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Environmental controls on early Cambrian macroevolution: Insights from the Tarim Basin

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ABSTRACT

The terminal Ediacaran to lower Cambrian (538–521 Ma) documents the disappearance of Ediacaran soft-bodied biota and the diversification of early animals, including the emergence of small shelly fauna, archaeocyath sponges and trilobites. Despite extensive study, the role of oceanic oxygenation in macroevolutionary events across this interval remains unclear, with understanding hindered by limited constraints on temporal and spatial variability in geochemical conditions, both regionally and globally. Here, we report multi-proxy geochemical data (including organic carbon concentrations, carbonate and organic carbon isotopes, Fe speciation and redox sensitive trace elements) from three sections documenting different water-depths through the early Cambrian (Terreneuvian) Yurtus Formation of the Tarim Basin, North China. Our data reveal a highly dynamic oxygen minimum zone (OMZ), distinguished by a core of unstable ferruginous to dysoxic conditions, with peripheral dysoxic to oxic conditions that developed on the inner-outer shelf at different stages. The temporal and spatial extent of the OMZ appears to have been controlled by changes in productivity, driven by sea-level and climatic influences on upwelling. We expand on regional observations by considering published geochemical data from globally distributed successions across this interval, in addition to the lowest global occurrence of key fossil taxa. Our integration of regional and global geochemical datasets, alongside mechanistic insight from regional and global stratal stacking patterns, suggest that marine redox fluctuations responded dynamically to changes in upwelling driven by major sea level transgression and climate. These connected processes and palaeoenvironmental conditions formed the backdrop for the main phase of the Cambrian explosion.

Keywords: Redox conditions; OMZ; Early Cambrian; Tarim Basin, sea level

INTRODUCTION

The early Cambrian was a critical period of Earth history characterized by the radiation of animals (metazoans) and the disappearance of the Ediacaran biota across the Ediacaran-Cambrian (E-C) transition (Marshall, 2006; Zhu et al., 2019). The Fortunian and Stage 2 (≤538.8 Ma to ca. 521 Ma) witnessed a major phase of emergence and diversification of Cambrian-type small shelly fauna (SSF), and the widespread co-option of biomineralization (skeletonization) that was previously limited to the tubular cloudinid morphogroup and *Namacalathus* in the terminal Ediacaran Period (Steiner et al., 2007; Bowyer et al., 2023a). This interval also encompasses the phylum-level diversification of large-body bilaterian metazoans, and the emergence of all modern animal phyla in the so-called 'Cambrian Explosion' (Knoll and Carroll, 1999).

Early Cambrian metazoan diversification is commonly considered to have been triggered by enhanced ocean oxygenation (Chen et al., 2015). However, the temporal and spatial nature of ocean redox conditions through the early Cambrian is far from resolved. Some studies have argued that the deep ocean remained predominantly anoxic and ferruginous (Fe^{2+}-containing; Goldberg et al., 2007; Schröder and Grotzinger, 2007; Cai et al., 2015; Sperling et al., 2015) until at least Series 2 of the Cambrian, whereafter more expanded oxygenation occurred (Li et al., 2017; Dahl et al., 2019a). More recently, dynamic seawater redox conditions have been proposed, with distinct spatiotemporal variability (e.g., Wei et al., 2018; He et al., 2019). The available data support redox-stratified water column conditions characterized by oxic surface waters and mid-depth euxinia (free aqueous H_2S) in productive continental margin settings, overlying deeper ferruginous waters (e.g., Feng et al., 2014; Cai et al., 2015; Jin et al., 2016; Liu et al., 2024), or ferruginous/euxinic oxygen minimum zones

(OMZs) overlying oxic deeper waters (e.g., Guilbaud et al., 2018). OMZ-type conditions that reflect changes in the extent of denitrification above anoxic deeper waters have also been inferred (Hammarlund et al., 2017).

Uncertainties in the precise spatiotemporal nature and evolution of water column redox conditions ultimately preclude a detailed understanding of how the redox state of the early Cambrian ocean impacted biological evolution. While intervals of expanded anoxia may have exerted stress on marine ecosystems, marine redox fluctuations may have also contributed to pulses of diversification (e.g., Wood and Erwin, 2017; Wei et al., 2018). Spatiotemporal changes in paleoredox conditions linked to sea level change may also have driven speciation of some sessile shallow marine fauna on the Siberian Craton during the Terreneuvian to Series 2 (Zhuravlev et al., 2023). It is notable that the development of an OMZ-type model for the early Cambrian has only been possible due to the analysis of multiple sections representing bathymetric transects across individual basins (Hammarlund et al., 2017; Guilbaud et al., 2018). However, studies of the spatial distribution of OMZ-type conditions, their significance in terms of biological radiations during the early Cambrian, and the drivers for observed temporal variability in paleoredox conditions, remain highly limited.

Early Cambrian strata are well preserved on the Tarim Block, North China, and contain a rich SSF assemblage (Qian, et al., 2000; Yao et al., 2005), thereby providing an opportunity to better understand potential links between ocean redox conditions and the early radiation of metazoans. Here, we document the chemostratigraphy of the terminal Ediacaran to lower Cambrian Yurtus Formation, utilizing Fe speciation, major and trace element concentrations, total organic carbon (TOC), and carbonate and organic carbon ($\delta^{13}C$) isotopes. These data were collected from three sections (Sugaitebulake, Kungaikuotan and Shiairike) that represent different paleo-water depths from inner to outer shelf, thereby allowing a detailed exploration of the relationship between spatiotemporal variability in ocean redox conditions on the Tarim Block and concurrent bio-evolutionary change.

GEOLOGICAL BACKGROUND

The Tarim Block (Fig. 1A) is one of the oldest cratonic blocks in China. Following the Neoproterozoic break-up of Rodinia, the North Tarim lithosphere evolved from a rift to a passive continental margin basin (Yu et al., 2009). On the northwestern margin of the Tarim Basin, in the Aksu area (Fig. 1A), the Yurtus Formation records deposition in a continental margin setting, which was linked to the infant southern Tianshan Ocean to the north (Yu et al., 2009; Gao et al., 2022). Litho- and bio-stratigraphic studies and palaeogeographic reconstruction indicate an unrestricted marine shelf depositional environment (Dong et al., 2009; Yao et al., 2005). Pulsed basin subsidence during ongoing development of the North Tarim passive margin, in addition to the effects of 2nd-order (10–80 Myr) eustatic sea level rise across the terminal Ediacaran to lower Cambrian, resulted in at least two distinct multi-million year transgressive episodes and the development of open marine connectivity to the global ocean (Fig. 1B, Yu et al., 2009; Zhang et al., 2020; Zhou et al., 2021).

The Yurtus Formation unconformably overlies the Ediacaran dolostone-dominated Qigebulake Formation (Fig. 1C), and conformably underlies the Xiaoerbulake Formation, which consists of thin-bedded dolostones and fossiliferous layers containing trilobites (Yue and Gao, 1992). Despite significant lateral variability, the Yurtus Formation can be subdivided into three lithological units: (1) a lower unit comprising chert and interbedded shale with phosphatic nodules; (2) a middle unit of black shale with carbonate interbeds, passing to grey shale and carbonate alternations; and (3) an upper unit of thin-bedded carbonates, occasionally interbedded with calcareous shales (Fig. 1B).

The Sugaitebulake section (SGTB, Fig. 2A) is the only sampled section where carbonates are dominantly preserved as limestone. The lower unit is characterized by chert and shale, followed by interbedded limestone and chert/shale of the middle unit (Fig. 2A). Limestone beds thicken-upwards through the middle unit, while mudstone interbeds become thinner (Fig. 2A; Gao et al., 2022). The overlying upper unit transitions from nodular limestone to dolostone, with a transgressive surface marked by the re-appearance of thin calcareous siliciclastic interbeds (Fig. 2A; Zhou et al., 2014). At Kungaikuotan (KGKT, Fig. 2B), the lower unit of the Yurtus Formation comprises a basal chert horizon overlain by shale. Muddy dolostone intercalations mark the beginning of the middle unit, with the frequency of muddy dolostone and dolostone interbeds increasing upwards until the lithostratigraphy is dominated by thicker dolostone beds. The transition from muddy dolostone to interbedded dolostone with thin calcareous siliciclastic interbeds in the upper unit is interpreted to represent a transgressive surface (Fig. 2B). In the Shiairike section (SARK, Fig. 2C), the lower unit is composed of alternating beds of chert and shale (Fig. 2C), with an up-section decrease in the frequency of chert interbeds, and an increase in shale interbeds (Zhou et al., 2014). The appearance of thin dolostone interbeds marks the base of the middle unit, with an increase in the frequency of dolostone beds culminating in a thick-bedded dolostone-dominated upper unit. Thin calcareous siliciclastic interbeds in the upper unit are rare, which results in the transgressive surface being less pronounced (Fig. 2C).

Whilst the paleodepth of SGTB relative to KGKT is difficult to discern from bulk lithostratigraphy alone, regional paleobathymetric reconstructions that incorporate insights from outcrop and drill core suggest that SGTB represents the shallowest section, KGKT an intermediate-depth section, and SARK the deepest section (Zhu et al., 2018). The overall lithostratigraphic architecture is therefore consistent with thickening of the basal Yurtus siliceous-shale facies, in this area of the Tarim Basin, to the south and east with distance from SGTB (Fig. 1A; Zhou et al., 2014). This reconstruction also implies that limestones are restricted to carbonates of the shallowest section (SGTB, Yao et al., 2014; Zhu et al., 2018).

Given the extreme stratigraphic condensation (<30 m representing ≥15 Myrs), the Yurtus Formation is relatively understudied compared to similar-aged successions in South China and Siberia. However, biostratigraphic constraints provide useful insight into the approximate age of different levels within the Yurtus Formation. Small shelly fossils of the *Anabarites-Protohertzina* assemblage (SSF I), as well as acritarchs of the *Asteridium-Heliosphaeridium-Comasphaeridium* (AHC) assemblage, have been identified in the lower Yurtus Formation (Xiao and Duan, 1992; Yao et al., 2005), which together characterize the lower Fortunian Stage (Fig. 3, Maloof et al., 2010; Zhu et al., 2019).

The second SSF zone (SSF II), comprising the *Paragloborilus-Siphogonuchites* assemblage, is found in the middle-upper Yurtus Formation, consistent with an upper Fortunian to lower Stage 2 age. The lowest occurrence (LO) of the mollusk species *Aldanella attleborensis* in the middle Yurtus Formation (Qian and Xiao, 1984), allows the base of Cambrian Stage 2 to be approximated (Fig. 3, ca. 529.7 Ma based on lowest occurrence information on the northern Siberian Platform; Kaufman et al., 2012; Grazhdankin et al., 2020). Limestones of the SGTB section, which have not undergone syndepositional or later dolomitization, and are therefore primed for fossil preservation, record the lowest occurrence of *Aldanella* at 4.1 m above the base of the Yurtus Formation (Fig. 3, Table S1, Xiao and Duan, 1992). The stratigraphic position of *Aldanella* is particularly important for accurate temporal calibration of $\delta^{13}C_{carb}$ trends in the Tarim succession relative to the global chemostratigraphic composite (see below, Fig. 3).

The third SSF zone (SSF III), comprising the *Sinosachites-Lapworthella* assemblage, is found in the uppermost Yurtus Formation, and is consistent with an assignment to Stage 2. Furthermore, the *Lapworthella-Ninella-Cambroclavus* assemblage in the upper Yurtus Formation (Xiao and Duan, 1992) supports an upper Stage 2 to lower Atdabanian age (Yue and Gao, 1992; Steiner et al., 2007). The *Sunyidiscus, Ushbaspis and Kepingaspis-Tianshanocephalus* trilobite zones are also recognized in the overlying Xiaoerbulake Formation (Xiao and Duan, 1992), with the *Shizhudiscus Sugaitensis Chang* assemblage, which occurs near the base of the Xiaoerbulake Formation, representing the lowermost level of definitively Atdabanian-aged (ca. ≤521 Ma) strata. Hence, despite extremely condensed deposition, the entirety of the Yurtus Formation can be correlated to the Terreneuvian Series based on readily correlatable global biostratigraphic information (Fig. 3).

METHODS

Shale, chert and carbonate samples were collected from the SGTB, KGKT and SARK sections (Fig. 1). After removing weathered surfaces, veins and nodules, samples were crushed to <200 mesh and oven dried at 40°C.

Iron speciation

Operationally-defined pools targeting carbonate Fe (Fe_{carb}), ferric (oxyhydr)oxide Fe (Fe_{ox}) and magnetite Fe (Fe_{mag}) were analyzed at the University of Leeds following well-established procedures (Poulton and Canfield, 2005; Poulton, 2021). Only samples with total iron (Fe_T) >0.5 wt.% were selected for iron speciation analyses, following standard protocols (Clarkson et al., 2014). In brief,

Fe_{carb} was determined via a 48 h, 50°C extraction using a sodium acetate solution at pH 4.5. The Fe_{ox} pool was then extracted using a 50 g/L sodium dithionite and 0.2 M sodium citrate solution at pH 4.8. Finally, the Fe_{mag} pool was extracted via a 6 h, 0.2 M ammonium oxalate and 0.17 M oxalic acid solution. All extracts were analyzed for Fe by atomic absorption spectroscopy. Pyrite Fe (Fe_{py}) was extracted via a hot $CrCl_2$ distillation and calculated stoichiometrically from the sulfide extracted as Ag_2S (Canfield et al., 1986). Replicate analyses of international reference material WHIT (Alcott et al., 2020) yielded a relative standard deviation (RSD) of <5% for all Fe phases.

Major and trace element analyses

For major elements, ~50 mg of each sample was dissolved in 2 ml of hydrofluoric acid (HF), 5 ml of nitric acid (HNO_3), and 2-3 drops of perchloric acid ($HClO_4$), followed by analysis by inductively coupled plasma optical emission spectrometry at the China University of Geosciences (Beijing). Accuracy was monitored relative to international standards AGV-2, GSR-1 and GSR-5, with a RSD of <3% for all elements of interest. For trace element analyses (Mo, U, V, Mn and Co), sample powders were leached with 2 mol/L HCl, followed by dissolution with a mixed solution of HNO_3 and HF with a volume ratio of 3:1. Samples were then heated to dryness and re-dissolved in 3% HNO_3 prior to analysis using inductively coupled plasma-mass spectrometry at the China University of Geosciences (Beijing). Analytical precision monitored by standards AGV-2, BHVO-2, W-2, GSR-1 and GSR-3 was <5% for each element of interest.

We utilize major element concentrations to assess chemical weathering intensity, via the chemical index of alteration (CIA) proxy. CIA values were calculated as molar $[(Al_2O_3)/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where CaO* represents the CaO content of the silicate fraction only (Nesbitt and Young, 1982). However, given the potential for a high degree of error when applying this approach to carbonates, we only report CIA values for siliciclastics. Therefore, for our samples with low carbonate contents, CaO* was calculated after correction using P_2O_5 data (CaO* = mole CaO − mole P_2O_5 × 10/3), however, if the remaining number of moles was higher than that of Na_2O, then CaO* was assumed to be equivalent to Na_2O (McLennan, 1993). When applied to fine-grained sediments, diagenetic K-metasomatism (conversion of kaolinite to illite) should also be taken into consideration (Fedo et al., 1995). The addition of diagenetic K_2O to shale samples (K_2O_{corr}) was quantified in moles [m × Al_2O_3 + m × (CaO^* + Na_2O)]/(1–m), where m was calculated as K_2O/(Al_2O_3 + CaO^* + Na_2O + K_2O), and these K_2O_{corr} values were used in the calculation of CIA_{corr} values (Table S1; Fedo et al., 1995).

Enrichment factors (EFs) were calculated to reveal possible authigenic trace element enrichments. However, application of EF values to sediments rich in silica (as is the case here) is problematic, as elevated values are commonly obtained relative to siliciclastic sediments, due to the low detrital Al component that tends to characterise such chemical sediments (Tribovillard et al., 2006; Krewer et al., 2024). Here, we overcome this problem by initially calculating excess element concentrations, where UCC represents Upper Continental Crust (McLennan, 2000):

$$\mathrm{Element_{excess}} = \mathrm{Element_{sample}} - \left(\mathrm{Al_{sample}} \times \frac{\mathrm{Element_{UCC}}}{\mathrm{Al_{UCC}}}\right) \qquad (1)$$

To then allow direct comparison with established techniques for identifying different paleoredox conditions (e.g., Mo_{EF} vs U_{EF} crossplots; Tribovillard et al., 2012), we use these excess values to calculate revised EF values (EF^*) for our silica-rich sediments (Krewer et al., 2024; Li et al., 2025):

$$\mathrm{Element_{EF}}^* = \frac{\mathrm{Element_{excess}} + \mathrm{Element_{UCC}}}{\mathrm{Element_{UCC}}} \qquad (2)$$

This approach overcomes the problem of low Al contents in chemical sediments, and allows EF^* values to be directly compared to EF values calculated for siliciclastic sediments.

Total organic carbon contents and carbon isotope analyses

To determine total organic carbon (TOC) and organic carbon isotopes, ~200 mg of sample was treated twice with 6 N HCl overnight to remove carbonate minerals, after which the residue was washed with distilled water to dissolve any acid residue (until the pH was >5.0) and dried overnight at 40°C. TOC was then determined using a Euro-EA3000 elemental analyzer at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The accuracy and precision for TOC were <10% and <5%, respectively. Organic C ($\delta^{13}C_{org}$) and carbonate C ($\delta^{13}C_{carb}$) isotopes were determined using a Finnigan MAT-253 gas mass spectrometer at IGGCAS. For $\delta^{13}C_{carb}$ analyses, around 50 mg of sample powder was reacted with phosphoric acid at 72°C to generated CO_2 for analysis. Carbon isotope results are reported in standard δ-notation relative to the Vienna Pee Dee belemnite (V-PDB), with an analytical precision of <0.15‰.

RESULTS

Total organic carbon and carbon isotopes

Total organic carbon contents range from 0.02 to 10.91 wt.% (mean = 1.62 wt.%), with the highest values recorded in the lower part of the Yurtus Formation in all three sections (Fig. 2). Carbonate and organic carbon isotopes show broadly covarying stratigraphic trends through the KGKT and SARK sections, but no clear covariance is present through the SGTB section (Fig. 2).

In the SGTB section, $\delta^{13}C_{carb}$ values range from -5.81 to +0.80‰ (mean = -0.51‰), $\delta^{18}O_{carb}$ ranges from -11.17 to -3.39‰ (mean = -6.11‰), and $\delta^{13}C_{org}$ ranges from -34.13 to -27.99‰ (mean = -32.02‰). Carbonaceous chert and shale samples yield $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ values that are consistent with the magnitude and trends of interbedded or overlying limestone and dolostone samples. Low $\delta^{13}C_{carb}$ values at the base of the SGTB section increase in the overlying middle interval of interbedded shale and limestone, whereupon $\delta^{13}C_{carb}$ data show two minor positive excursions, separated by values near 0‰ (Fig. 2). Values of $\delta^{13}C_{carb}$ then decrease through the nodular limestone interval, before increasing in interbedded dolostones and shales above the transgressive surface near the top of the section (Fig. 2).

In the KGKT section, $\delta^{13}C_{carb}$ values range from -12.84 to +1.86‰ (mean = -3.81‰), $\delta^{18}O_{carb}$ ranges from -12.96 to -1.44‰ (mean = -7.55‰), and $\delta^{13}C_{org}$ ranges from -37.59 to -28.25‰ (mean = -33.43‰). Carbonaceous shales, cherts and interbedded dolostones show consistent stratigraphic trends in $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ through the section (Fig. 2). The most negative $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ data are recorded at the base of the section, whereafter scattered values show a gradual increase to a maximum near the base of the middle unit of muddy dolostone. There is a gap in data across the middle Yurtus Formation, but both $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ show another negative excursion in muddy dolostones and shales that overlie the transgressive surface (ca. 11–12 m). Values then increase progressively throughout the uppermost dolostone-dominated interval.

In the SARK section, $\delta^{13}C_{carb}$ values range from -9.83 to +3.06‰ (mean = -0.03‰), $\delta^{18}O_{carb}$ ranges from -14.80 to -3.55‰ (mean = -7.17‰), and $\delta^{13}C_{org}$ ranges from -36.13 to -23.94‰ (mean = -31.21‰). As with the SGTB and KGKT sections, carbonaceous shales, cherts and dolostones in the SARK section track consistent trends in $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ up-section (Fig. 2). Both $\delta^{13}C_{carb}$ and

$\delta^{13}C_{org}$ are low throughout the shale and chert-dominated lower Yurtus Formation, but show two prominent positive excursions through the middle and upper Yurtus Formation, reaching values of +3.06‰ and 1.58‰, respectively. The excursions are separated by a negative excursion down to -3.47‰ (Fig. 2).

Iron speciation and redox sensitive trace elements

Highly reactive Fe (Fe_{HR}), representing Fe phases that are potentially reactive towards dissolved sulfide in surface and near-surface environments (Canfield et al., 1992; Poulton et al., 2004), was calculated as the sum of Fe_{carb} + Fe_{ox} + Fe_{mag} + Fe_{py} (Poulton and Canfield, 2011). In the SARK section, all samples have Fe_{HR}/Fe_{T} ratios >0.38 (Fig. 2; see Supplementary Table S1 for all data). However, for the KGKT and SGTB sections, while most samples have Fe_{HR}/Fe_{T} ratios >0.38, a few samples from the middle of the Yurtus Formation have ratios that fall between 0.22-0.38, with one sample below 0.22 in the KGKT section (Fig. 2). All samples have Fe_{py}/Fe_{HR} ratios <0.6 (Fig. 2).

Redox sensitive trace element (RSTE) data are plotted as both enrichment factors and normalized to TOC (Fig. 2). When normalized to TOC, the data generally show considerable scatter, suggesting that redox conditions, rather than simply TOC content, exerted a strong control on RSTE drawdown to the sediments. Mo_{EF}^{*}, U_{EF}^{*} and V_{EF}^{*} values display broadly similar stratigraphic trends across the three sections, but with some notable differences (note that the enrichment factor data show similar trends to RSTE concentrations; see Table S1). The lower Yurtus Formation (Interval I; Fig. 2) is characterized by high RSTE EF^{*} values at KGKT and SARK (Fig. 2B, C), with Mo_{EF}^{*} ranging from 2.4 to 45.6 (mean 13.3), U_{EF}^{*} ranging from 2.1 to 41.2 (mean 10.1), and V_{EF}^{*} ranging from 1.3 to 28.9 (mean 6.4). By contrast, the SGTB section generally exhibits moderate enrichments, with Mo_{EF}^{*}

ranging from 1.2 to 10.3 (mean 2.7), U_{EF}^* ranging from 2.8 to 9.4 (mean 4.6), and V_{EF}^* ranging from 2.8 to 10.1 (mean 5.0). These RSTE EF^* values then decrease with increasing stratigraphic height in the lower Yurtus Formation (Interval II; Fig. 2) in the KGKT and SARK sections (with an increase to moderate values in the upper part of Interval II in the SARK section), while moderate values persist in the SGTB section.

The overlying Interval III (Fig. 2) is generally characterized by moderate RSTE enrichments at all three sites, although limited data are available for this interval at KGKT. Interval IV is not present in the interval sampled at SARK, but the base of Interval IV shows higher enrichments at both the SGTB and KGKT sections (Fig. 2). Manganese concentrations fluctuate considerably, with enrichments in the lower part of Interval I and throughout most of intervals II and III at SARK, and depletions throughout intervals I, II and lower Interval III at SGBT. Highly variable Mn_{EF} values occur in Interval I and the lower part of Interval II at the KGKT section, followed by general enrichments up-section (Fig. 2).

Upwelling proxies

Hydrographic conditions in the early Cambrian can be assessed based on Co (ppm) × Mn (wt%) values. Generally, sediments in upwelling systems are characterized by Mn and Co depletion, while sediments from restricted basins show elevated values. As a result, low Co × Mn (< 0.4 ppm.wt%) are typical for coastal upwelling settings (Böning et al., 2004), while typical restricted settings such as the Black Sea exhibit higher Co × Mn (> 0.4 ppm.wt%). All Co × Mn values during Interval I across the three sections are lower than 0.4 ppm.wt% (Fig. 6), suggesting extensive upwelling during the early to middle Fortunian, consistent with an open marine setting (Dong et al., 2009; Zhou et al., 2021). Values of Co × Mn show an increasing trend during Interval II (Fig. 6), with some larger than the 0.4 threshold (Fig. 6), indicating waning upwelling during the late Fortunian to early Stage 2. Co × Mn values decrease again during intervals III to IV (Fig. 6), supporting another interval of more intense upwelling. This trend is consistent with previous studies of the Yurtus Formation, which record upwelling in both the lower and upper part of the succession (Li et al., 2022; Zhang et al., 2020).

DISCUSSION

Diagenetic evaluation

We use a combination of thin section petrography and geochemical data to evaluate the extent of diagenetic alteration. Chert samples are largely homogeneous in their mineral distribution but contain scattered monocrystalline quartz grains (Fig. S1A), while shale/mudstone samples show well-developed parallel laminations, with lighter laminae composed primarily of micritic dolomite and calcite, and darker laminae dominated by clay minerals and organic matter (Fig. S1B). Most dolostone samples are composed of homogeneous fine-grained micritic matrix that shows little evidence for coarse recrystallization (Fig. S1C). Some chert and fine-grained carbonate samples yield well-preserved, filamentous cyanobacteria (Fig. S1D), possible sponge spicules and radiolarians (Fig. S1E), shell fragments (Fig. S1F), benthic red algae (Fig. S1G) and algal fragments (Fig. S1H). The fidelity of preservation visible in thin section suggests that these carbonates have undergone limited diagenetic alteration.

We also consider correlations between $\delta^{13}C_{carb}$ and geochemical indicators that are commonly inferred to reflect the pervasiveness of diagenesis. First, carbonates that have undergone extensive diagenetic alteration often yield elevated Mn/Sr ratios (Derry et al., 1994), and may also exhibit low $\delta^{18}O$ values (Kaufman et al., 1993). However, Mn enrichments may also be associated with syn-depositional redox conditions, and so these data should also be considered in stratigraphic context to reveal secular changes relative to other palaeoredox indicators. Second, pervasive diagenetic alteration during later-stage dolomitization may result in statistically significant covariations between $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$, $\delta^{13}C_{carb}$ and Mn/Sr, and/or $\delta^{13}C_{carb}$ and Mg/Ca (Marenco et al., 2008). All samples from the three sections have Mn/Sr <10 [with the majority of samples (80%) yielding Mn/Sr <5]. The majority of $\delta^{18}O_{carb}$ values are greater than -10‰ (Table S1), with the five samples with $\delta^{18}O_{carb}$ < -10‰ yielding Mn/Sr ≤1 (Table S1). There is no strong and statistically significant correlation between Mn/Sr and $\delta^{18}O_{carb}$ (Fig. S2A). In particular, samples of the Yurtus Formation with exceptionally low $\delta^{13}C_{carb}$ values near the base of each section (-12.8‰ to -9.8‰) also have very low Mn/Sr ratios of 0.02–0.3, and there is no systematic up-section relationship between Mn/Sr values and $\delta^{13}C_{carb}$ in any of the three sections (Fig. S2B). Moreover, cross-plots of $\delta^{13}C_{carb}$ versus Sr concentrations and Mg/Ca ratios show no significant, strong correlations (Fig. S2C, D). Whilst all carbonate samples have undergone some diagenesis, we consider the trends in $\delta^{13}C_{carb}$ data to primarily reflect long-term global trends in seawater composition.

Evaluation of CIA values

During chemical weathering, mobile elements (K, Na) are preferentially dissolved relative to immobile elements (e.g., Al), leading to elevated CIA ratios (Nesbitt and Young, 1982). Therefore, high CIA values reflect high chemical weathering under humid and warm climate conditions, while low CIA values indicate low chemical weathering and consequently reflect cool conditions (Nesbitt and Young, 1982). However, CIA values can be influenced by provenance composition, sedimentary recycling and K-metasomatism, which should be evaluated prior to application of CIA values (Fedo et al., 1995).

The distribution of major and trace elements can provide valuable information on sedimentary provenance (McLennan and Taylor, 1991). Crossplots of Zr vs. TiO_2 (Fig. S3A) and La/Sc vs. Th/Co ratios (Fig. S3B), as well as a La–Th–Sc ternary diagram (Fig. S3C), suggest that the Yurtus Formation was derived predominantly from felsic igneous rocks. Furthermore, during the Ediacaran to Cambrian transition, the Tarim Block evolved into a passive continental margin basin (Yu et al., 2009), permitting the Yurtus Formation to have developed within a relatively stable tectonic setting, which also supports a stable provenance composition. The crossplot of Zr/Sc vs. Th/Sc ratios (Fig. S3D) shows that most data are within the range of the first cycle of the parent rocks, indicating a primary control from the composition of the source rocks, rather than by the polycyclic reworking of sedimentary material (McLennan, 1993). Some samples from the SARK section are consistent with the trend reflecting transport recycling of their provenance rocks (Fig. S3D). Therefore, we present these samples with open circles in the CIA plot (Fig. 2C).

Diagenetic K-metasomatism (conversion of kaolinite to illite) should also be taken into consideration, especially for our fine-grained samples, as K-metasomatism may be a major diagenetic process in shales (Fedo et al., 1995). The extent of K-metasomatism can be identified using an $Al_2O_3 - (CaO^* + Na_2O) - K_2O$ (A-CN-K) ternary diagram (Fedo et al., 1995). The theoretical weathering trends of the source rocks should be parallel to the A–CN boundary (Fig. S4). Here, similar to a previous study of the Yurtus Formation (Li et al., 2022), deviation from the predicted weathering trends towards the K_2O apex on the A–CN–K diagram is observed, suggesting the effects of K metasomatism (Fig. S4). This can be corrected by projecting each data point back to its original (predicted) position on the A–CN–K diagram (Fedo et al., 1995). To minimize the effect of K metasomatism, we use CIA_{corr} (see above) to interpret the paleo-weathering intensity and climatic patterns.

Chronostratigraphy

The terminal Ediacaran through lower Cambrian record hosts numerous globally-recognized negative $\delta^{13}C$ excursions (e.g., the basal Cambrian negative carbon isotope excursion, '1n/BACE') and positive $\delta^{13}C$ excursions (2p-6p, II, III, IV; Maloof et al., 2010; Zhu et al., 2006, 2019; Topper et al., 2022; Bowyer et al., 2023a, 2023b; Yang et al., 2023a). When combined with available biostratigraphic information, these $\delta^{13}C$ data may therefore aid temporal correlations between the Tarim Basin and globally distributed sections (Fig. 3). The basal Cambrian GSSP at Fortune Head on the Burin Peninsula, Newfoundland, is defined at the level of the lowest occurrence of the ichnospecies *Treptichnus pedum* (Brasier et al., 1994). Globally distributed successions that have $\delta^{13}C$ chemostratigraphic utility (e.g., carbonate or mixed siliciclastic-carbonate successions), record the lowest occurrence of *T. pedum* coincident with peak 2p, or even later, suggesting that the 1n/BACE, by definition, is terminal Ediacaran in age (Nelson et al., 2023; Bowyer et al., 2023a, 2023b). Given the paucity of radiometric constraints and ongoing uncertainty in global correlation between ca. 538–533 Ma, the maximum age for the Ediacaran-Cambrian boundary is currently thought to be ca. ≤538 Ma (Nelson et al., 2022).

Highly negative $\delta^{13}C_{carb}$ values at the base of the Yurtus Formation at KGKT, SGBT and SARK (Figs. 2, 3) correlate with the 1n/BACE interval, and this is corroborated by the constituent Fortunian small shelly fossil assemblage found in the SGTB section (Yang et al., 2023b; Yao et al., 2014; Xiao and Duan, 1992). $\delta^{13}C_{carb}$ values in the basal Yurtus Formation at KGKT (as low as -12.8‰) and SARK (as low as -9.8‰) are generally lower than, or similar to, previously reported minimum values from the Yurtus Formation in other sections of the Tarim Basin (e.g., -9.8‰ in the Wushi phosphorite section, -7.7‰ in Dongergou section, -5.4‰ in Penglaiba section; Guo et al., 2017).

Subsequent to the BACE interval, values of $\delta^{13}C_{carb}$ generally increase in each section; a pattern which is mirrored in the global composite $\delta^{13}C_{carb}$ record of the Fortunian Stage (Fig. 3). Whilst confident $\delta^{13}C_{carb}$ correlation of the Yurtus Formation is partially obscured by extremely condensed deposition, the specific levels of fossil assemblages guide the most parsimonious temporal calibration when considering the global lowest occurrences of small shelly fossils based on published global chronostratigraphic schemes (Fig. 3; e.g., Bowyer et al., 2023a; Yang et al., 2023a).

The precise stratigraphic levels of reported fossil occurrences at SGTB are shown in Fig. 3, which emphasizes the utility of SSF occurrence data in informing accurate chemostratigraphic correlation. Specifically, the lowest documented occurrence of *Aldanella* corresponds to a stratigraphic height of 4.1 m in SGTB, coincident with $\delta^{13}C_{carb}$ values of <0.5‰. The lowest occurrence of *Aldanella* in global chronostratigraphic schemes occurs approximately coincident with $\delta^{13}C_{carb}$ peak 5p in both South China ('ZHUCE'; Steiner et al., 2020; Yang et al., 2023a) and the Siberian Platform (Grazhdankin et al., 2020), where $\delta^{13}C_{carb}$ values peak at >5‰ (Fig. 3). The absence of a significant positive $\delta^{13}C_{carb}$ excursion at this level in SGTB is either due to aliasing of $\delta^{13}C_{carb}$ data as a result of stratigraphic condensation, or diagenesis that has skewed the $\delta^{13}C_{carb}$ magnitude to more negative values but retained the overall trend in seawater composition recorded by the global composite record. In recognition of the influence of condensation on the regional $\delta^{13}C_{carb}$ record, only broad trends in $\delta^{13}C_{carb}$ throughout the Yurtus Formation, in addition to biostratigraphic constraints, are herein considered useful for informing best-fit correlation to the global chemostratigraphic composite (see Supplementary Materials and Fig. 3). Maximum $\delta^{13}C_{carb}$ values are achieved in the thicker SARK section, which we interpret to correspond with peak 5p (ZHUCE, Fig. 3). Peak 5p is then followed by a negative $\delta^{13}C_{carb}$ shift (labelled 5n in Fig. 3), which can be correlated across the Tarim Basin and globally, and is recorded during early transgression in sections of the Siberian Platform (Bowyer et al., 2023b). This chemostratigraphic correlation is consistent with the underlying lowest occurrence of *Aldanella* at SGTB, and with increasing SSF diversity in the overlying middle Yurtus Formation.

Small shelly fossil diversity increases dramatically in many successions across the Fortunian/Stage 2 boundary (e.g., Khomentovsky and Karlova, 1993), and this increase is also recorded in the middle to upper Yurtus Formation in other sections, including Shayilike, Linkuanggou and Xiaoerbulake that are proximal to SARK, and the Wushilinkuang section near KGKT (Fig. 3; Qian et al., 2009). The globally recognized 6p peak may be absent from isotope profiles of the upper Yurtus Formation, similar to the $\delta^{13}C_{carb}$ record across sections of South China (e.g., Ishikawa et al., 2008; Yang et al., 2023a). However, peak values at SGTB and SARK, in the absence of additional biostratigraphic information, may correspond with peak 6p or later Stage 2 positive $\delta^{13}C_{carb}$ values (Fig. 3). At present, this appears to be the most parsimonious correlation, as it is consistent with observed patterns of relative sea level change between each of the three sections, in addition to available biostratigraphic and chemostratigraphic data. The uppermost negative $\delta^{13}C_{carb}$ excursion in the Tarim Basin sections likely corresponds to the negative $\delta^{13}C_{carb}$ excursion in the aftermath of peak 6p on the global chemostratigraphic scale in middle-late Stage 2, and to the SHIyantou Carbon isotope Excursion (SHICE) in South China (Zhu et al., 2006; Maloof et al., 2010; Li et al., 2013). The appearance of the third, and most diverse, SSF assemblage in the uppermost Yurtus Formation recorded in the Xiaoerbulake, Linkuanggou, Wushilinkuang and Shayilike sections, then approximates to the upper boundary of Stage 2 (Qian et al., 2009; Maloof et al., 2010).

Reconstruction of paleo-redox conditions

Fe speciation has been widely applied to ancient sediments to evaluate oceanic redox conditions, and is based on extensive calibration in modern and ancient marine settings (Raiswell and Canfield, 1998; Raiswell et al., 2001; Poulton and Raiswell, 2002; Clarkson et al., 2014), the latter of which specifically includes the effects of diagenesis. Fe_{HR}/Fe_T ratios >0.38 are commonly indicative of water column anoxia, while values <0.22 suggest oxic depositional conditions, and values between 0.22-0.38 are considered equivocal (Poulton and Canfield, 2011). For anoxic samples, Fe_{py}/Fe_{HR} ratios >0.8 commonly occur under euxinic conditions, whereas ferruginous conditions are characterized by lower ratios (<0.6), with ratios between 0.6-0.8 considered equivocal (Poulton, 2021). As discussed in the literature (e.g., Poulton, 2021), Fe speciation is best utilized in combination with other indicators for water column redox chemistry, such as RSTE systematics. Therefore, to provide the most robust redox interpretation, we consider Fe speciation results alongside RSTE data.

Mn oxides are reduced under dysoxic-anoxic conditions, commonly resulting in sediment depletion relative to UCC (e.g., Algeo and Li, 2020). Under oxic conditions, V occurs as the vanadate ion ($H_2V(V)O_4^-$) and is deposited in sediments via adsorption onto Mn oxides. During Mn oxide reduction, the adsorbed V may be released from sediments (Emerson and Huested, 1991; Nameroff et al., 2002), resulting in V depletion under dysoxic conditions. By contrast, under anoxic conditions, vanadate is reduced to the highly surface-reactive vanadyl ion ($V(III)O_2^+$), which is commonly retained in the sediment (Emerson and Huested, 1991).

Uranium tends to be transported as uranyl carbonate complexes ($U(VI)O_2(CO_3)_3^{4-}$) under oxic conditions (Tribovillard et al., 2006), with U reduction occurring at the Fe(II)–Fe(III) redox boundary (Klinkhammer and Palmer, 1991). This reduction primarily occurs in anoxic sediments, promoting authigenic enrichments regardless of whether free sulfide is available (Klinkhammer and Palmer, 1991). Molybdenum is transported as the molybdate anion (MoO_4^{2-}) and is largely unreactive in oxic settings, with the main removal pathway to the sediments being via uptake by Fe-Mn (oxyhydr)oxide minerals (Bertine and Turekian, 1973). Under ferruginous conditions, the water column precipitation of Fe (oxyhydr)oxides or green rust (e.g., Zegeye et al., 2012) can promote moderate Mo enrichments by a particulate shuttle mechanism (e.g., Algeo and Tribovillard, 2009; Tribovillard et al., 2012). However, at elevated concentrations of free sulfide (>11 μM), molybdate is converted to particle-reactive thiomolybdate (Helz et al., 1996), potentially resulting in substantial Mo enrichment in the sediments (Emerson and Huested, 1991; Helz et al., 1996; Erickson and Helz, 2000).

To test the validity of our redox data and to provide preliminary insight, we initially consider general relationships between Fe_{HR}/Fe_T ratios and U_{EF} values across the three sections (Fig. S5), since both proxies require only anoxia to promote enrichments (e.g., He et al., 2022). The SGTB and KGKT sections are commonly enriched in both Fe_{HR} and U (Fig. S5), providing strong support for anoxic depositional conditions (e.g., He et al., 2022; Li et al., 2024). However, some samples, particularly for the SARK section, have elevated Fe_{HR}/Fe_T ratios, but enrichments in U are either small or absent

(Fig. S5). This signal may arise when Fe^{2+} is transported from anoxic ferruginous waters into oxic or dysoxic settings, promoting precipitation of Fe (oxyhydr)oxides (and hence Fe_{HR}/Fe_T enrichments), but no enrichment in U. We consider this nuanced behaviour in more detail below. For samples deposited under anoxic water column conditions, enrichments in both Fe_{py}/Fe_{HR} and Mo provide a robust indication of water column euxinia. Our samples show consistent behaviour between the two proxies, with low Fe_{py}/Fe_{HR} ratios and low to moderate Mo_{EF} values (Figs. 2 and 4) providing strong support for non-sulfidic water column conditions throughout the depositional setting.

Redox conditions at the Sugaitebulake section (inner shelf)

During intervals I and II, elevated Fe_{HR}/Fe_T ratios, combined with moderate enrichments in U and V, and depletions in Mn (Fig. 2A), suggest dominantly anoxic depositional conditions during the Fortunian to early Stage 2. However, generally low Mo_{EF} values (Fig. 2A) imply dysoxic water column conditions (Fig. 4A). These combined signals suggest that bottom waters were likely dominantly dysoxic, with anoxic conditions generally being restricted to porewaters at the sediment-water interface. These redox conditions generally persisted into middle Stage 2 (Interval III), with similar RSTE systematics (Figs. 2A and 4C). However, the decrease in Fe_{HR}/Fe_T ratios towards equivocal values, alongside decreasing U_{EF}^* and V_{EF}^* values (Fig. 2A), may imply that the water column became more oxygenated. These conditions continued into the late Stage 2 (Interval IV), but an increase in Fe_{HR}/Fe_T, combined with a major increase in U_{EF}^*, V_{EF}^* and Mo_{EF}^* values across a temporally-restricted zone at the bottom of Interval IV, suggests the development of anoxic ferruginous conditions (Figs. 2A and 4D).

Redox conditions at the Kungaikuotan section (mid shelf)

During Interval I, enrichments in Fe_{HR}/Fe_T, U_{EF}^*, V_{EF}^* and Mo_{EF}^* suggest that early to middle Fortunian water column conditions were dominantly anoxic and ferruginous (Figs. 2B and 4A). However, occasional enrichments in Mn (Fig. 2B), combined with relatively increased enrichments in Mo relative to U (Fig. 4A), suggest that the water column may have periodically become oxic, with Mo drawdown being enhanced via uptake by sinking Fe-Mn (oxyhydr)oxide minerals formed in the water column (Algeo and Tribovillard, 2009). This particulate shuttle mechanism becomes particularly pronounced during the late Fortunian to early Stage 2 (Fig. 4B), where fluctuating Mn contents, Fe_{HR}/Fe_T ratios and RTSE concentrations suggest unstable dysoxic to oxic water column conditions (Interval II, Fig. 2B).

Subsequently, during the upper part of Interval III (middle Stage 2), the RSTE data suggest that fluctuating dysoxic-oxic conditions continued, finally giving way to anoxic ferruginous conditions in the lower part of Interval IV (Figs. 2B and 4C), coincident with ferruginous conditions documented at SGTB. During Interval IV, however, a subsequent progressive transition to more persistently oxic conditions appears to have occurred, as indicated by relatively low U_{EF}^*, V_{EF}^* and Mo_{EF}^* values, as well as Mn_{EF}^* values that plot close to the UCC value (Fig. 2B). Again, relatively elevated Mo_{EF}^* values suggest a partial control from drawdown via the particulate shuttle mechanism (Fig. 4D).

Redox conditions at the Shiairike section (outer shelf)

During the early-middle Fortunian (Interval I), elevated Fe_{HR}/Fe_T ratios (>0.38), combined with high U_{EF} and V_{EF} values, suggest dominantly anoxic depositional conditions at SARK. Low Fe_{py}/Fe_{HR} ratios suggest ferruginous, rather than euxinic, water column conditions (Poulton and Canfield, 2011), which is consistent with the data dominantly plotting in the non-sulfidic field on a Mo_{EF} vs U_{EF} crossplot (Fig. 4A; Algeo and Tribovillard, 2009; Tribovillard et al., 2012). However, two samples in the lower half of Interval I have elevated Mn contents (Fig. 2C), implying that the water column may have periodically transitioned to a fully oxic state.

During the late Fortunian to early Stage 2 (Interval II), Fe_{HR}/Fe_T ratios remain elevated, but U_{EF}^*, V_{EF}^* and Mo_{EF}^* values initially decrease to low levels below the upper part of Interval II (Fig. 2C), with the data plotting in the oxic zone on a Mo_{EF}^* vs U_{EF}^* crossplot (Fig. 4B). These geochemical signals suggest that Fe^{2+} was transported from nearby anoxic waters and oxidized to Fe (oxyhydr)oxides in the oxic water column (e.g., Scholz, 2018), which is supported by similar enrichments in Mn (Fig. 2C). Towards the top of Interval II, relatively minor enrichments in U and V, coupled with fluctuations in Mn_{EF}^* values (Fig. 2C), suggest that the water column likely fluctuated between fully oxic and dysoxic.

Persistent oxic (potentially occasionally dysoxic) conditions then developed during middle Stage 2 (Interval III), as indicated by low U_{EF}^*, V_{EF}^* and Mo_{EF}^* values (Figs. 2C and 4C). Enrichments in Fe_{HR}/Fe_T ratios and Mn_{EF}^* values again suggest oxidation of reduced Fe and Mn transported from nearby anoxic or dysoxic waters. Similar geochemical signals (Figs. 2C and 4D) suggest that these conditions persisted through the middle part of Stage 2.

Synthesis: A redox-environmental model for the early Cambrian Tarim Basin

Our consideration of redox dynamics through the three sections demonstrates that a fluctuating oxygen minimum zone (OMZ)-type setting developed during the early Cambrian (Fig. 5). This OMZ appears to have expanded and contracted, and varied in reducing intensity, likely in response to sea level and productivity changes, which we explore in more detail below.

During the early Fortunian, the dysoxic water mass at the edge of the OMZ initially expanded on the inner and outer shelf, while the extent of ferruginous anoxia fluctuated in the upper and lower part of the OMZ (Fig. 5A). This redox regime may have been driven, at least in part, by transgression (Figs. 1, 7A; Yao et al., 2014; Zhang et al., 2020), which likely brought nutrient-rich water to the shelf, resulting in relatively high productivity and organic export (Fig. 2; Chen et al., 2019). However, the precise redox structure likely reflects a balance between both upwelling and continental weathering nutrient sources.

Although the data show considerable scatter, CIA values are particularly low during Interval I (57 ± 9%), with some indication of a progressive increase throughout this interval, particularly in the KGKT section (Fig 2B). This increase in chemical weathering intensity is consistent with the suggestion that initial marine transgression during the early Cambrian was accompanied by a progressively warming climate (e.g., Hearing et al., 2018; Zhang et al., 2020). Nevertheless, generally low CIA values in the lower Yurtus Formation are consistent with relatively low chemical weathering intensity on the continents, which may be due to a relatively cool regional climate. This is consistent with suggestions that the lower part of the Yurtus Formation records a low terrigenous input due to colder climatic conditions relative to the upper part (e.g., Li et al., 2022; Zhang et al., 2020). Other evidence for a cool climate during the terminal Ediacaran to lower Fortunian includes contemporaneous glacial diamictites identified in North China, and elsewhere, although uncertainty remains regarding the isochroneity of glacial deposition in this interval (Chen et al., 2020; Zhang et al., 2021). A cool climate would be expected to provide a relatively diminished (but progressively increasing) influx of nutrients (e.g., P) from continental weathering. By contrast, the relatively cool climate through most of this interval would be expected to promote enhanced upwelling (Zhang et al., 2020; Yao et al., 2014; Yu et al., 2009), and hence we speculate that the relatively intense reducing conditions during Interval I (Fig. 5), including their focus in shallower water regions of the shelf, likely dominantly reflects enhanced upwelling of nutrient-rich deeper waters. Prevalent upwelling is supported by the generally lower Co × Mn values during Interval I across the three sections (Fig. 6).

The Tarim Block underwent post-rift subsidence during the E-C transition (Dong et al., 2009), and the stratigraphic expression of eustatic transgression is therefore expected to have been overprinted, to some degree, by relative sea level change associated with pulsed basin subsidence (Yu et al., 2009). However, as noted above, deposition of the Yurtus Formation broadly archives lower Cambrian 2^{nd}-order eustatic sea level rise, equivalent to the Sauk megasequence of Laurentia (Sloss, 1963). Terreneuvian third-order sequences (<5 Myr duration) have also been identified in stratal stacking patterns of the Siberian Craton (e.g., Bowyer et al., 2023b), and in lower Cambrian deposits of South China (e.g., Zhu et al., 2019). The condensed SGTB and KGKT sections may similarly record at least two nested 3^{rd}-order sequences, broadly expressed as decameter-scale stacking patterns of shallowing-upward lithofacies (Fig. 2), which can be further subdivided into a hierarchy of small-scale (centimeter to decimeter scale) sequences that are associated with regional basin subsidence and shorter-term climatic variability.

As sea-level decreased through the first 3^{rd}-order cycle during the late Fortunian to early Stage 2 (Fig. 1; Yao et al, 2014; Zhang et al., 2020), the spatial extent of the OMZ contracted, with anoxic waters at the heart of the OMZ giving way to dysoxic-dominated conditions (Fig. 5B). This was likely in response to lower rates of primary productivity, as indicated by TOC contents and higher Co × Mn values (Figs. 2, 6). The CIA values are generally high during this interval (63 ± 11%), but the trends are rather variable (Fig. 2). The SGTB and KGKT sections show the least scatter in the CIA data, perhaps reflecting the most robust chemical weathering signal, with the former shows an initial decrease in CIA values, followed by a subsequent increase through the upper part of Interval II (Fig. 2). The KGKT section does not show a clear signal (Fig. 2), which may be attributed to the sparse sample collection in Interval II (Fig. 2B). A jump to generally higher values is also apparent in the SARK section, but they scattered, which could have been affected by sedimentary recycling (Figs. 2C and S3D). These general trends are consistent with short-lived climate cooling and widespread regression during lower Stage 2, at the peak of $\delta^{13}C_{carb}$ 5p (Ishikawa et al., 2008). Indeed, global cooling at this time has been suggested to result from CO_2 drawdown associated with increased organic carbon burial, which is manifest as increasing $\delta^{13}C_{carb}$ up to peak 5p (Figs. 2 and 3; Ishikawa et al., 2008). The cooling climate would have limited the chemical weathering of nutrients, and while upwelling may have been somewhat enhanced at the peak of regression, the overall delivery of nutrients was only sufficient to maintain dysoxic, rather than fully anoxic, conditions in the Tarim Basin (Fig. 5B).

Successions deposited during middle Stage 2 record $\delta^{13}C_{carb}$ peak 6p (e.g., Morocco, and some sections of the Siberian Platform), which may also have been deposited during a 3rd-order eustatic sequence (Fig. 3; Braiser, 1990; Zhang et al., 2020; Bowyer et al., 2023b). Peak 6p may be preserved in the SGTB and SARK sections (Fig. 3), but the lithostratigraphic expression of a distinct 3rd-order sea level cycle in this interval is not clearly preserved in the Tarim Basin (Fig. 2). At this time, the OMZ appears to have further weakened, culminating in the development of fully oxic conditions towards the top of the SARK section (Fig. 5C).

The lower part of the subsequent 3rd-order sequence, immediately above the transgressive surface at SGTB and KGKT, records the redevelopment of a relatively small ferruginous OMZ core, but conditions were otherwise dominantly dysoxic (Fig. 5D). Relatively high chemical weathering is indicated by CIA values that are generally high (87 ± 8%), with a particularly strong influx of nutrients from enhanced chemical weathering resulting in shallowing of the OMZ. Whilst the upwelling flux of nutrients may have been relatively weak due to sluggish circulation under a relatively warm climate, short-lived upwelling may also have been induced during transgression at the base of this 3rd-order sequence, as indicated by low Co × Mn values in intervals III and IV (Fig. 6). Sea level fall is also recorded through late Stage 2 in the Tarim Basin (Fig. 1), which may reflect shallowing near the top of a 3rd-order sequence given that an isochronous sequence is also preserved on the Siberian Platform from 6p/7p to IV (see correlations in Bowyer et al., 2023b; Zhuravlev et al., 2023). In the Tarim Basin, the OMZ appears to have shallowed during late Stage 2 (Fig. 5D).

Global sea level cycles, paleoredox and macroevolutionary patterns

Our redox reconstruction for the Tarim Basin builds upon more recent evidence for the development of OMZ-type conditions in the early Cambrian (Hammarlund et al., 2017; Guilbaud et al., 2018), but provides new insight into regional OMZ chemistry, as well as a more nuanced evaluation of OMZ dynamics and links to biological evolution, and local and eustatic sea level change. Specifically, Guilbaud et al. (2018) found evidence for a more reducing OMZ setting in the Baltic Basin from the Fortunian stage though to the middle Cambrian Stage 5. Here, mid-depth settings were characterized by fluctuating euxinic and ferruginous anoxia, and this redox structure was linked to the distribution of small carbonaceous fossils in oxic inner- and outer-shelf settings and ferruginous mid-shelf environments. Hammarlund et al. (2017) found evidence for a progressive shift from euxinic to oxygen-depleted conditions during deposition of the younger (~518 Ma) Yu'anshan Formation of Yunnan, China. This formation includes the Chengjiang biota, which appears to have been deposited under oxygen-depleted mid-depth waters, with deeper waters that were assumed to have been anoxic (Hammarlund et al., 2017).

By contrast, the highly dynamic OMZ-type setting we document for the early Cambrian Tarim Basin was dominantly characterized by relatively mild reducing conditions, with dysoxic conditions around a ferruginous core (Fig. 5). Indeed, although we find no evidence for ferruginous conditions during the late Fortunian to early Stage 2 (Fig. 5B), it is possible that a ferruginous core existed between our sample localities at this time as well. Significantly, however, the intensity of reducing conditions appears to have declined with time, alongside a general retraction in the overall spatial extent of the OMZ (Fig. 5). Moreover, the most reducing conditions are recorded during 3rd-order transgressions (Figs. 3, 7), which may point to a common mechanism for regional oxygen depletion associated with enhanced productivity driven by pulsed nutrient upwelling. We expand upon this observation below, by considering a compilation of published data that reflect changing global paleoredox conditions alongside patterns of global macroevolution from the terminal Ediacaran to Cambrian Stage 3.

The timing of multiple shallow marine oxygenation events that punctuate the Cambrian from middle Stage 2 to Stage 4 have been inferred from patterns of $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ (sulfur isotopic composition of carbonate associated sulfate) in Siberian Platform carbonates (He et al., 2019). Co-occurring increases in $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ are interpreted to have resulted from the progressive burial of organic carbon and pyrite under reducing water column conditions (He et al., 2019). This increasing reductant burial would have resulted in a progressive increase in atmospheric oxygen concentrations, resulting in shallow marine oxygenation events (OOEs) at peaks in $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$. These peaks are followed by decreasing $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ that reflect expanding oxygenation and a corresponding reduction in the areal extent of reducing conditions conducive to organic carbon and pyrite burial, which would slow/stifle atmospheric oxygenation (He et al., 2019).

Here, we temporally calibrate additional published $\delta^{34}S_{CAS}$ data throughout the Fortunian to lower Stage 2 (Fig. 7C, Table S2, Loyd et al., 2012; Dahl et al., 2019). This compilation clearly shows that, whilst regional differences in the magnitude of $\delta^{34}S_{CAS}$ data exist, the general pattern of co-occurring trends in $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ extends down to at least the base of Stage 2 (Fig. 7C). By contrast, positive correlation between $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ is less apparent in the Fortunian, across the interval that records recovery from the 1n/BACE and increasing $\delta^{13}C_{carb}$ in advance of peak 5p (Fig. 7B). A similar decoupling of $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ throughout the Botoman-Toyonian is hypothesized to have resulted from a decrease in the marine sulfate reservoir and expanded shallow marine anoxia (He et al., 2019).

Globally-distributed Fortunian strata record the initiation of transgressive cratonic flooding coincident with the base of the Sauk megasequence (Sloss, 1963). This interval is also characterized by a global episode of phosphorite deposition, and widespread phosphatic preservation of SSFs (Cook, 1992). Our Tarim Basin geochemical data, in addition to global compilations of Fe speciation (Fig. S6, Table S2) and $\delta^{34}S_{CAS}$ data (Fig. 7C), strongly suggest that Fortunian phosphogenesis was promoted under globally widespread shallow marine ferruginous anoxia, where P was likely sourced from both organic matter and adsorption to Fe minerals, similar to later Series 2 to 3 phosphatic deposits of Australia (Creveling et al., 2014).

The onset of 2nd-order transgression may have been driven, in part, by flattening global hypsometry associated with circum-Gondwana subduction (Tasistro-Hart and Macdonald, 2023), and coincides with geochemical and stratigraphic evidence for cool climatic conditions. We suggest that the combination of major transgression during cool climatic conditions in the Fortunian may have primed shelf environments for enhanced nutrient upwelling, which fueled primary productivity, drove expanded ferruginous anoxia, and cultivated conditions that were ideally suited to widespread phosphorite deposition. Global flooding of shallow platform environments during the Sauk transgression, in combination with anoxic expansion, allowed for the progressive burial of organic carbon and pyrite that culminated in the major shallow marine OOE at peak 5p (Fig. 7).

This interval also documents a major diversification of SSFs associated with the appearance of a wide variety of skeletal Cambrian taxa (Maloof et al., 2010). Evolutionary innovations that are archived by the multitude of Fortunian taxa therefore emerged during an interval of global redox instability characterized by frequent expansion and contraction of anoxic-dysoxic OMZs into shallow marine environments. The pattern of rapid diversification and oscillating paleoredox conditions throughout the Fortunian may be consistent with hypotheses that invoke anoxia as a driving mechanism for morphological novelties that were subsequently co-opted as evolutionary innovations (Wood and Erwin, 2017). Gradual shallowing of Cambrian environments through 3rd-order sequences correspond with waning nutrient upwelling (Figs. 5B, C, 7D-F) and OOEs that correspond with peak $\delta^{13}C_{carb}$ (Fig. 7B-D). The OOE at peak 5p approximately coincides with the lowest global occurrence of hyoliths and mollusks, including *Aldanella* and *Watsonella* (e.g., Grazhdankin et al., 2020; Yang et al., 2023a).

In sum, the integration of regional and global geochemical data suggests that the evolutionary innovations of the Fortunian were promoted under redox and nutrient regimes that developed in response to tectonically-induced transgression and prevailing climatic conditions. An increase and stabilization of global temperatures in late Stage 2, as suggested by elevated CIA values in the upper Yurtus Formation (Fig. 2), in addition to phosphate oxygen isotopes of eastern Avalonian SSFs (Hearing et al., 2018), may have stifled upwelling of anoxic waters and created favorable shallow marine conditions conducive to habitation by skeletonizing fauna (Fig. 4, 7C, D). Increasing stability of paleomarine redox conditions may also be inferred by the longer duration of oxic episodes recorded from the base of Stage 2 (Fig. 7D). These longer-lived oxic pulses, in turn, promoted increasing metacommunity complexity in shallow marine Cambrian ecosystems (e.g., Zhuravlev et al., 2022).

CONCLUSIONS

We present new geochemical data from the Tarim Basin that constrain paleoredox and climate throughout the terminal Ediacaran to upper Stage 2 of the Cambrian. Iron speciation and redox sensitive trace element data, when considered in the context of basin-wide stratal stacking patterns, reveals a consistent pattern of paleoredox conditions that developed in response to sea level change. These data suggest that the extent and strength of reducing conditions that characterized the core of an OMZ responded directly to transgression-induced nutrient upwelling into the Tarim Basin. The integration of paleontological data from the Tarim Basin, when considered in light of available global biostratigraphic constraints, indicates that the most extensive and long-lived episode of expanded OMZ anoxia in the Tarim Basin occurred during the Fortunian. This anoxic expansion was driven by nutrient upwelling, which was enhanced at the onset of global 2^{nd}-order transgression during cool climatic conditions. A subsequent interval of basin-wide anoxia is also recorded during transgression, but is associated with a 3^{rd}-order sequence. The development of expanded OMZ conditions was therefore consistently associated with transgression-induced nutrient upwelling.

Temporally calibrated global $\delta^{13}C_{carb}$, $\delta^{34}S_{CAS}$ and Fe-speciation data further support a dominant driver for globally-widespread nutrient upwelling-driven anoxia and phosphogenesis during 2nd and 3rd-order eustatic transgressions. Together, these data provide a common mechanism for widespread development of anoxic conditions associated with sea-level change.

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FIGURE CAPTIONS

Figure 1. Geological details and geographic position of the Yurtus Formation in the Tarim Basin. (A)

Geological map of the Tarim Basin (modified after Zhou et al., 2014); (B) Stratigraphy of the Lower Cambrian Yurtus Formation and sea level curve (modified after Zhou et al., 2014; Zhu et al., 2019); (C) Paleo-bathymetric locations of the Kungaikuotan (KGKT), Sugaitebulake (SGTB) and Shiairike (SARK) sections (modified after Gao et al., 2022).

Figure 2. Lithostratigraphy, and stratigraphic variability in $\delta^{13}C$, TOC, redox and climate proxies in the Yurtus Formation, Tarim Basin. (A) The Sugaitebulake section (SGTB); (B) The Kungaikuotan (KGKT) section; (C) The Shiairike (SARK) section. Open circles on the CIA plot in the SARK section represent those affected by the polycyclic reworking of sedimentary material. The basal dolostone in the lithostratigraphic columns in each section is the Qigebulake Formation. Vertical dashed lines in each column mark key threshold values for Fe speciation and redox-sensitive elements documented in the text. I, II, III and IV correspond to: the early to middle Fortunian (I), late Fortunian to early Stage 2 (II), and middle to late Stage 2 (III-IV).

Figure 3. A possible model for the chemostratigraphic and biostratigraphic correlation of the Yurtus Formation with the global composite record. Global composite $\delta^{13}C_{carb}$ curve with lowest fossil occurrence information and summarized biotic diversity, anchored by available radiometric ages (after compilations of Bowyer et al., 2023a, b, and references therein). Note lowest known global occurrence of *Aldanella* calibrated during $\delta^{13}C_{carb}$ peak 5p, beneath radiometric age of 529.7 Ma in the Olenek Uplift of the Siberian Platform (Kaufman et al., 2012; Grazhdankin et al., 2020). Published fossil occurrence information for the Sugaitebulake section is shown, tied to absolute stratigraphic height relative to $\delta^{13}C_{carb}$ data reported herein, with *Aldanella* recovered at 4.1 m above the base of

the Yurtus Formation (Xiao and Duan, 1992).

Figure 4. Mo_{EF}* versus U_{EF}^* cross plot for the Kungaikuotan (KGKT), Sugaitebulake (SGTB) and Shiairke (SARK) sections during early Fortunian (A), middle to late Fortunian (B), early Stage 2 (C), and late Stage 2 (D). Cross plot is modified from Algeo and Tribovillard (2009) and Tribovillard et al. (2012).

Figure 5. Schematic representation of a dynamic OMZ model for the early Cambrian Tarim Block. The dotted lines indicate the OMZ range, with possible expanded direction shown by different arrows. The one-way arrows present the expanding direction while the double-sided arrows for the fluctuant redox conditions.

Figure 6. Co (ppm) × Mn (wt%) values at the Sugaitebulake (SGTB), Kungaikuotan (KGKT) and Shiairke (SARK) sections. Dashed line indicates the threshold of 0.4 ppm.wt% to differentiate upwelling from a restricted setting (Sweere et al., 2016).

Figure 7. Summarized terminal Ediacaran to Cambrian Stage 3 biotic diversity (A) and compiled and temporally calibrated $\delta^{13}C_{carb}$ data (B), after Bowyer et al. (2023b). (C) Temporally calibrated $\delta^{34}S_{CAS}$ data from multiple sources (Table S2). (D) Hypothesized average global redox state after modelling results of $\delta^{13}C_{carb}$ and $\delta^{34}S_{CAS}$ data of He et al. (2019). (E) Global 2nd and 3rd-order sequences from multiple sources (e.g., Tasistro-Hart and Macdonald, 2023; Bowyer et al., 2023a). (F) Schematic paleoredox reconstructions of the Tarim Basin after data and interpretations herein.

[1]Supplemental Material. *[Tables S1-S2 and Figures S1-S6]*. Please visit https://doi.org/10.1130/XXXX to access the supplemental material, and contact editing@geosociety.org with any questions.