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Recent advances in understanding the terminal Ediacaran Earth-life system in South China and Arctic Siberia

Avances recientes en la comprensión del sistema de vida terrestre del Ediacárico tardío en China meridional y el Ártico siberiano

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ABSTRACT

The terminal Ediacaran contains dramatic changes in biogeochemical cycles, many of which are closely coupled with evolutionary transitions in the corresponding fossil records. Dynamic redox conditions may have caused a profound impact on early animal evolution. Our work highlights the significance of integrated bio-, litho-, and chemo-stratigraphy in geobiology research of the deep time.

Keywords: Chemostratigraphy; Redox condition; Early macroorganisms; Biogeochemical cycles; Geobiology; Animal biomineralization; Alkalinity; *Cloudina*.

RESUMEN

El Ediacárico terminal incluye una serie de cambios drásticos en los ciclos biogeoquímicos, muchos de los cuales se asocian con modificaciones evolutivas en los registros fósiles correspondientes. Entre ellos destacan las condiciones redox, las cuales pueden haber causado un impacto profundo en la evolución animal temprana. Este trabajo destaca el significado de la lito-, bio- y quimioestratigrafía en la investigación geobiológica del tiempo profundo.

Palabras clave: Quimioestratigrafía; Condiciones redox; Macroorganismos tempranos; Ciclos biogeoquímicos; Geobiología; Biomineralización animal; Alcalinidad; *Cloudina*.

Introduction

The terminal Ediacaran witnessed the first appearance of macroscopic organisms including the earliest biomineralizing animals in Earth history (Narbonne *et al.*, 2012; Xiao *et al.*, 2016). However, the biogeochemical context for this evolutionary milestone remains uncertain due to the absence of radiometric constraints for key events recorded in palaeontological and chemostratigraphic datasets, and to uncertainties in the correlation of these biogeochemical events worldwide. Moreover, soft-bodied Ediacara biotas are typically preserved as impressions in fine-grained siliciclastic rocks (Gehling, 1999), which offer limited opportunities for palaeoenvironmental analysis using geochemical tools. In contrast, two rare soft-bodied Ediacara assemblages are preserved in well-exposed marine carbonate successions of the Dengying Formation in South China (Chen *et al.*, 2014) and the Khatyspyt Formation in Arctic Siberia (Grazhdankin *et al.*, 2008), where comprehensive chemostratigraphic studies have recently been completed.

Results

In the Gaojiashan Member of the Dengying Formation, integrated bio- and chemo-stratigraphic profiles (2019) show that the first appearance of the biomineralizing animal fossil *Cloudina* is closely associated with positive anomalies of $\delta^{13}\text{C}_{\text{carb}}$, $\delta^{34}\text{S}_{\text{pyrite}}$, and Sr/Ca values (Fig. 1). In contrast,

S isotope values of carbonate-associated sulfate ($\delta^{34}\text{S}_{\text{CAS}}$) remain steady throughout the succession, resulting in anomalously large (>70‰) sulfur isotope fractionations ($\delta^{34}\text{S}_{\text{CAS-pyrite}}$) in the lower half of the member that decline to ~30‰ in the upper half. This fractionation trend likely relates to changes in microbial communities, with sulfur disproportionation dominating in the lower interval, whereas microbial sulfate reduction was the principal metabolic pathway in the upper. We propose that the coupled palaeontological and biogeochemical transition may have coincided with an increase in terrestrial weathering fluxes of sulfate (evidenced by gypsum pseudomorphs), alkalinity (evidenced by Sr/Ca positive anomaly), and nutrients to the depositional basin, which stimulated primary productivity (evidenced by high $\delta^{13}\text{C}_{\text{carb}}$ values) and the spread of an oxygen minimum zone (evidenced by high $\delta^{15}\text{N}$ and low $\delta^{238}\text{U}$ values). Enhanced production and burial of organic matter is thus directly connected to the $\delta^{13}\text{C}_{\text{carb}}$ anomaly, and through bottom water anoxia likely promoting microbial sulfate reduction and pyritization as the main taphonomic pathway for *Conotubus* and other soft-bodied Ediacara biota. These results suggest that environmental and physiological pressures from an increase in seawater alkalinity - likely coupled with ecological pressures from predation (Hua *et al.*, 2003, 2007) - set the stage for the evolutionary novelty of animal biomineralization.

In the Khatyspyt Formation, the profound sulfur isotope fractionation trend seen in the Dengying is preserved, with $\delta^{34}\text{S}_{\text{pyrite}}$ values rising from ca. -20‰

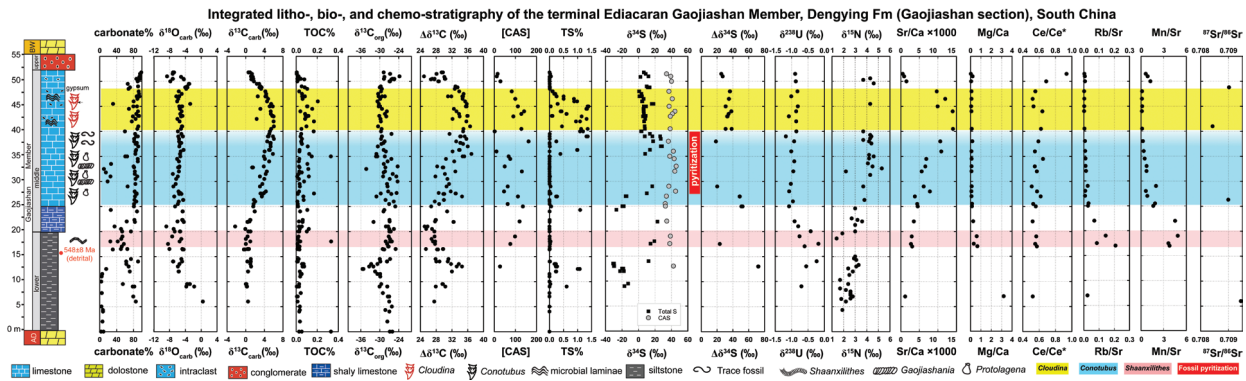


Figure 1.—Integrated litho-, bio-, and chemo-stratigraphy of the Gaojiashan Member, Dengying Formation at the Gaojiashan section, South China. Geochemical profiles include carbonate content (wt. %), carbonate oxygen isotopes ($\delta^{18}\text{O}_{\text{carb}}$, ‰ VPDB), carbonate carbon isotopes ($\delta^{13}\text{C}_{\text{carb}}$, ‰ VPDB), total organic carbon content (TOC), organic carbon isotopes ($\delta^{13}\text{C}_{\text{org}}$, ‰ VPDB), carbon isotope fractionations ($\Delta\delta^{13}\text{C}_{\text{carb-org}}$), CAS concentration ([CAS] in ppm), total sulfur content (TS%, dominated by pyrite with trace amount of organic S), total sulfur isotopes in acidified residuals ($\delta^{34}\text{S}_{\text{TS}}$, ‰ VCDT), CAS sulfur ($\delta^{34}\text{S}_{\text{CAS}}$, ‰ VCDT) isotopes, sulfur isotope fractionations ($\Delta\delta^{34}\text{S}_{\text{CAS-pyrite}}$) assuming the $\delta^{34}\text{S}_{\text{TS}}$ signals are dominantly derived from pyrite, uranium isotopes ($\delta^{238}\text{U}$, ‰ CRM145), nitrogen isotopes ($\delta^{15}\text{N}$, ‰ AIR), Sr/Ca, Ce anomaly (Ce/Ce* calculated using the formula $\text{Ce/Ce}^* = \text{Ce}_{\text{PAAS}} / ([\text{Pr}]_{\text{PAAS}}^2 / [\text{Nd}]_{\text{PAAS}})$), Rb/Sr, Mn/Sr, $^{87}\text{Sr}/^{86}\text{Sr}$ values measured from limestone beds or limestone nodules. BW = Beiwan, AD = Algal Dolomite. Data source: $\delta^{15}\text{N}$ data, $\delta^{238}\text{U}$ data, all the other data. Modified after Cui et al. (2016b, 2019).

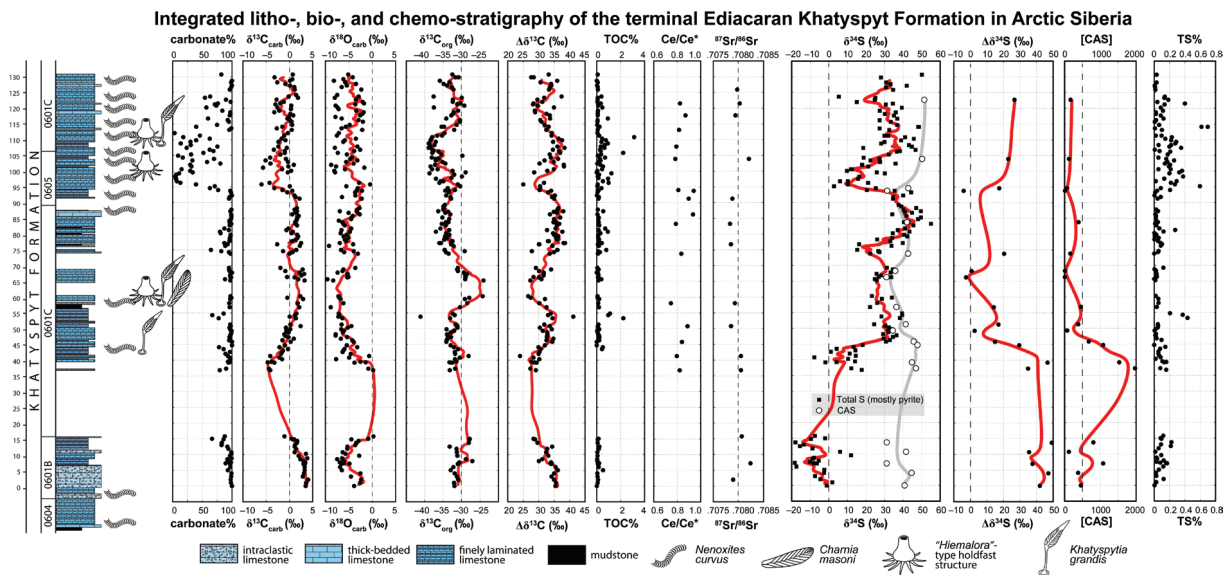


Figure 2.—Integrated litho-, bio-, and chemo-stratigraphy of the Khatyspyt Formation at the 0601 and 0605 sections, Arctic Siberia, Russia. Measured geochemical profiles include carbonate percentage (carbonate%), carbonate carbon ($\delta^{13}\text{C}_{\text{carb}}$, ‰ VPDB) and oxygen isotopes ($\delta^{18}\text{O}_{\text{carb}}$, ‰ VPDB), organic carbon isotopes ($\delta^{13}\text{C}_{\text{org}}$, ‰ VPDB), carbon isotope fractionations ($\Delta\delta^{13}\text{C}_{\text{carb-org}}$), total organic carbon content (TOC, %), Ce anomaly (Ce/Ce* calculated using the formula $\text{Ce/Ce}^* = [\text{Ce}]_{\text{PAAS}} / ([\text{Pr}]_{\text{PAAS}}^2 / [\text{Nd}]_{\text{PAAS}})$), strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$), total sulfur isotopes in acidified residuals ($\delta^{34}\text{S}_{\text{TS}}$, ‰ VCDT; including pyrite and trace amount of organic S), CAS sulfur isotopes ($\delta^{34}\text{S}_{\text{CAS}}$, ‰ VCDT), sulfur isotope fractionations ($\Delta\delta^{34}\text{S}_{\text{CAS-pyrite}}$) assuming the $\delta^{34}\text{S}_{\text{TS}}$ signals are dominantly derived from pyrite, CAS concentration ([CAS] in ppm), and total sulfur content (TS%, dominated by pyrite with trace amount of organic S). Fitted lines represent five-point running average for $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{34}\text{S}_{\text{TS}}$ data, and two-point running average for $\delta^{34}\text{S}_{\text{CAS}}$, $\Delta\delta^{34}\text{S}$ and [CAS] data. Modified after Cui et al. (2016a).

to ca. 50‰ through an interval of general invariance in $\delta^{34}\text{S}_{\text{CAS}}$ (Fig. 2). The step function shift in sulfur isotope compositions is closely associated with the

first occurrence of soft-bodied Ediacara biotas preserved in thinly bedded limestones, which suggests a possible link between seawater redox conditions

and the distribution of these enigmatic macroscopic organisms. Based on multiple lines of sedimentological and geochemical evidence, we propose that the development of oceanic euxinia - which could be widespread in the continental margins due to enhanced oxidative weathering (delivering both nutrients and sulfate to ocean margins) in the terminal Ediacaran Period - may have locally prohibited the colonization of Ediacara-type organisms. The progressive secular transition from euxinic to non-euxinic and more habitable conditions may have allowed for the colonization of Ediacara-type and other macro-organisms in the upper part of the studied section of the Khatyspyt Formation.

Conclusions

In the Gaojiashan Member of the Dengying Formation, China, environmental and physiological pressures were linked to an increase in seawater alkalinity, probably coupled with ecological pressures from predation, setting the stage for the evolutionary novelty of animal biomineralization. In the Khatyspyt Formation of Arctic Siberia, the progressive secular transition from euxinic to non-euxinic and more habitable conditions may have allowed for the colonization of Ediacara-type and other macro-organisms.

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