (2012). Rapid variability of seawater chemistry over the past 130 million years. Science, 337: 334–336. https://doi.org/10.1126/science.1220656