



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/241019/>

Version: Accepted Version

Article:

Zhang, Y., Yang, T., He, T. et al. (2026) Shoaling of anoxic water as a driver of the Cambrian ROECE event: new sulfur isotope evidence from the Tarim Basin. *Global and Planetary Change*, 261. 105403. ISSN: 0921-8181

<https://doi.org/10.1016/j.gloplacha.2026.105403>

This is an author produced version of an article published in *Global and Planetary Change*, made available via the University of Leeds Research Outputs Policy under the terms of the Creative Commons Attribution License (CC-BY), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

**Shoaling of anoxic water as a driver of the Cambrian ROECE event: new sulfur
isotope evidence from the Tarim Basin**

Yinggang Zhang^{1,4*}, Tao Yang^{2*}, Tianchen He^{3,4*}, Benjamin J.W. Mills⁴, Robert J.
Newton⁴, Mingyu Zhao⁵, Liu Willow Yang², Maoyan Zhu^{1,6}

¹Key Laboratory of Palaeobiology and Petroleum Stratigraphy, Nanjing Institute of
Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, China.

²State Key Laboratory of Critical Earth Material Cycling and Mineral Deposits,
Nanjing University, Nanjing, China.

³College of Oceanography, Hohai University, Nanjing, China.

⁴School of Earth and Environment, University of Leeds, Leeds, UK.

⁵State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of
Geology and Geophysics, Chinese Academy of Sciences, Beijing, China.

⁶College of Earth and Planetary Sciences, University of Chinese Academy of Sciences,
Beijing, China.

*Corresponding authors: Tao Yang, Tianchen He, and Yinggang Zhang.

E-Mail: yangtao@nju.edu.cn; tianchenhe@hhu.edu.cn; ygzhang@nigpas.ac.cn.

Accepted manuscript in *Global and Planetary Change*, March 2026

Abstract

The first trilobite mass extinction, known as the Redlichiid–Olenellid extinction, occurred at the Cambrian Series 2–3 boundary and is associated with the Redlichiid–Olenellid Extinction negative Carbon isotope Excursion (ROECE). The causes of the ROECE event remain debated, with some researchers attributing it to the Kalkarindji volcanism and others linking it to a coeval large-scale transgression event. Continuous seawater sulfur isotope records across this boundary are crucial for resolving this debate. In this study, we present sulfur isotope data of carbonate-associated sulfate (CAS) across the Cambrian Series 2–3 boundary from the Xiaoerbrak section, Tarim Basin and reconstruct a seawater $\delta^{34}\text{S}$ variation curve for this critical period. Our findings show that seawater $\delta^{34}\text{S}$ values were likely positively coupled with $\delta^{13}\text{C}$ values during Cambrian Series 2 but showed an abrupt increase across the Series 2–3 boundary, marking a shift from coupled to decoupled carbon-sulfur isotope behaviour. According to the prevailing ROECE hypothesis, this decoupling of carbon and sulfur isotopes may be caused by isotopically light carbon inputs to surface water from Kalkarindji volcanism or from anoxic bottom water. These two hypotheses are tested quantitatively using a biogeochemical box model. The modelling results show that light carbon emission from volcanism is insufficient to explain the recorded seawater isotope variations. Instead, the best fit comes from a dissolved organic carbon (DOC) oxidation hypothesis, an updated version of the anoxic bottom water shoaling/upwelling hypothesis. This hypothesis posits that DOC-enriched anoxic bottom water was

42 upwelled and oxidised by oxygen during a large-scale transgression, leading to a
43 negative seawater $\delta^{13}\text{C}$ excursion. Along with oxygen consumption and expanded
44 anoxia, increased pyrite burial resulted in a sharp rise in seawater $\delta^{34}\text{S}$ at the Cambrian
45 Series 2–3 boundary. The proposed DOC oxidation hypothesis effectively explains the
46 decoupled carbon and sulfur isotope behaviour at this boundary and highlights the
47 significant role of reduced oxygen levels in the Redlichiid–Olenellid extinction.

48 **Keywords:** Sulfur isotopes, Cambrian Series 2–3, Redlichiid–Olenellid extinction,
49 Biogeochemical modelling, Dissolved organic carbon.

50

1. Introduction

During the Cambrian radiation, trilobites, one of the earliest known arthropod groups, first appeared at the beginning of Cambrian Series 2 and rapidly diversified. However, a rapid diversity decline in the Redlichiid and Olenellid trilobites occurred at the Cambrian Series 2–3 boundary, marking the earliest known trilobite mass extinction (Fan et al., 2011; Zhu et al., 2019, 2006). This event is associated with a globally reported negative carbon isotope excursion, known as the Redlichiid–Olenellid Extinction Carbon isotope Excursion (ROECE; (Zhu et al., 2006)).

The causes of the ROECE event have been widely debated. One prevailing hypothesis suggests that eruptions of flood basalts from the Kalkarindji large igneous province (LIP) around 510 Ma triggered this event due to their possible temporal coincidence (Glass and Phillips, 2006; Hough et al., 2006; Liu et al., 2021). In this scenario, the eruptions released vast amounts of isotopically light carbon (with $\delta^{13}\text{C}$ values $< -5\text{‰}$), driving intense global warming and ocean anoxia that directly triggered the Redlichiid and Olenellid extinctions; this massive carbon input might be reflected by the observed negative seawater carbon isotope excursion (Zhang et al. 2022). Another prevailing hypothesis links the ROECE event to a large-scale transgression, during which the shoaling or upwelling of anoxic bottom waters (Guo et al., 2017, 2010; Montañez et al., 2000) drove the turnover by inundating the trilobites' shallow oxygenated habitats. The associated upwelling of isotopically light carbon would

72 subsequently result in negative carbon isotope excursions in surface waters. Other
73 proposed drivers for the ROECE include declining primary productivity and enhanced
74 carbonate weathering (Chang et al., 2017; Marshall et al., 2021). Currently, no
75 consensus exists on the mechanism and drivers behind the ROECE, limiting our
76 comprehension of the environmental changes that led to the Phanerozoic's first trilobite
77 mass extinction event.

78
79 The biogeochemical sulfur cycle, particularly through microbial sulfate reduction
80 (MSR), is closely linked to the carbon cycle and seawater redox variations, both of
81 which are key to understanding seawater carbon isotope excursions and biological
82 extinctions. For example, positive carbonate-associated sulfate (CAS) sulfur isotope
83 excursions, along with the late Cambrian Steptoean positive carbon isotope excursion
84 (SPICE), are thought to reflect increased burial of organic carbon and pyrite as a
85 combined result of enhanced productivity and expanded anoxia (Gill et al., 2011;
86 Rooney et al., 2022; Saltzman et al., 2011; Yang et al., 2024). Such environmental
87 perturbations were invoked to explain the trilobite turnover during the late Cambrian
88 (Saltzman et al., 2000; Yang et al., 2024). Consequently, constraining seawater $\delta^{34}\text{S}$
89 variations across the Cambrian Series 2–3 boundary is critical for deciphering the
90 causes of the ROECE and the associated trilobite extinction.

91

92 Although several proxy studies have investigated seawater $\delta^{34}\text{S}$ variations across
93 the Cambrian Series 2–3 boundary (Guo et al., 2014; Hough et al., 2006; Liu et al.,
94 2021; Wotte et al., 2012), a consensus on the evolution of seawater $\delta^{34}\text{S}$ remain elusive.
95 Most previous studies have focused on pyrite (Guo et al., 2014; Liu et al., 2021), whose
96 isotopic composition can be influenced by factors such as sedimentation rates, making
97 it challenging to obtain a global seawater signal (Halevy et al., 2023; Lang et al., 2020).
98 Other more reliable archives show different trends. For example, francolite-bound
99 sulfate from Australia shows an abrupt $\delta^{34}\text{S}$ rise across the Cambrian Series 2–3
100 boundary (Hough et al., 2006), while carbonate-associated sulfate (CAS) shows no
101 significant variation (Wotte et al., 2012). Some researchers suggest that the abrupt $\delta^{34}\text{S}$
102 rise may be caused by local environmental factors (Wotte et al., 2012), while others
103 argue that the lack of significant isotope variation in CAS isotope records may be due
104 to possible stratigraphic hiatuses in their sections (c.f. Chang et al. (2017)). These
105 discrepancies highlight the need for proxy records from continuous sections to resolve
106 seawater $\delta^{34}\text{S}$ evolution.

107
108 To reconstruct the primary seawater sulfate-sulfur isotope composition, this study
109 utilizes CAS from bulk marine carbonate. CAS is a trace constituent incorporated into
110 the marine carbonate crystal lattice, where the sulfate ion structurally substitutes for the
111 carbonate ion (Kampschulte and Strauss, 2004). Due to the widespread distribution of
112 carbonate sequences in the geological record, CAS has become a widely applied proxy

for paleo-seawater sulfur isotope compositions (e.g. Kampschulte and Strauss (2004); He et al. (2019)). Crucially, while diagenetic recrystallization may expel sulfate from the lattice (reducing concentration), it typically occurs with negligible sulfur isotope fractionation. Therefore, if CAS is appropriately extracted from carbonate samples and screened for possible secondary contamination, CAS $\delta^{34}\text{S}$ signatures are considered to reflect the isotopic composition of contemporaneous seawater sulfate (e.g. Gill et al. (2011); Kampschulte and Strauss (2004); He et al. (2019))

This study presents CAS sulfur isotope data from Cambrian Series 2–3 carbonates at the Xiaoerbrak section in the Keping area, Tarim Basin, NW China (Figure 1). Using previously reported (and paired) carbon isotope values (Zhang et al., 2020), we reconstruct continuous seawater sulfur isotope variations across the Cambrian Series 2–3 boundary. In addition, we apply a biogeochemical model to test promising hypotheses, such as the Kalkarindji eruption and transgression-related anoxia expansion, to investigate the causes of the ROECE event.

2. Geological background

During the Ediacaran to Cambrian periods, the Tarim Basin was located in the northern low-middle latitudes ($\sim 0\text{--}35^\circ\text{N}$, Figure 1B), near the paleo-continent of South China and Australia (Mckerrrow et al., 1992; Merdith et al., 2017; Zhan et al., 2007). Cambrian carbonates are widely distributed in the Keping (northwestern Tarim Basin)

and Kruqtagh (northeastern Tarim Basin) regions. The Keping area is believed to have formed a shallow carbonate platform during Cambrian Series 2–3, while the Kruqtagh area likely represented a deeper water environment (Feng et al., 2007). Geochemical studies indicate that the Keping area was well-connected to the open ocean during Cambrian (Guo et al., 2017; Zhang et al., 2020), whereas carbonate $^{87}\text{Sr}/^{86}\text{Sr}$ data from the Kruqtagh area indicate possibly significant terrestrial influences from surrounding continents (Zhang et al., 2023). This makes the Keping carbonates ideal for studying seawater sulfur isotope variations across the Cambrian Series 2–3 boundary.

The Xiaoerbrak section in the Keping area (GPS locations: N 40°55'23", E 79°53'53"), located 50 km southwest of the Aksu city in NW Xinjiang Uygur Autonomous Region (Figure 1A), exposes over 800 meters of Cambrian marine sediments. The Cambrian Series 2–3 boundary is constrained within the lower part of the Shayilik Formation, which continuously overlays the Wusonger Formation (Figure 1C).

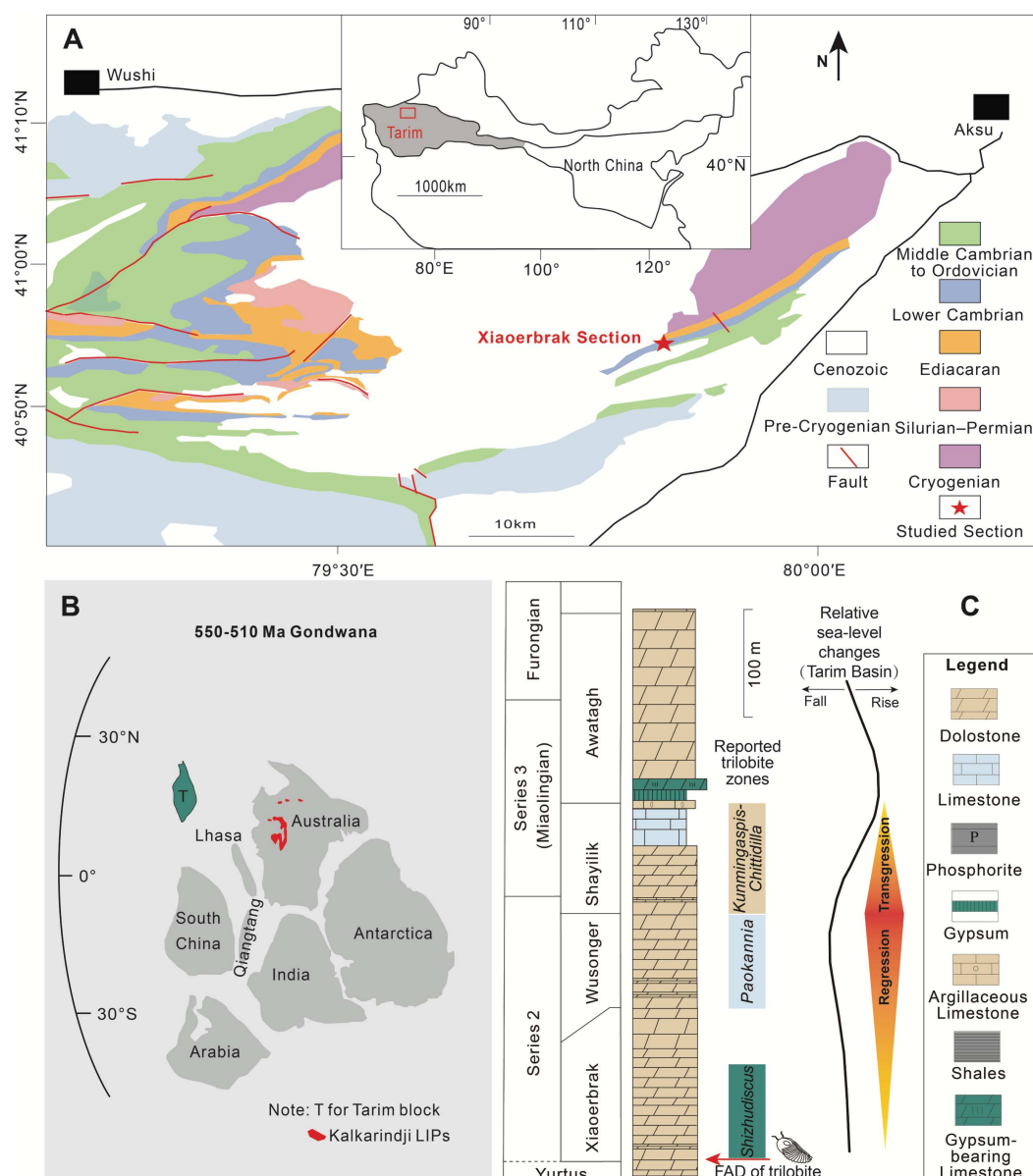


Figure 1. Geological background of the study area. Panel A: Geological map of the Keping area, NW Xinjiang Uygur Autonomous Region (modified from Zhou et al. (2015)). Panel B: Paleogeographic position of the Tarim block and the Kalkarindji LIPs during 550–510 Ma (modified from Faggetter et al. (2019) and Liu et al. (2021)). Panel C: Simplified lithologic log of the Xiaerbrak section (modified from Zhang et al. (2020)) and relative sea-level changes in the Tarim Basin (modified from Gao and Fan (2014)).

157

158 The Wusonger Formation, consisting of fine-grained micritic dolostones and
159 muddy dolostones, contains *Paokannia* trilobite fossils in the lower part (Peng, 2009).
160 This trilobite zone corresponds to the *Paokannia-Sichuanolenus* trilobite Zone in the
161 Yangtze region, which represents the upper part of Cambrian Stage 3 (Zhao et al., 2019).
162 A prominent negative seawater carbon isotope excursion in this formation (Zhang et al.,
163 2020), likely equivalent to the Archaeocyathid Extinction Carbon isotope Excursion
164 (AECE; Zhu et al., 2019, 2006), suggests that its deposition mainly took place during
165 Cambrian Stage 4. The overlying Shayilik Formation is composed of micritic to fine-
166 grained dolomites in the lower part and dolomite-bearing limestones in the upper part,
167 capped by algal microbialites. The occurrence of the *Kunmingaspis-Chittidilla* trilobite
168 biozone in the upper part (Peng, 2009), constrains this interval to Cambrian Stage 5,
169 the first Stage in Cambrian Series 3. Detailed lithofacies studies reveal a deepening-
170 upward trend in the Shayilik Formation, indicating a sea-level rise during the deposition
171 of the Shayilik Formation (Figure 1; Gao and Fan, 2014). An extremely negative carbon
172 isotope excursion (approximately from -1‰ to <-6‰) at the base of this formation, is
173 widely interpreted as the ROECE event (Guo et al., 2017; Wang et al., 2011; Zhang et
174 al., 2020), while a decrease of strontium ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) in the lower part of this
175 formation is also globally comparable (Wang et al., 2011; Zhang et al., 2020). Together
176 with the available trilobite occurrences, these data constrain the Cambrian Series 2–3
177 boundary to the lowest part of the Shayilik Formation in the Keping area.

178

179 We acknowledge that the precise Redlichiid-Olenellid extinction level remains
180 unclear due to the absence of corresponding trilobite fossils in these dolostones.
181 However, the presence of the ROECE negative $\delta^{13}\text{C}$ records in the Tarim Basin (Guo
182 et al., 2017; Wang et al., 2011; Zhang et al., 2020) and its global coincidence with the
183 extinction of the Redlichiid and Olenellid trilobites elsewhere (Zhu et al., 2019) suggest
184 that, if preserved, the extinction horizon in the Tarim Basin would lie near the base of
185 the Shayilik Formation.

186

187 At the Xiaoerbrak section, 34 carbonate samples were collected from the base of
188 the Wusonger Formation to the uppermost part of the Shayilik Formation to study
189 carbonate associated sulfate sulfur isotope variations in the Tarim Basin across the
190 Cambrian Series 2–3 boundary.

191

192 **3. Methods**

193

194 **3.1 CAS extraction, sulfur isotope and elemental analyses**

195 Hand specimens free from visible alterations, such as weathering crusts, were
196 collected and crushed into small chips. The best-preserved chips were hand-picked and
197 ground into powder (~200–400 mesh) in an agate mill for CAS extraction and further
198 element/isotope analyses.

199

200 The CAS extraction procedure followed the methods outlined by He et al. (2019).
201 Briefly, approximately 10 g of sample powder was weighed in a 50 mL centrifuge tube
202 and reacted with ~40 mL of 6% NaOCl solution for about 12 hours to remove the
203 contaminants (e.g. pyrite and organic sulfur). After centrifugation, the NaOCl
204 supernatant containing the contaminants was discarded. The residue was then washed
205 five times with ultrapure water, 5% NaCl solution, and 10% NaCl solution to ensure
206 the removal of non-CAS components. The carbonate residues were then treated with 6
207 mol/L HCl solution to dissolve the carbonate lattice and obtain the carbonate solution.
208 This step was conducted quickly to prevent possible reactions with other sulfur-
209 containing minerals, such as pyrite oxidation. The supernatant containing the dissolved
210 carbonates was obtained by centrifugation and filtration using a 0.22 μm polyethylene
211 filter membrane. Around one-tenth of the supernatant solution was transferred to
212 another centrifuge tube, diluted to half concentration, and doped with internal standard
213 element solutions (Lu and Y) for subsequent analyses of CAS and other element (Al,
214 Mn, and Sr) concentrations. The remaining supernatants were refrigerated at $\sim 2^{\circ}\text{C}$ for
215 over 72 hours after adding 2 mL of saturated BaCl_2 solution for barium sulfate
216 precipitation. The precipitated materials were washed with ultrapure water more than
217 three times to dissolve any BaCl_2 crystals and obtain purified BaSO_4 . Finally, the
218 purified BaSO_4 was dried at $\sim 50^{\circ}\text{C}$ for sulfur isotope analyses.

219

Element (S, Al, Mn, and Sr) concentrations were determined using a Thermo iCAP 7400 ICP-OES at the School of Earth and Environment, University of Leeds. During the analyses, 100 ppb of Lu and Y elements were used as internal standards for instrument drift corrections. The detection limits for S, Al, Mn, and Sr are approximately 0.17 mg/L, 0.03 mg/L, 0.03 mg/L, and 0.06 mg/L, respectively. Repeated analyses on a multi-element standard solution with a matched matrix yielded a precision better than 5%.

Sulfur isotopic analysis of dried BaSO₄ precipitated from CAS solution was conducted at the Key Laboratory of Palaeobiology and Petroleum Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. The analysis used a Thermo Finnigan Delta V Advantage gas source mass spectrometry coupled with a Thermo Flash 2000 high-temperature elemental analyzer. The BaSO₄ was reacted with V₂O₅ in the elemental analyzer to produce SO₂ gas, which was then purified via online gas chromatography and transferred into the mass spectrometry for sulfur isotope analysis. Repeated analysis of the BaSO₄ standard (NBS-127) per ten samples yielded an average sulfur isotopic composition of $\sim 20.3 \pm 0.3$ ‰ (1SD), which is consistent with the widely recognized isotope values of NBS-127 (20.3‰). In addition, two duplicate samples are included in our analysis sequences. The analytical precisions of standard NBS-127 and duplicate analysis are better than 0.3‰. The analytical blank was routinely monitored and <0.5% of the total sulfur signal, therefore no blank

correction was applied in this study. The sulfur isotopic composition in this study is reported as per mil (‰) relative to Vienna Canyon Diablo Troilite (VCDT). All reported data are provided in Supplementary Table S1.

3.2 The COPSE model

The global Carbon, Oxygen, Phosphorus, Sulfur, and Evolution (COPSE) biogeochemical model (Lenton et al., 2018; Tostevin and Mills, 2020) was employed to quantify the mechanisms driving variations in seawater carbon and sulfur isotopes. The COPSE framework is particularly suitable for testing mechanistic hypotheses against geochemical data because it uses a forward modelling approach; this means the system is driven by independent external forcings, such as metamorphic and volcanic degassing (D), and produces estimates of isotope behavior rather than being driven by the isotope records themselves.

For this study, we utilized the modified version of COPSE that incorporates a dissolved organic carbon (DOC) reservoir to better simulate the marine carbon cycling during the Ediacaran (Tostevin and Mills, 2020). The core mass balance equations governing the evolution of the surface reservoir for carbon (A) and sulfur (S), along with their isotopic compositions, are defined as follows:

$$\frac{dA}{dt} = f_{ccdeg} + f_{ocdeg} + f_{carb w} + f_{oxid w} - f_{mccb} - f_{moch} - f_{locb} - f_{sfw} + DOC_{ox} \quad (\text{Eq. 1})$$

$$\frac{dS}{dt} = f_{pyrdeg} + f_{gypdeg} + f_{pyrw} + f_{gypw} - f_{mpsb} - f_{mgsb} \quad (\text{Eq. 2})$$

$$\frac{d(A \cdot \delta A)}{dt} = f_{ccdeg} \cdot \delta A + f_{ocdeg} \cdot \delta G + f_{carbw} \cdot \delta C + f_{oxidw} \cdot \delta G - f_{mccb} \cdot \delta A - f_{mocb} \cdot (\delta A - \Delta C) - f_{locb} \cdot (\delta A - \Delta C) + DOC_{ox} \cdot \delta DOC - f_{sfw} \cdot \delta C \quad (\text{Eq. 3})$$

$$\frac{d(S \cdot \delta S)}{dt} = f_{pyrdeg} \cdot \delta PYR + f_{gypdeg} \cdot \delta GYP + f_{pyrw} \cdot \delta PYR + f_{gypw} \cdot \delta GYP - f_{mpsb} \cdot (\delta S - \Delta S) - f_{mgsb} \cdot \delta S \quad (\text{Eq. 4})$$

267

268 Here, the flux terms (f) represent sources and sinks including degassing (deg),
 269 weathering (w), and burial (b) of carbonate (cc/carb), organic carbon (oc), pyrite (pyr),
 270 and gypsum (gyp). A detailed description of all parameters and forcing constructions is
 271 provided in the Supplementary Information.

272

273 To simulate the specific impact of the Kalkarindji LIP eruptions (scenario A), we
 274 incorporated an additional emission flux into the model atmosphere/ocean carbon
 275 reservoir: " $C_{emission} \cdot f_{ocd}$ ", where $C_{emission}$ represents the total CO₂ emission rate
 276 estimated for the Kalkarindji LIP (Marshall et al., 2021), and f_{ocd} denotes the fraction
 277 of this release derived from organic carbon sources. Similarly, the degassing of SO₂ is
 278 incorporated into the fluxes of pyrite sulfur degassing (f_{pyrdeg}) and gypsum sulfur
 279 degassing (f_{gypdeg}): $f_{pyrdeg} = k_{pyrdeg} \cdot D \cdot \left(\frac{PYR}{PYR_0} \right) + S_{emission} \cdot f_{pyd}$ and $f_{gypdeg} =$
 280 $k_{gypdeg} \cdot D \cdot \left(\frac{GYP}{GYP_0} \right) + S_{emission} \cdot (1 - f_{pyd})$, where $S_{emission}$ represents the estimated
 281 total SO₂ flux derived from the Kalkarindji LIP (Marshall et al., 2021) and f_{pyd}
 282 denotes the fraction of this sulfur from pyrite thermal decomposition. In addition, basalt

eruption from the Kalkarindji LIP and its effects on weathering are also considered in this scenario – as a compilation of all known LIPs was already used to derive continental weatherability in the model (Lenton et al., 2018; Tostevin and Mills, 2020).

To simulate the possible DOC oxidation (DOC_{ox}) during the ROECE event (scenario B), we modified the parameterization of the DOC oxidation rate starting at 509.7 Ma. In the baseline COPSE model, DOC_{ox} is regulated by average oceanic oxygen levels and DOC reservoir sizes to simulate the effects of additional oxidant inputs on DOC-oxidation (Tostevin and Mills, 2020), which is particularly relevant for the Ediacaran Shuram event (Zhang and Zhu, 2025). However, to test the hypothesis that sea-level transgression induced the upwelling of anoxic DOC-enriched bottom waters into oxygenated shallow-marine environments during the Cambrian ROECE event, we decoupled the DOC_{ox} flux from the global oceanic oxygen dependence term for the duration of the event interval.

Given that the COPSE model utilizes a single-box ocean framework, it cannot spatially resolve water-column mixing or localized upwelling dynamics. Consequently, this decoupling serves as a numerical simplification to represent a supply-limited oxidation scenario, where the oxidation rate is governed by the physical transport of DOC into the oxic zone, rather than by fluctuations in global oceanic oxygen levels. In this formulation, the onset of DOC oxidation is forced by timing of the transgression,

ensuring that DOC_{ox} acts as a linear function of the reservoir size (Eq. 5).

$$DOC_{ox} = \begin{cases} 0, & DOC < 1 \times 10^{12} \text{ mol} \\ \frac{-k_{DOC}}{1+e^{-a_{DOC}(1-ANOX-c_{DOC})}} \cdot \left(\frac{DOC}{DOC_0}\right), & DOC \geq 1 \times 10^{12} \text{ mol}, \text{Pre-event} \\ k_{DOC} \cdot \left(\frac{DOC}{DOC_0}\right), & 507 \leq t \leq 509.7 \text{ Ma} \end{cases} \quad (\text{Eq. 5})$$

It is important to note that while the control mechanism for DOC_{ox} was modified to bypass the model's spatial limitations, the process itself remains a mechanistic oxidation flux; the resulting stoichiometric oxygen consumption is fully accounted for in the global oxygen mass balance (see section 3.2 in Supplementary Information). The pre-event DOC reservoir size was calibrated by adjusting anoxia sensitivity parameters (a_{DOC} and c_{DOC}) to ensure consistency with steady-state baseline conditions prior to the onset of the transgression-induced event.

To test the other scenarios for the ROECE event in the model (i.e., decreased productivity and carbonate weathering), we decreased the phosphorus inputs to the ocean and increased carbonate weathering fluxes during the ROECE interval in the model, respectively. Their corresponding model outputs are shown in the Figure S2.

4. Results

To eliminate the effects of outliers, LOWESS fits spanning 80% of the data were applied to obtain smoothed trends for the $\delta^{34}S_{CAS}$ values and CAS concentrations

(Figure 2). For greater clarity, we compare the $\delta^{34}\text{S}_{\text{CAS}}$ and CAS concentrations with the carbonate carbon isotopes of the same set of samples (Zhang et al., 2020).

The $\delta^{34}\text{S}_{\text{CAS}}$ values decrease from $\sim 34\text{‰}$ to $\sim 30\text{‰}$ in the lower part of the Wusonger Formation, exhibiting a gradual negative excursion of $\sim 4\text{‰}$ in terms of stratigraphical spans (red line in Figure 2B). This trend coincides with the AECE-equivalent negative $\delta^{13}\text{C}$ excursion (Zhang et al., 2020; Zhu et al., 2019). In contrast, CAS concentrations rise in the lower part of the Wusonger Formation and remain relatively high in the upper part.

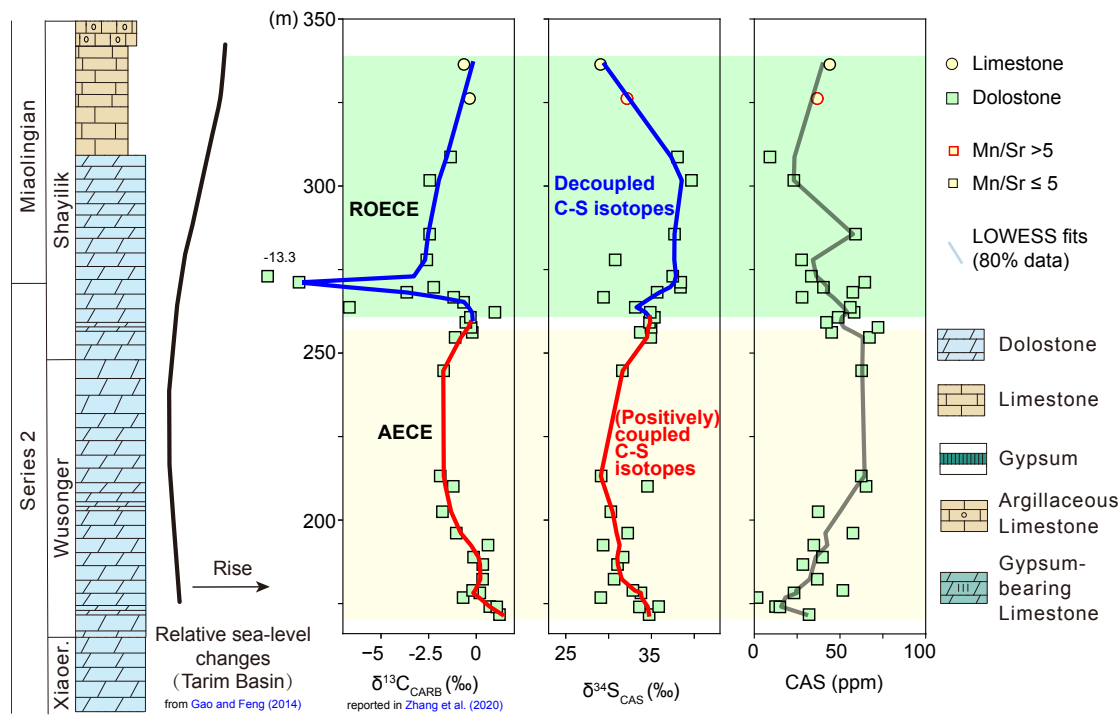


Figure 2. Variations in sea level, $\delta^{13}\text{C}$, $\delta^{34}\text{S}_{\text{CAS}}$ values and CAS contents of the carbonates from the Wusonger to Shayilik formations in the Xiaerbrak section. Note that carbonate carbon isotope data have been reported in Zhang et al. (2020) and relative sea-level changes in the Tarim Basin are from Gao and Fan (2014). Note that the

LOWESS fits are obtained using the “lowess” function with a frac parameter of 0.2 from the python “statsmodels” package, which is expected to cover 80% of the data.

The previously reported carbonate carbon isotope values show unusual negative values (as low as -13.3‰) in the lower part of the Shayilik Formation, corresponding to the ROECE have been reported (Guo et al., 2017; Zhang et al., 2020). During this ROECE-equivalent carbon isotope excursion, $\delta^{34}\text{S}_{\text{CAS}}$ values show an increase from ~33‰ to ~40‰, while CAS concentrations exhibit a decline from ~60 ppm to ~10 ppm. Subsequently, $\delta^{34}\text{S}_{\text{CAS}}$ values decrease from ~40‰ to ~28‰ in the upper part of the Shayilik Formation, where CAS concentrations remain low at ~10–30 ppm. This appears to denote a shift from a positive to a negative correlation between the $\delta^{34}\text{S}_{\text{CAS}}$ and $\delta^{13}\text{C}$ values (Figures 2-3).

Most samples have relatively low Mn/Sr ratios (<5), averaging at ~2 (Figure 3). Mn/Sr ratios remain stable and do not correlate with lithological shifts or variations in $\delta^{13}\text{C}$, $\delta^{34}\text{S}_{\text{CAS}}$ values, or CAS concentrations. Additionally, all carbonate samples show low Al concentrations (< 0.35%; Figure 3).

5. Discussion

5.1 Preservation and diagenetic evaluation of the $\delta^{34}\text{S}_{\text{CAS}}$ record

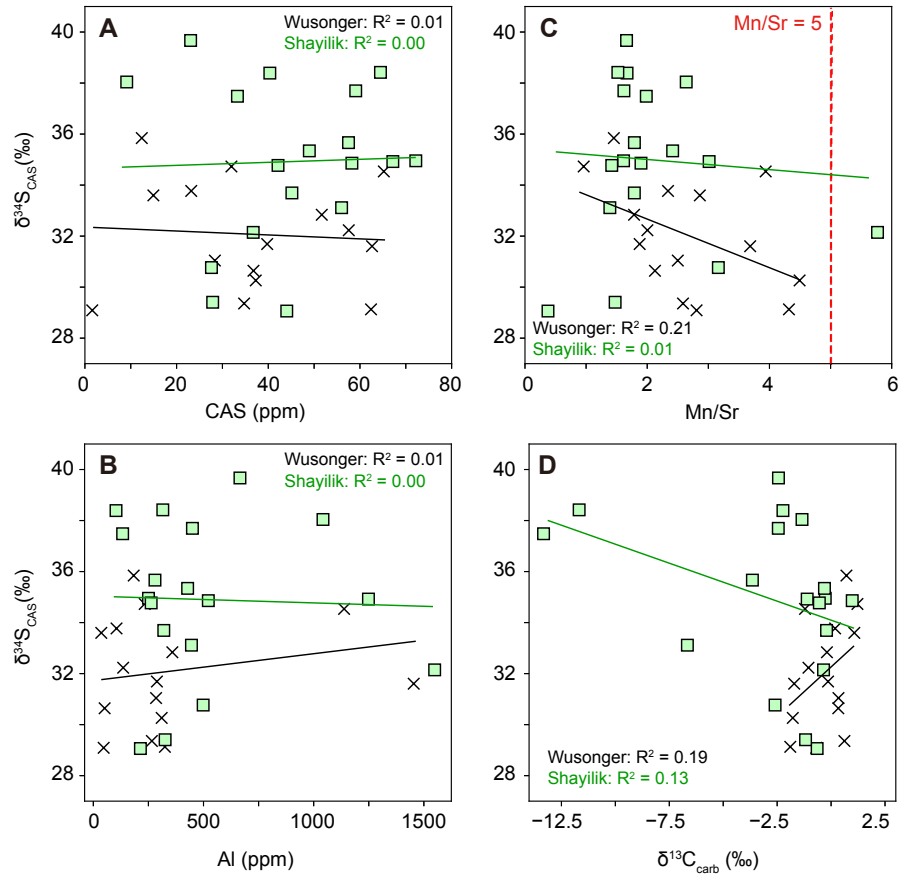


Figure 3. Cross plots between $\delta^{34}\text{S}_{\text{CAS}}$ and CAS concentrations, Al, Mn/Sr, and $\delta^{13}\text{C}$ values of the carbonates. Note that carbonate carbon isotope data were reported in Zhang et al. (2020).

The $\delta^{34}\text{S}_{\text{CAS}}$ value is widely regarded as a reliable tracer for the isotopic composition of seawater sulfate (e.g. Bottrell and Newton (2006); Gill et al. (2011), 2008; He et al. (2019); Tostevin et al. (2017)). However, some studies suggest that $\delta^{34}\text{S}_{\text{CAS}}$ can be significantly altered by contamination from non-CAS sulfur (e.g. reduced sulfur, secondary sulfate, and sulfur from silicates) during CAS extractions (e.g. Marenco et al. (2008a); Peng et al. (2014)) and diagenetic alteration (e.g. Marenco et al. (2008b); Present et al. (2019)). To investigate these potential effects on the $\delta^{34}\text{S}_{\text{CAS}}$

record from the Xiaoerbrak section, we plot $\delta^{34}\text{S}_{\text{CAS}}$ values against Al concentrations, Mn/Sr ratios, and CAS contents in Figure 3.

In this study, we used a CAS extraction process involving NaOCl bleach, repeated NaCl rinses and quick HCl digestion to remove non-CAS sulfur and minimize possible contaminations from reduced-sulfur oxidation. The amount of NaOCl used for pre-bleaching was excessive to oxidize reduced sulfur, and more than five NaCl rinses effectively removed secondary sulfate from the carbonates (He et al., 2019; Peng et al., 2014). The lack of obvious correlations in the $\delta^{34}\text{S}_{\text{CAS}}$ -CAS cross plot (Figure 3A) supports the effective removal of reduced sulfur, as contamination from reduced sulfur would typically decrease $\delta^{34}\text{S}$ and increase sulfur content (Marenco et al., 2008a). Additionally, all carbonate samples show low Al contents ($<0.35\%$), a threshold value for testing silicate contaminations during carbonate digestion (Ling et al., 2013; Zhang et al., 2023), which indicates no substantial dissolution of detrital silicates during CAS extraction. The absence of correlations in the $\delta^{34}\text{S}_{\text{CAS}}$ -Al cross plot (Figure 3B) further suggests negligible impacts of silicate contamination on our $\delta^{34}\text{S}_{\text{CAS}}$ values. Thus, CAS was effectively extracted without substantial contamination from non-CAS sulfur.

The Mn/Sr ratio, a common proxy for diagenesis, is also plotted against $\delta^{34}\text{S}_{\text{CAS}}$ (Figure 3C). Carbonate Mn/Sr ratios above five generally indicate meteoric-fluid alteration (Derry et al., 1994; Zhang et al., 2020; Zhou et al., 2020). In this study, almost

all carbonate samples have Mn/Sr ratios below this threshold, and no obvious correlations are observed between $\delta^{34}\text{S}_{\text{CAS}}$ values and Mn/Sr ratios (Figure 3C), suggesting a limited impact of diagenetic alteration on $\delta^{34}\text{S}_{\text{CAS}}$ values.

Therefore, dolostone samples in the Wusonger and Shayilik formations likely preserve coeval open-ocean seawater isotope values. This conclusion is supported by (a) the lack of obvious correlations between $\delta^{34}\text{S}_{\text{CAS}}$ values and CAS contents or Mn/Sr ratios (Figure 3A and 3C) and (b) their relatively higher $\delta^{34}\text{S}_{\text{CAS}}$ values compared to other coeval $\delta^{34}\text{S}_{\text{CAS}}$ records (e.g. Hough et al. (2006); Kampschulte and Strauss (2004); Wotte et al. (2012)).

5.2 Seawater $\delta^{34}\text{S}$ variations during Cambrian Series 2–3

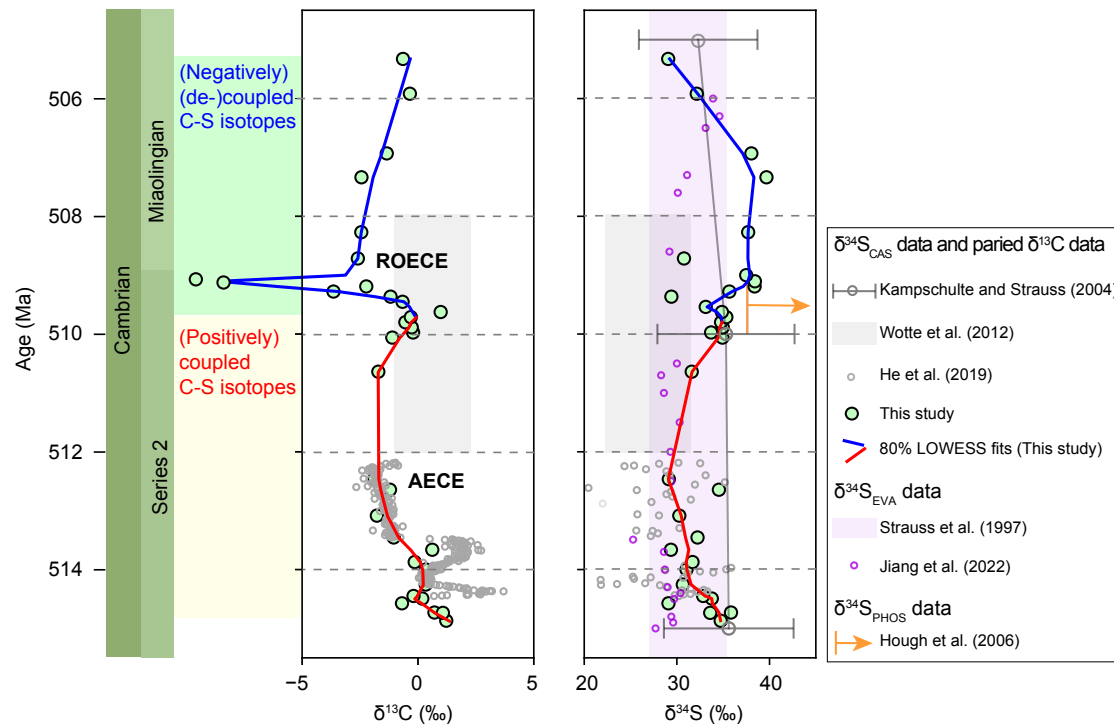


Figure 4. Seawater sulfate $\delta^{34}\text{S}$ variations during Cambrian Series 2–3 from carbonate

(CAS; compared with references (He et al., 2019; Kampschulte and Strauss, 2004; Wotte et al., 2012)), evaporite (Jiang et al., 2022; Strauss, 1997), and phosphate (Hough et al., 2006) sources. Note that the data represented by rectangles are relatively stable and show no obvious excursions or fluctuations. The LOWESS fits is derived from the Xiaerbrak carbonate isotope data only using the “lowess” function with a frac parameter of 0.2 from the python “statsmodels” package.

Based on previous biogeochemical stratigraphical studies (Guo et al., 2017; Wang et al., 2011; Zhang et al., 2020), we establish a geochronological timeframe for the $\delta^{34}\text{S}_{\text{CAS}}$ data of the Wusonger and Shayilik formations by assuming a stable sedimentation rate (see supplementary information for details). To investigate seawater $\delta^{34}\text{S}$ variations across the Cambrian Series 2–3 boundary, a LOWESS fitting curve constructed from our new $\delta^{34}\text{S}_{\text{CAS}}$ data is compared with published coeval $\delta^{34}\text{S}$ data from carbonate (He et al., 2019; Kampschulte and Strauss, 2004; Wotte et al., 2012), evaporite (Jiang et al., 2022; Strauss, 1997), and phosphate (Hough et al., 2006) (Figure 4).

Our new $\delta^{34}\text{S}_{\text{CAS}}$ data, which generally fall within the range of estimated seawater $\delta^{34}\text{S}$ values for the Cambrian Series 2–3, exhibit a negative excursion followed by a pronounced positive shift (Figure 4). In contrast, previously published evaporite $\delta^{34}\text{S}$ records display relatively stable values across this interval (Jiang et al., 2022; Strauss,

1997), likely due to their low temporal resolution and the influence of local depositional setting. Nevertheless, the general trend observed in our dataset is consistent with $\delta^{34}\text{S}$ data from the Cambrian Series 2 carbonates (Stage 3) (He et al., 2019) and from Cambrian Series 3 phosphate (Hough et al., 2006) in different continents, supporting the global significance of this isotopic pattern. The negative $\delta^{34}\text{S}_{\text{CAS}}$ excursion during Cambrian Series 2 (Stage 3) coincides with the negative carbonate carbon isotope excursion (i.e., AECE), while the subsequent positive $\delta^{34}\text{S}_{\text{CAS}}$ excursion aligns with the ROECE, marking a shift from positively coupled to decoupled C-S isotope behaviour around the Cambrian Series 2–3 boundary (Figures 3D and 4).

Organic matter burial affects pyrite burial rates via MSR process (e.g. Berner and Raiswell (1983); Raiswell and Berner (1986)). This coupled relationship between pyrite and organic matter burial is generally expressed as coupled carbon and sulfur isotope fluctuations, which have been widely reported in the Palaeozoic strata (e.g. Cambrian (Gill et al., 2011; He et al., 2019; Li et al., 2020b) and Ordovician–Silurian (Hints et al., 2014; Richardson et al., 2019; Yan et al., 2009)). On a Phanerozoic timescale, high organic carbon burial typically leads to increased atmospheric O_2 production, which in turn limits pyrite burial by reducing anaerobic environments; this creates a negative correlation between carbon and sulfur isotope records (Garrels and Lerman 1981). However, decoupled seawater C-S isotope behaviours on shorter timeframes (e.g. several million years) generally require unbalanced isotope inputs or outputs to the

ocean, such as the decoupling of pyrite burial from organic carbon burial induced by iron depletion (Goldberg et al., 2007).

The recorded negative $\delta^{34}\text{S}_{\text{CAS}}$ excursion and the AECE likely indicate decreased net burial fluxes of reduced phases (both carbon and sulfur) due to the shrinking of the oceanic anoxic area. However, there are differences compared to the coeval Siberian record. As illustrated in He et al. (2019), Siberian seawater sulfate concentration decreased after the Sinsk transgression event, causing significant fluctuations in its $\delta^{34}\text{S}_{\text{CAS}}$ record and a decoupling from the seawater $\delta^{13}\text{C}$ record (Figure 4). Nonetheless, Siberian $\delta^{34}\text{S}_{\text{CAS}}$ data also shows an overall decreasing trend accompanying seawater $\delta^{13}\text{C}$ declines during the AECE event (Figure 4; He et al., 2019), although superimposed with short-term fluctuations. The rapidly changing seawater sulfur isotopes in Siberia indicate a maximum sulfate concentration lower than $\sim 0.4\text{--}1.4$ mM around 514 to 512 Ma (He et al., 2019), suggesting a sulfate-heterogeneous ocean during Cambrian Series 2 (Wotte et al., 2012), which may explain the difference between the Tarim and Siberia $\delta^{34}\text{S}_{\text{CAS}}$ records. Relatively higher seawater sulfate concentrations in the Tarim Basin are indicated by the record of long-term variation without significant short-term fluctuations.

Around the Cambrian Series 2–3 boundary (i.e. during the ROECE event), the Tarim $\delta^{34}\text{S}_{\text{CAS}}$ values increase, and C-S isotope behaviour are decoupled (Figures 3D

and 4). This $\delta^{34}\text{S}$ shift is also observed in the coeval francolite-bound sulfate $\delta^{34}\text{S}$ data from Australia (Figure 4; Hough et al., 2006), and pyrite $\delta^{34}\text{S}$ data from South China (Guo et al., 2014; Liu et al., 2021). However, Wotte et al. (2012) reported relatively stable $\delta^{34}\text{S}_{\text{CAS}}$ values within their studied section, though differences were noted across sections. Even with these differences, their $\delta^{34}\text{S}_{\text{CAS}}$ data are still much lower than the Tarim $\delta^{34}\text{S}_{\text{CAS}}$ data, possibly indicating slight pyrite oxidation during their CAS extraction (Marenco et al., 2008a). Additionally, their paired $\delta^{13}\text{C}$ data are relatively stable (Figure 4), making it challenging to recognize the ROECE event (e.g. Chang et al. (2017)). Considering the increasing $\delta^{34}\text{S}$ trends observed in other independent archives from different regions (Hough et al., 2006; Liu et al., 2021), an increase in seawater $\delta^{34}\text{S}$ values during the ROECE event (or the Cambrian Series 2–3 boundary) seems to have occurred at the global scale.

Overall, our Tarim $\delta^{34}\text{S}_{\text{CAS}}$ record aligns with published $\delta^{34}\text{S}$ data from seawater archives and provides a reliable comparison with paired seawater $\delta^{13}\text{C}$ records. This new dataset confirms an increase in seawater $\delta^{34}\text{S}$ values during the ROECE event (or the Cambrian Series 2–3 boundary), and a shift from positively coupled to decoupled C-S behaviour. These decoupled C-S isotope features will be used to investigate the causes of the ROECE event in the next section.

5.3 Causes of decoupled C-S isotope records during the ROECE event

The negative $\delta^{13}\text{C}$ excursion near the Cambrian Series 2–3 boundary (i.e. ROECE) marks the disappearance of the Redlichiid and Olenellid trilobites and a global diversity decline (Zhu et al., 2019, 2006). This negative carbon isotope excursion has been linked to the following possible drivers: (a) decline in primary productivity (Chang et al., 2017); (b) carbonate weathering (Marshall et al., 2021); (c) the Kalkarindji eruptions (Glass and Phillips, 2006; Hough et al., 2006; Liu et al., 2021); and (d) the shallowing of oxygen-depleted bottom waters during transgression (Guo et al., 2017, 2010; Montañez et al., 2000).

Reduced primary productivity in an already oxygen-poor ocean should act to lessen the rate of organic carbon burial, and consequently, can lead to less pyrite burial (c.f. He et al. (2019); Liu et al. (2024); Zhang et al. (2025)). From this coupled relationship between the organic carbon and pyrite burial fluxes, this proposed driver would cause negative shifts in both carbon and sulfur isotopes, rather than decoupled C-S isotopes. This is also shown in our modelling results of the scenario of decreased productivity (Figure S2). For comparison, increased carbonate weathering (and burial) may act to implicitly reduce the organic carbon burial fraction, potentially driving a negative carbon isotope excursion during periods of high $\delta^{13}\text{C}$ (e.g. Shields and Mills (2017)). However, this mechanism does not appear to apply to the ROECE, as the pre-event seawater $\delta^{13}\text{C}$ was relatively low ($<1\text{‰}$, based on the global compilation by Guo et al. (2017)). This is confirmed by the modelling results in the scenario of increased

carbonate weathering (Figure S2). Moreover, there is no geological evidence indicating enhanced carbonate weathering during this time. It is also noteworthy that the mechanistic links to the trilobite extinction in these two hypotheses remain speculative and insufficiently constrained in the existing literature, rendering them less plausible explanations. Therefore, these two hypotheses fail to explain the divergent carbon and sulfur isotope trends and the relevant trilobite turnovers during the ROECE event (see Figure S2).

In contrast, Kalkarindji volcanism (Glass and Phillips, 2006; Hough et al., 2006; Liu et al., 2021) and anoxic bottom water shoaling/upwelling (Guo et al., 2017, 2010; Montañez et al., 2000), are the most promising hypotheses for explaining the ROECE. They have the potential to disturb the coupled seawater C-S isotope system by introducing disproportionate amounts of isotopically light carbon and sulfur into the atmosphere-ocean system. Specifically, volcanic emissions release vast quantities of ^{13}C -depleted CO_2 (with $\delta^{13}\text{C}$ values $< -5\text{‰}$), while upwelling transports anoxic ^{13}C -depleted waters (with $\delta^{13}\text{C}$ values as low as -30‰) into the surface ocean. Because volcanic sulfur emissions (SO_2) are typically one order of magnitude less than those of CO_2 (Marshall et al., 2021, 2016), and the Cambrian deep ocean was notably sulfate-poor (Jin et al., 2016; Sperling et al., 2021), these inputs contribute massive amounts of light carbon but significantly less light sulfur. Consequently, they may drive a pronounced negative carbon isotope excursion while allowing the oceanic sulfur

isotope response to be controlled by other processes.

To test the Kalkarindji volcanism hypothesis (scenario A), we constrain the major eruptive phase of the Kalkarindji LIP near the ROECE event based on the Hg record from South China (Liu et al., 2021). Then, previously estimated CO₂, SO₂ degassing fluxes from the Kalkarindji volcanism (Marshall et al., 2021, 2016) and basalt area variations are incorporated in the model (Lenton et al., 2018; Tostevin and Mills, 2020) to simulate the effects of Kalkarindji LIP eruptions on ocean chemistry across the Cambrian 2–3 boundary interval (Figure 5).

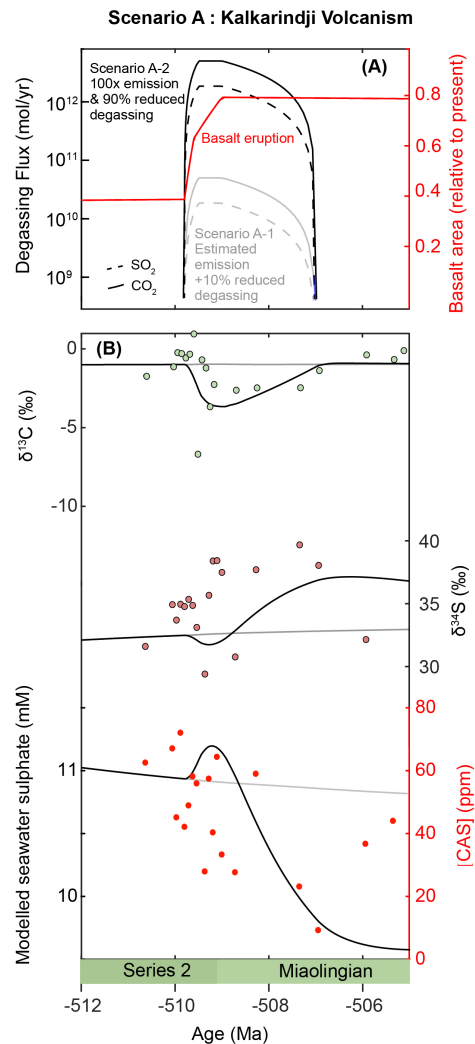


Figure 5. Modelling forcings and results for the Kalkarindji eruption scenario. Panel A shows the modelling forcings, i.e. CO₂ degassing fluxes (solid black and grey line), SO₂ degassing fluxes (dashed black and grey line), and basalt eruptions (red line), while panel B shows the modelled seawater $\delta^{13}\text{C}$, $\delta^{34}\text{S}$, and sulfate concentrations in the Kalkarindji eruption scenario, respectively. Note that the solid and dashed lines represent CO₂ and SO₂ emissions, respectively, while grey and black colours represent estimated emissions and an arbitrary 100-fold increase respectively.

In scenario A-1 (Figure 5 grey lines), our modelling results show that the potential global impact of the estimated CO₂ and SO₂ released from Kalkarindji volcanism is minimal (c.f. Marshall et al. (2021), (2016)). The emitted carbon amount ($\sim 3.7 \times 10^{16}$ mol) is $\sim 1/320$ of the atmospheric and oceanic carbon reservoir size in the model (which is $\sim 1.2 \times 10^{19}$ mol, around 4 $\times$ present values). We considered the warming effects on weathering and productivity (Zhang et al., 2022); however, such a small amount exerts little effect on the seawater carbon and sulfur cycles (grey lines in Figure 5). To trigger significant seawater carbon isotope excursions, not only would the degassing fluxes need to multiply a hundredfold, but the involvement of organic-carbon-related degassing would also need to increase (scenario A-2 in Figure 5). Under such an enhanced Kalkarindji eruption scenario, enhanced silicate weathering, due to increased atmospheric CO₂ level and greater basalt exposure, results in increased nutrient inputs, promotes primary productivity, and expands ocean anoxia, leading to increased pyrite

burial and rising seawater $\delta^{34}\text{S}$ values (Hough et al., 2006). Regarding the carbon cycle, the organic-carbon-related carbon emissions with much more negative $\delta^{13}\text{C}$ values likely overwhelm the positive $\delta^{13}\text{C}$ shifts associated with enhanced primary productivity and increased organic carbon burials (c.f. Zhang et al. (2023)). However, such amplification and degassing-source shifts in the Kalkarindji volcanism are not well supported by geological evidence, and even with this enhancement, the modelled seawater variations do not match our records well (black lines in Figure 5).

Given the debated spatiotemporal relationship between Kalkarindji volcanism and the ROECE event and our model prediction of minimal environmental change for this scenario, we conclude that the role of the Kalkarindji volcanism requires further assessment as the major cause for the ROECE event and the decoupled C-S isotope behaviour. The reported isotope ages for the Kalkarindji volcanism range from ~514 to ~505 Ma (Evins et al., 2009; Glass and Phillips, 2006; Jourdan et al., 2014). While these ages partially overlap with the ROECE event at ~510 Ma, the peak interval of the volcanism is not clearly constrained to this time (e.g. Myrow et al. (2024)) and volcanism-related Hg enrichments were absent in several regions during the ROECE event (Faggetter et al., 2019). Therefore, although ongoing Kalkarindji volcanism might have contributed to the negative $\delta^{13}\text{C}$ excursion and environmental stress, it alone is insufficient to explain the full magnitude of the ROECE event and the decoupled C-S isotope behaviour.

583

584 To examine the anoxic bottom water shoaling/upwelling hypothesis, we update
585 previous versions (Guo et al., 2017, 2010; Montañez et al., 2000) and propose that the
586 contribution of ^{13}C -depleted signals likely comes from the oxidation of an assumed
587 dissolved organic carbon (DOC) reservoir (c.f. Ishikawa et al. (2014)). This is because
588 the previous hypothesis implicitly assumes the negative carbon isotope excursion might
589 only occur in surface water and cannot well explain the widely reported negative carbon
590 isotope records across different water depths (e.g. Chang et al. (2017)). At the same
591 time, many ROECE carbonate records, which show $\delta^{13}\text{C}$ values below -6‰, such as
592 those from the Tarim Basin (Guo et al., 2017; Zhang et al., 2020), South China (Guo et
593 al., 2010), and South Sweden (Álvaro et al., 2010), also require large fluxes of light
594 carbon into the ocean inorganic carbon system. Deep anoxic (predominantly
595 ferruginous) water, which likely existed widely in the stratified Cambrian ocean (Jin et
596 al., 2016; Sperling et al., 2021), favours the development and preservation of a DOC
597 reservoir, and a wide transgression event promotes the shoaling of the DOC reservoir
598 and its exposure to oxidation. To test this DOC-oxidation hypothesis (scenario B), we
599 assume the DOC reservoir has a baseline size of 1.3×10^{18} mol to ~9 times this value
600 (12×10^{18} mol) before the ROECE event in the model (see Method section and
601 Supplementary Information). This baseline size is taken from previous long-term runs
602 of the COPSE model (Tostevin and Mills, 2020), and the assumed increases in the DOC
603 reservoir size are in line with the larger DOC reservoir sizes that have been indicated

in the studies of the carbon cycle for Cambrian Series 2–3 (e.g. Ishikawa et al. (2014); Li et al. (2020a)). Considering that the deep anoxic waters were predominantly ferruginous, we do not consider H_2S oxidation in the model (Jin et al., 2016; Sperling et al., 2021). We vary the DOC reservoir sizes (scenarios B-1, B-2, B-3 and B-4) and assume a DOC-oxidation rate controlled by the DOC reservoir size (see Supplementary Information for details), to study the effects of DOC-oxidation caused by transgression on the seawater C-S isotope compositions (Figure 6).

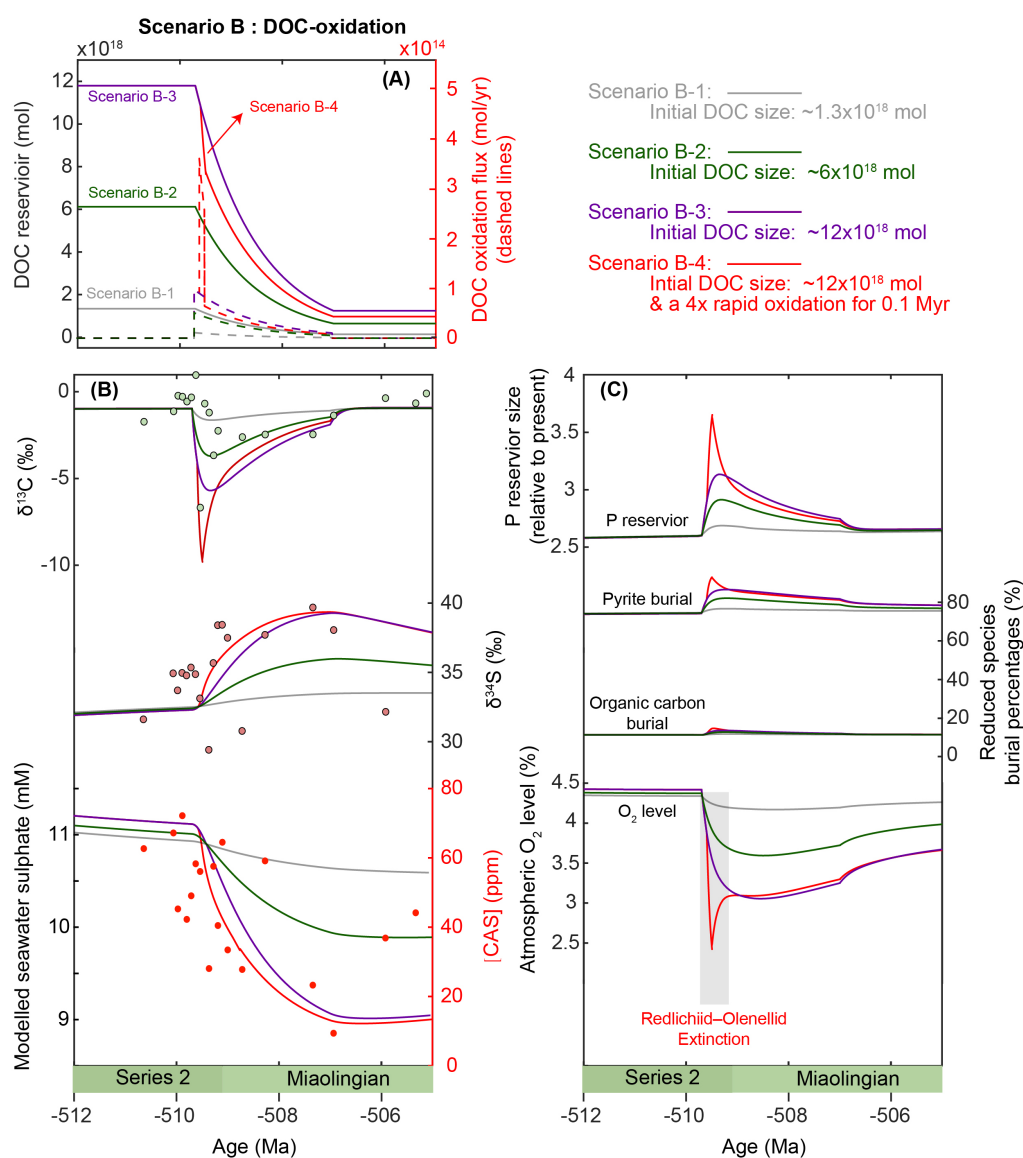


Figure 6. Modelling forcings and results for the DOC-oxidation scenario. This DOC-

oxidation scenario is divided into four sub-scenarios: (B-1) a DOC reservoir size of 1.3×10^{18} mol, (B-2) a DOC reservoir size of 6×10^{18} mol, (B-3) a DOC reservoir size of 12×10^{18} mol, and (B-4) a ~ 4 times more rapid oxidation rate superimposed on the transgression-oxidation trend in the B-3 scenario. Panel A shows the DOC-reservoir sizes and oxidation rates in these four sub-scenarios, while panels B and C show other key model results.

Figure 6 shows that the DOC-oxidation hypothesis can produce comparable simulation results to our observational records. Assuming transgression timing at ~ 509 Ma – around the boundary of Cambrian Series 2–3 (Karlstrom et al., 2018), we set the activation of DOC oxidation from the onset of this transgression (509.7 Ma in the model). As a result, our model predicts a negative seawater $\delta^{13}\text{C}$ excursion, a positive shift in seawater $\delta^{34}\text{S}$ values, and a decline in seawater sulfate concentrations (Figure 6B). With a DOC reservoir size of $\sim 12 \times 10^{18}$ mol and a DOC oxidation rate from $\sim 10 \times 10^{13}$ to $\sim 0.5 \times 10^{13}$ mol/year during the transgression event, the model can produce comparable long-term shifting magnitudes to all our compiled records (scenario B-3 in Figure 6). Such a DOC oxidation rate is consistent with the previously estimated DOC-oxidation rate during the middle Cambrian (Li et al., 2020a). In addition, a large DOC reservoir has been widely suggested to exist during the Cambrian (e.g. Ishikawa et al. (2014); Li et al. (2020a)).

To capture the sharp decrease in seawater $\delta^{13}\text{C}$ values, a 0.1-Myr rapid DOC-oxidation (~ 4 times the baseline rate) is superimposed on the long-term gradual DOC-oxidation forcing (scenario B-4 in Figure 6). With this forcing, we obtain the best fit for the isotope and concentration records. With this best fit, the negative carbon isotope excursion during the ROECE event is attributed to DOC oxidation during the large-scale transgression event, while some short-term abnormally negative $\delta^{13}\text{C}$ values reflect rapid DOC oxidation pulses.

During DOC oxidation, vast amounts of phosphorus are likely released from DOC (c.f. Dodd et al. (2023)), which stimulate primary productivity, increase ocean anoxia, and consequently, increase the organic carbon and pyrite burial fluxes (Figure 6C). The light carbon inputs from DOC-oxidation are much more significant in the carbon isotope balance than the light carbon removal from increased organic carbon burial. In contrast, without light sulfur inputs, increased pyrite burial leads to a rise in seawater $\delta^{34}\text{S}$ values and a decrease in seawater sulfate concentrations (Figure 6B). Simultaneously, DOC oxidation consumes oxygen, potentially resulting in a halving of the atmospheric O_2 level (Figure 6C). When coupled with the environmental stressors possibly induced by the Kalkarindji volcanism (Glass and Phillips, 2006; Zhang et al., 2022), the profound ocean anoxia and atmospheric oxygen loss driven by DOC oxidation would exert catastrophic pressure on the Redlichiid–Olenellid trilobite fauna, ultimately driving their turnover.

655

656 The proposed DOC-oxidation hypothesis can explain the carbonate carbon and
657 sulfur isotope records across the Cambrian Series 2–3 boundary. In addition, it aligns
658 with the previous hypothesis of upwelling or shoaling of ^{13}C -depleted anoxic bottom
659 water into surface water during the transgression event (Guo et al., 2017, 2010;
660 Montañez et al., 2000) but also explains the abundant records of the negative $\delta^{13}\text{C}$
661 excursion across different water depths (Chang et al., 2017). Moreover, widely recorded
662 abnormally negative values ($\delta^{13}\text{C}$ values below -6‰) (Álvaro et al., 2010; Guo et al.,
663 2017, 2010; Zhang et al., 2020) can also be explained by this hypothesis (e.g. scenario
664 4 in Figure 6). Therefore, we suggest that the ROECE event is most likely to have been
665 caused by the oxidation of DOC during the shoaling of anoxic bottom water.

666

667 **6. Conclusion**

668 Based on CAS-based sulfur isotope records from the Tarim Basin, we reconstruct
669 seawater sulfur isotope variations across the Cambrian Series 2–3 boundary. This new
670 record reveals positively coupled $\delta^{34}\text{S}$ - $\delta^{13}\text{C}$ variations below the boundary, but an
671 abrupt rise in $\delta^{34}\text{S}$ coinciding with the ROECE event at the Cambrian Series 2–3
672 boundary. This denotes a shift from coupled to decoupled carbon and sulfur isotope
673 records across the Cambrian Series 2–3 boundary.

674

675 Biogeochemical modelling suggests that the decoupled C-S isotope records during

the ROECE event are best explained by significant inputs of light carbon from DOC oxidation during a widespread marine transgression. The massive oxygen consumption associated with DOC oxidation likely accelerated pyrite burial, leading to the observed rise in seawater $\delta^{34}\text{S}$ values. Aside from the environmental stress associated with the Kalkarindji volcanism, reduced oxygen levels may have also played a crucial role in the Redlichiid–Olenellid trilobite extinction. Additionally, our study suggests that light carbon emissions from DOC oxidation could explain other instances of C-S decoupling during the Precambrian–Palaeozoic periods.

Acknowledgements

This work is funded by the National Key Research and Development Program of China (2022YFF0800100) to MZ and the National Natural Science Foundation of China (42402312, 42488201) to YZ and TH. In addition, YZ is funded by the Jiangsu Funding Program for Excellent Postdoctoral Talent and BJWM is funded by UKRI project EP/Y008790/1. The authors would like to acknowledge the help of Stephen Reid and the use of the ICP laboratory within the Cohen Lab, School of Earth and Environment, at the University of Leeds.

References

Álvaro, J.J., Ahlberg, P., Axheimer, N., 2010. Skeletal carbonate productivity and phosphogenesis at the lower–middle Cambrian transition of Scania, southern

697 Sweden. *Geol. Mag.* 147, 59–76. <https://doi.org/10.1017/S0016756809990021>

698 Berner, R.A., Raiswell, R., 1983. Burial of organic carbon and pyrite sulfur in
699 sediments over phanerozoic time: a new theory. *Geochimica et Cosmochimica*
700 *Acta* 47, 855–862. [https://doi.org/10.1016/0016-7037\(83\)90151-5](https://doi.org/10.1016/0016-7037(83)90151-5)

701 Bottrell, S.H., Newton, R.J., 2006. Reconstruction of changes in global sulfur cycling
702 from marine sulfate isotopes. *Earth-Science Reviews*, *ISOTopes in*
703 *PALaeoenvironmental reconstruction (ISOPAL)* 75, 59–83.
704 <https://doi.org/10.1016/j.earscirev.2005.10.004>

705 Chang, C., Hu, W., Wang, X., Yu, H., Yang, A., Cao, J., Yao, S., 2017. Carbon isotope
706 stratigraphy of the lower to middle Cambrian on the eastern Yangtze Platform,
707 South China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 479, 90–101.
708 <https://doi.org/10.1016/j.palaeo.2017.04.019>

709 Derry, L.A., Brasier, M.D., Corfield, R.M., Rozanov, A.Y., Zhuravlev, A.Y., 1994. Sr
710 and C isotopes in Lower Cambrian carbonates from the Siberian craton: A
711 paleoenvironmental record during the “Cambrian explosion.” *Earth and Planetary*
712 *Science Letters* 128, 671–681. [https://doi.org/10.1016/0012-821X\(94\)90178-3](https://doi.org/10.1016/0012-821X(94)90178-3)

713 Dodd, M.S., Shi, W., Li, C., Zhang, Z., Cheng, M., Gu, H., Hardisty, D.S., Loyd, S.J.,
714 Wallace, M.W., vS. Hood, A., Lamothe, K., Mills, B.J.W., Poulton, S.W., Lyons,
715 T.W., 2023. Uncovering the Ediacaran phosphorus cycle. *Nature* 618, 974–980.
716 <https://doi.org/10.1038/s41586-023-06077-6>

717 Evins, L.Z., Jourdan, F., Phillips, D., 2009. The Cambrian Kalkarindji Large Igneous

Province: Extent and characteristics based on new $^{40}\text{Ar}/^{39}\text{Ar}$ and geochemical data. *Lithos* 110, 294–304. <https://doi.org/10.1016/j.lithos.2009.01.014>

Faggetter, L.E., Wignall, P.B., Pruss, S.B., Jones, D.S., Grasby, S., Widdowson, M., Newton, R.J., 2019. Mercury chemostratigraphy across the Cambrian Series 2 – Series 3 boundary: evidence for increased volcanic activity coincident with extinction? *Chemical Geology* 510, 188–199. <https://doi.org/10.1016/j.chemgeo.2019.02.006>

Fan, R., Deng, S.H., Zhang, X.L., 2011. Significant carbon isotope excursions in the Cambrian and their implications for global correlations. *Science China Earth Sciences* 54, 1686–1695. <https://doi.org/10.1007/s11430-011-4313-z>

Feng, Z., Bao, Z., Wu, M., Jin, Z., Shi, X., 2007. Lithofacies palaeogeography of the Cambrian in Tarim area. *Frontiers of Earth Science in China* 1, 265–274. <https://doi.org/10.1007/s11707-007-0033-2>.

Gao, Z., Fan, T., 2014. Intra-platform tectono-sedimentary response to geodynamic transition along the margin of the Tarim Basin, NW China. *Journal of Asian Earth Sciences* 96, 178–193. <https://doi.org/10.1016/j.jseaes.2014.08.023>

Gill, B.C., Lyons, T.W., Frank, T.D., 2008. Behavior of carbonate-associated sulfate during meteoric diagenesis and implications for the sulfur isotope paleoproxy. *Geochimica et Cosmochimica Acta* 72, 4699–4711. <https://doi.org/10.1016/j.gca.2008.07.001>

Gill, B.C., Lyons, T.W., Young, S.A., Kump, L.R., Knoll, A.H., Saltzman, M.R., 2011.

739 Geochemical evidence for widespread euxinia in the Later Cambrian ocean.
740 Nature 469, 80–83. <https://doi.org/10.1038/nature09700>

741 Glass, L.M., Phillips, D., 2006. The Kalkarindji continental flood basalt province: A
742 new Cambrian large igneous province in Australia with possible links to faunal
743 extinctions. Geol 34, 461. <https://doi.org/10.1130/G22122.1>

744 Garrels, R.M., Lerman, A., 1981. Phanerozoic cycles of sedimentary carbon and sulfur.
745 Proc. Natl. Acad. Sci. 78, 4652–4656. <https://doi.org/10.1073/pnas.78.8.4652>

746 Goldberg, T., Strauss, H., Guo, Q., Liu, C., 2007. Reconstructing marine redox
747 conditions for the Early Cambrian Yangtze Platform: Evidence from biogenic
748 sulphur and organic carbon isotopes. Palaeogeography, Palaeoclimatology,
749 Palaeoecology 254, 175–193. <https://doi.org/10.1016/j.palaeo.2007.03.015>

750 Guo, Q., Deng, Y., Hu, J., Wang, L., 2017. Carbonate carbon isotope evolution of
751 seawater across the Ediacaran–Cambrian transition: evidence from the Keping
752 area, Tarim Basin, NW China. Geological Magazine 154, 1–13.
753 <https://doi.org/10.1017/s0016756817000206>

754 Guo, Q., Strauss, H., Liu, C., Zhao, Y., Yang, X., Peng, J., Yang, H., 2010. A negative
755 carbon isotope excursion defines the boundary from Cambrian Series 2 to
756 Cambrian Series 3 on the Yangtze Platform, South China. Palaeogeography,
757 Palaeoclimatology, Palaeoecology.

758 Guo, Q., Strauss, H., Zhao, Y., Yang, X., Peng, J., Yang, Y., Deng, Y., 2014.
759 Reconstructing marine redox conditions for the transition between Cambrian

760 Series 2 and Cambrian Series 3, Kaili area, Yangtze Platform: Evidence from
 761 biogenic sulfur and degree of pyritization. *Palaeogeography, Palaeoclimatology,*
 762 *Palaeoecology* 398, 144–153. <https://doi.org/10.1016/j.palaeo.2013.10.003>
 763 Halevy, I., Fike, D.A., Pasquier, V., Bryant, R.N., Wenk, C.B., Turchyn, A.V., Johnston,
 764 D.T., Claypool, G.E., 2023. Sedimentary parameters control the sulfur isotope
 765 composition of marine pyrite. *Science* 382, 946–951.
 766 <https://doi.org/10.1126/science.adh1215>
 767 He, T., Zhu, M., Mills, B.J.W., Wynn, P.M., Zhuravlev, A.Y., Tostevin, R., Pogge von
 768 Strandmann, P.A.E., Yang, A., Poulton, S.W., Shields, G.A., 2019. Possible links
 769 between extreme oxygen perturbations and the Cambrian radiation of animals.
 770 *Nature Geoscience* 12, 468–474. <https://doi.org/10.1038/s41561-019-0357-z>
 771 Hints, O., Martma, T., Männik, P., Nõlvak, J., Põldvere, A., Shen, Y., Viira, V., 2014.
 772 New data on Ordovician stable isotope record and conodont biostratigraphy from
 773 the Viki reference drill core, Saaremaa Island, western Estonia. *GFF* 136, 100–
 774 104. <https://doi.org/10.1080/11035897.2013.873989>
 775 Hough, M.L., Shields, G.A., Evins, L.Z., Strauss, H., Henderson, R.A., Mackenzie, S.,
 776 2006. A major sulphur isotope event at *c.* 510 Ma: a possible anoxia–extinction–
 777 volcanism connection during the Early–Middle Cambrian transition? *Terra Nova*
 778 18, 257–263. <https://doi.org/10.1111/j.1365-3121.2006.00687.x>
 779 Ishikawa, T., Ueno, Y., Shu, D., Li, Y., Han, J., Guo, J., Yoshida, N., Maruyama, S.,
 780 Komiya, T., 2014. The $\delta^{13}\text{C}$ excursions spanning the Cambrian explosion to the

781 Canglangpuian mass extinction in the Three Gorges area, South China. *Gondwana*
782 *Research* 25, 1045–1056. <https://doi.org/10.1016/j.gr.2013.03.010>

783 Jiang, L., Zhao, M., Shen, A., Huang, L., Chen, D., Cai, C., 2022. Pulses of atmosphere
784 oxygenation during the Cambrian radiation of animals. *Earth and Planetary*
785 *Science Letters* 590, 117565. <https://doi.org/10.1016/j.epsl.2022.117565>

786 Jin, C., Li, C., Algeo, T.J., Planavsky, N.J., Cui, H., Yang, X., Zhao, Y., Zhang, X., Xie,
787 S., 2016. A highly redox-heterogeneous ocean in South China during the early
788 Cambrian (~529–514 Ma): Implications for biota-environment co-evolution.
789 *Earth and Planetary Science Letters* 441, 38–51.
790 <https://doi.org/10.1016/j.epsl.2016.02.019>

791 Jourdan, F., Hodges, K., Sell, B., Schaltegger, U., Wingate, M.T.D., Evins, L.Z.,
792 Söderlund, U., Haines, P.W., Phillips, D., Blenkinsop, T., 2014. High-precision
793 dating of the Kalkarindji large igneous province, Australia, and synchrony with
794 the Early–Middle Cambrian (Stage 4–5) extinction. *Geology* 42, 543–546.
795 <https://doi.org/10.1130/G35434.1>

796 Kampschulte, A., Strauss, H., 2004. The sulfur isotopic evolution of Phanerozoic
797 seawater based on the analysis of structurally substituted sulfate in carbonates.
798 *Chemical Geology* 204, 255–286.

799 Karlstrom, K., Hagadorn, J., Gehrels, G., Matthews, W., Schmitz, M., Madronich, L.,
800 et al., 2018. Cambrian Sauk transgression in the Grand Canyon region redefined
801 by detrital zircons. *Nature Geosciences* 11, 438–43.

802 <https://doi.org/10.1038/s41561-018-0131-7>.

803 Lang, X., Tang, W., Ma, H., Shen, B., 2020. Local environmental variation obscures
804 the interpretation of pyrite sulfur isotope records. *Earth and Planetary Science*
805 *Letters* 533, 116056. <https://doi.org/10.1016/j.epsl.2019.116056>

806 Lenton, T.M., Daines, S.J., Mills, B.J.W., 2018. COPSE reloaded: An improved model
807 of biogeochemical cycling over Phanerozoic time. *Earth-Science Reviews* 178, 1–
808 28. <https://doi.org/10.1016/j.earscirev.2017.12.004>

809 Li, D., Zhang, Xiaolin, Zhang, Xu, Zhu, H., Peng, S., Sun, L., Shen, Y., 2020a. A paired
810 carbonate–organic $\delta^{13}\text{C}$ approach to understanding the Cambrian Drumian carbon
811 isotope excursion (DICE). *Precambrian Research* 349, 105503.
812 <https://doi.org/10.1016/j.precamres.2019.105503>

813 Li, D., Zhang, X., Hu, D., Li, Da, Zhang, G., Zhang, Xu, Ling, H.-F., Xu, Y., Shen, Y.,
814 2020b. Multiple S-isotopic constraints on paleo-redox and sulfate concentrations
815 across the Ediacaran-Cambrian transition in South China. *Precambrian Research*
816 349, 105500. <https://doi.org/10.1016/j.precamres.2019.105500>

817 Ling, H.-F., Chen, X., Li, D., Wang, D., Shields-Zhou, G.A., Zhu, M., 2013. Cerium
818 anomaly variations in Ediacaran–earliest Cambrian carbonates from the Yangtze
819 Gorges area, South China: Implications for oxygenation of coeval shallow
820 seawater. *Precambrian Research, Biogeochemical changes across the Ediacaran-*
821 *Cambrian transition in South China* 225, 110–127.
822 <https://doi.org/10.1016/j.precamres.2011.10.011>

823 Liu, J., Luo, G., Algeo, T.J., Qie, W., Yao, L., Huang, J., Xie, S., 2024. Marine sulfate
 824 sulfur isotopic evidence for enhanced terrestrial weathering and expansion of
 825 oceanic anoxia during the Devonian-Carboniferous transition. *Global and*
 826 *Planetary Change* 239, 104494. <https://doi.org/10.1016/j.gloplacha.2024.104494>
 827 Liu, Z.-R.R., Zhou, M.-F., Chen, W.T., Williams-Jones, A.E., Li, X.-D., Yin, R.-S.,
 828 O'Brien, H., Lahaye, Y., 2021. Mercury and sulfur isotopic evidence for the
 829 linkages between the ca. 510 Ma Kalkarindji large igneous province and trilobite
 830 crisis. *Earth and Planetary Science Letters* 566, 116947.
 831 <https://doi.org/10.1016/j.epsl.2021.116947>
 832 Marenco, P.J., Corsetti, F.A., Hammond, D.E., Kaufman, A.J., Bottjer, D.J., 2008a.
 833 Oxidation of pyrite during extraction of carbonate associated sulfate. *Chemical*
 834 *Geology* 247, 124–132. <https://doi.org/10.1016/j.chemgeo.2007.10.006>
 835 Marenco, P.J., Corsetti, F.A., Kaufman, A.J., Bottjer, D.J., 2008b. Environmental and
 836 diagenetic variations in carbonate associated sulfate: An investigation of CAS in
 837 the Lower Triassic of the western USA. *Geochimica et Cosmochimica Acta* 72,
 838 1570–1582. <https://doi.org/10.1016/j.gca.2007.10.033>
 839 Marshall, P.E., Faggetter, L.E., Widdowson, M., 2021. Was the Kalkarindji Continental
 840 Flood Basalt Province a Driver of Environmental Change at the Dawn of the
 841 Phanerozoic? in: Ernst, R.E., Dickson, A.J., Bekker, A. (Eds.), *Geophysical*
 842 *Monograph Series*. Wiley, pp. 435–447.
 843 <https://doi.org/10.1002/9781119507444.ch19>

844 Marshall, P.E., Widdowson, M., Murphy, D.T., 2016. The Giant Lavas of Kalkarindji:
845 rubbly pāhoehoe lava in an ancient continental flood basalt province.
846 *Palaeogeography, Palaeoclimatology, Palaeoecology* 441, 22–37.
847 <https://doi.org/10.1016/j.palaeo.2015.05.006>

848 Mckerrow, W.S., Scotese, C.R., Brasier, M.D., 1992. Early Cambrian continental
849 reconstructions. *JGS* 149, 599–606. <https://doi.org/10.1144/gsjgs.149.4.0599>

850 Merdith, A.S., Collins, A.S., Williams, S.E., Pisarevsky, S., Foden, J.D., Archibald,
851 D.B., Blades, M.L., Alessio, B.L., Armistead, S., Plavsa, D., Clark, C., Müller,
852 R.D., 2017. A full-plate global reconstruction of the Neoproterozoic. *Gondwana*
853 *Research* 50, 84–134. <https://doi.org/10.1016/j.gr.2017.04.001>

854 Montañez, I.P., Osleger, D.A., Banner, J.L., Mack, L.E., Musgrove, M., 2000.
855 Evolution of the Sr and C isotope composition of Cambrian Oceans. *GSA Today*
856 10, 1–7.

857 Myrow, P.M., Goodge, J.W., Brock, G.A., Betts, M.J., Park, T.-Y.S., Hughes, N.C.,
858 Gaines, R.R., 2024. Tectonic trigger to the first major extinction of the
859 Phanerozoic: The early Cambrian Sinsk event. *Sci. Adv.* 10, eadl3452.
860 <https://doi.org/10.1126/sciadv.adl3452>

861 Peng, S., 2009. The newly-developed Cambrian biostratigraphic succession and
862 chronostratigraphic scheme for South China. *Chin. Sci. Bull.* 54, 4161–4170.
863 <https://doi.org/10.1007/s11434-009-0667-4>

864 Peng, Y., Bao, H., Pratt, L.M., Kaufman, A.J., Jiang, G., Boyd, D., Wang, Q., Zhou, C.,

865 Yuan, X., Xiao, S., Loyd, S., 2014. Widespread contamination of carbonate-
 866 associated sulfate by present-day secondary atmospheric sulfate: Evidence from
 867 triple oxygen isotopes. *Geology* 42, 815–818. <https://doi.org/10.1130/G35852.1>
 868 Present, T.M., Gutierrez, M., Paris, G., Kerans, C., Grotzinger, J.P., Adkins, J.F., 2019.
 869 Diagenetic controls on the isotopic composition of carbonate-associated sulphate
 870 in the Permian Capitan Reef Complex, West Texas. *Sedimentology* 66, 2605–
 871 2626. <https://doi.org/10.1111/sed.12615>
 872 Raiswell, R., Berner, R.A., 1986. Pyrite and organic matter in Phanerozoic normal
 873 marine shales. *Geochimica et Cosmochimica Acta* 50, 1967–1976.
 874 [https://doi.org/10.1016/0016-7037\(86\)90252-8](https://doi.org/10.1016/0016-7037(86)90252-8)
 875 Richardson, J.A., Keating, C., Lepland, A., Hints, O., Bradley, A.S., Fike, D.A., 2019.
 876 Silurian records of carbon and sulfur cycling from Estonia: The importance of
 877 depositional environment on isotopic trends. *Earth and Planetary Science Letters*
 878 512, 71–82. <https://doi.org/10.1016/j.epsl.2019.01.055>
 879 Rooney, A.D., Millikin, A.E.G., Ahlberg, P., 2022. Re-Os geochronology for the
 880 Cambrian SPICE event: Insights into euxinia and enhanced continental weathering
 881 from radiogenic isotopes. *Geology* 50, 716–720.
 882 <https://doi.org/10.1130/G49833.1>
 883 Saltzman, M.R., Ripperdan, R.L., Brasier, M.D., Lohmann, K.C., Robison, R.A.,
 884 Chang, W.T., Peng, S., Ergaliev, E.K., Runnegar, B., 2000. A global carbon
 885 isotope excursion (SPICE) during the Late Cambrian: relation to trilobite

886 extinctions, organic-matter burial and sea level. *Palaeogeography,*
 887 *Palaeoclimatology, Palaeoecology* 162, 211–223. [https://doi.org/10.1016/s0031-](https://doi.org/10.1016/s0031-0182(00)00128-0)
 888 [0182\(00\)00128-0](https://doi.org/10.1016/s0031-0182(00)00128-0)
 889 Saltzman, M.R., Young, S.A., Kump, L.R., Gill, B.C., Lyons, T.W., Runnegar, B., 2011.
 890 Pulse of atmospheric oxygen during the late Cambrian. *Proceedings of the*
 891 *National Academy of Sciences* 108, 3876–3881.
 892 <https://doi.org/10.1073/pnas.1011836108>
 893 Shields, G.A., Mills, B.J.W., 2017. Tectonic controls on the long-term carbon isotope
 894 mass balance. *Proc. Natl. Acad. Sci. U.S.A.* 114, 4318–4323.
 895 <https://doi.org/10.1073/pnas.1614506114>
 896 Sperling, E.A., Melchin, M.J., Fraser, T., Stockey, R.G., Farrell, U.C., Bhajan, L.,
 897 Brunoir, T.N., Cole, D.B., Gill, B.C., Lenz, A., Loydell, D.K., Malinowski, J.,
 898 Miller, A.J., Plaza-Torres, S., Bock, B., Rooney, A.D., Tecklenburg, S.A., Vogel,
 899 J.M., Planavsky, N.J., Strauss, J.V., 2021. A long-term record of early to mid-
 900 Paleozoic marine redox change. *Science Advances* 7.
 901 <https://doi.org/10.1126/sciadv.abf4382>
 902 Strauss, H., 1997. The isotopic composition of sedimentary sulfur through time.
 903 *Palaeogeography, Palaeoclimatology, Palaeoecology* 132, 97–118.
 904 [https://doi.org/10.1016/S0031-0182\(97\)00067-9](https://doi.org/10.1016/S0031-0182(97)00067-9)
 905 Tostevin, R., He, T., Turchyn, A.V., Wood, R.A., Penny, A.M., Bowyer, F., Antler, G.,
 906 Shields, G.A., 2017. Constraints on the late Ediacaran sulfur cycle from carbonate

907 associated sulfate. *Precambrian Research* 290, 113–125.
 908 <https://doi.org/10.1016/j.precamres.2017.01.004>

909 Tostevin, R., Mills, B.J.W., 2020. Reconciling proxy records and models of Earth's
 910 oxygenation during the Neoproterozoic and Palaeozoic. *Interface Focus* 10,
 911 20190137. <https://doi.org/10.1098/rsfs.2019.0137>.

912 Wang, X., Hu, W., Yao, S., Chen, Q., Xie, X., 2011. Carbon and strontium isotopes and
 913 global correlation of Cambrian Series 2-Series 3 carbonate rocks in the Keping
 914 area of the northwestern Tarim Basin, NW China. *Marine and Petroleum Geology*
 915 28, 992–1002. <https://doi.org/10.1016/j.marpetgeo.2011.01.006>

916 Wotte, T., Strauss, H., Fugmann, A., Garbe-Schönberg, D., 2012. Paired $\delta^{34}\text{S}$ data from
 917 carbonate-associated sulfate and chromium-reducible sulfur across the traditional
 918 Lower–Middle Cambrian boundary of W-Gondwana. *Geochimica et*
 919 *Cosmochimica Acta* 85, 228–253. <https://doi.org/10.1016/j.gca.2012.02.013>

920 Yan, D., Chen, D., Wang, Q., Wang, J., Wang, Z., 2009. Carbon and sulfur isotopic
 921 anomalies across the Ordovician–Silurian boundary on the Yangtze Platform,
 922 South China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 274, 32–39.
 923 <https://doi.org/10.1016/j.palaeo.2008.12.016>

924 Yang, A., Chen, B., Sun, Z., Tostevin, R., He, T., Chen, X., Chen, Jitao, Lu, M., Hu,
 925 C., Du, S., Chen, Jun, Jiao, W., Zhu, M., 2024. Shallow ocean deoxygenation
 926 drove trilobite turnover during the late Cambrian SPICE event. *Geology*.
 927 <https://doi.org/10.1130/G52200.1>

928 Zhan, S., Chen, Y., Xu, B., Wang, B., Faure, M., 2007. Late Neoproterozoic
929 paleomagnetic results from the Sugetbrak Formation of the Aksu area, Tarim basin
930 (NW China) and their implications to paleogeographic reconstructions and the
931 snowball Earth hypothesis. *Precambrian Research* 154, 143–158.

932 Zhang, P., Wang, Y., Zhang, X., Wei, Z., Wang, G., Zhang, T., et al., 2022. Carbon,
933 Oxygen and Strontium isotopic and elemental characteristics of the Cambrian
934 Longwangmiao formation in South China: paleoenvironmental significance and
935 implications for carbon isotope excursions. *Gondwana Research* 106, 174–90.
936 <https://doi.org/10.1016/j.gr.2022.01.008>.

937 Zhang, Y., Yang, T., Hohl, S.V., Zhu, B., He, T., Pan, W., Chen, Y., Yao, X., Jiang, S.,
938 2020. Seawater carbon and strontium isotope variations through the late Ediacaran
939 to late Cambrian in the Tarim Basin. *Precambrian Research* 345, 105769.
940 <https://doi.org/10.1016/j.precamres.2020.105769>.

941 Zhang, Y., Mills, B., He, T., Hu, X., Zhu, M. 2023. Modeling hyperthermal events in
942 the Mesozoic-Paleogene periods: a review. *Frontiers in Ecology and Evolution* 11,
943 1226349. <https://doi.org/10.3389/fevo.2023.1226349>.

944 Zhang, Y., Yang, T., Newton, R.J., Pan, W., Chen, Y., Yu, H., 2023. Seawater carbon
945 and strontium isotope variations in the eastern Tarim Basin during the Cambrian:
946 Implications for connection with the open ocean. *Journal of Asian Earth Sciences*
947 253, 105702. <https://doi.org/10.1016/j.jseaes.2023.105702>.

948 Zhang, Y., Mills, B., Newton, R., He, T., Roper, A., Yang, T., Zhu, M., 2025. Orbitally-

949 driven nutrient pulses linked to early Cambrian periodic oxygenation and animal
 950 radiation. *Geophysical Research Letters* 52, e2025GL118689.
 951 <https://doi.org/10.1029/2025GL118689>.

952 Zhang, Y., Zhu, M., 2025. Meta-analysis of the DOUNCE event (Shuram/Wonoka
 953 excursion): pattern, variation, causal mechanism, and global correlation. *Earth-*
 954 *Science Reviews* 261, 105000. <https://doi.org/10.1016/j.earscirev.2024.105000>.

955 Zhou, X., Chen, D., Dong, S., Zhang, Y., Guo, Z., Wei, H., Yu, H., 2015. Diagenetic
 956 barite deposits in the Yurtus Formation in Tarim Basin, NW China: Implications
 957 for barium and sulfur cycling in the earliest Cambrian. *Precambrian Research* 263,
 958 79–87. <https://doi.org/10.1016/j.precamres.2015.03.006>.

959 Zhou, Y., Pogge von Strandmann, P.A.E., Zhu, M., Ling, H., Manning, C., Li, D., He,
 960 T., Shields, G.A., 2020. Reconstructing Tonian seawater $^{87}\text{Sr}/^{86}\text{Sr}$ using calcite
 961 microspar. *Geology*. <https://doi.org/10.1130/g46756.1>

962 Zhu, M., Yang, A., Yuan, J., Li, G., Zhang, J., Zhao, F., Ahn, S.-Y., Miao, L., 2019.
 963 Cambrian integrative stratigraphy and timescale of China. *Science China Earth*
 964 *Sciences* 62, 25–60.

965 Zhu, M.-Y., Babcock, L.E., Peng, S.-C., 2006. Advances in Cambrian stratigraphy and
 966 paleontology: integrating correlation techniques, paleobiology, taphonomy and
 967 paleoenvironmental reconstruction. *Palaeoworld* 15, 217–222.