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High-resolution geochemical evidence for oxic bottom waters in three Cambrian Burgess Shale-type deposits

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ABSTRACT

The Cambrian radiation of complex animals is a fundamental event in the history of life on Earth. Much of our understanding of this event is made possible through the study of exceptionally preserved fossils in Burgess Shale-type (BST) deposits. Based on bioturbation levels in BST deposits, they are often interpreted as representing restricted oxygen settings. This study tests the low-oxygen interpretation through analysis of geochemical paleoredox proxies and bioturbation levels in three BST deposits: the early Cambrian Maotianshan Shale (China), the middle Cambrian Wheeler Shale (USA), and the middle Cambrian Spence Shale (USA). Results from 96 samples show fine-scale geochemical evidence for oxic bottom water conditions during the deposition of these three BST deposits. Trace element paleoredox indices (PI) give consistent oxic signals in all three shales. In addition, total organic carbon (TOC) and total sulfur (TS) levels in the Spence Shale are extremely low. The average C/S ratio is 3.1, comparable to values for modern oxic marine water. Bioturbation levels in all three shales are low, with rare development of minimal to moderate horizontal bioturbation. While short-term oxygen fluctuations, or poikiloaerobic conditions, could still have sporadically existed in these settings, this study shows that these BST deposits were deposited in a dominantly oxic paleoredox setting. Evidence for low bioturbation levels coupled with paleoredox geochemistry indicative of oxic bottom waters suggests that pervasive exaerobic conditions, with an oxic water column positioned above oxygen-depleted sediment pore waters, may have existed in many Cambrian BST deposit paleoenvironments.

1. Introduction

The Cambrian radiation of animals contains the earliest definitive evidence for macrophagous predation, widespread skeletonization, intense deep burrowing into the seafloor, and macroscopic sense organs (e.g. Gould, 1989; Seilacher and Pflüger, 1994; Bottjer et al., 2000; Plotnick et al., 2010; Erwin et al., 2011). Exceptionally preserved fossils in Burgess Shale-type (BST) deposits provide key insight into this critical event (e.g. Caron et al., 2014). These deposits provide evidence of soft tissues that is typically missing from the normal shelly fossil record and is more common during the early and middle Cambrian than later in the Phanerozoic (Allison and Briggs, 1993). Because of limited or absent evidence for bioturbation in BST deposits, they are often interpreted as representing low-oxygen or anoxic settings (e.g. Butterfield, 2003). This oxygen-limited interpretation guides most studies on the preservation mechanisms of animal fossils in BST deposits and the evolutionary paleoecology of Cambrian radiation animals in general (e.g. Gaines and Droser, 2003; Gaines, 2014). This study tests this oxygen-restricted hypothesis through systematic analysis of geochemical paleoredox proxies and bioturbation levels in three Cambrian BST deposits: the Maotianshan Shale of Yunnan Province, China, the Wheeler Shale of Utah, USA, and the Spence Shale of Idaho and Utah, USA.

The high-resolution nature of the geochemical data (5-cm to 1-cm scale) utilized in this study represents sampling on a finer scale than used in previous studies of comparable Cambrian BST deposits. McKirdy et al. (2011) examined the paleoredox geochemistry of the early Cambrian Emu Bay Shale (Australia) with 24 samples over 7.1 m of strata, with a minimum distance of 15 cm between sampling intervals and an average of 29.6 cm. Powell (2009) analyzed 27 samples from the lower to middle Cambrian Kinzers Shale (USA) over about 20 to 50 m of strata. The methodology of Powell et al. (2003) in examining the paleoredox geochemistry of the middle Cambrian Burgess Shale (Canada) suggests that sampling occurred on the decimeter-to-meter scale.

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This previous work found evidence for oxic conditions in the Emu Bay and Burgess Shales and oxic to dysoxic conditions for the Kinzers Shale (Powell et al., 2003; Powell, 2009; McKirdy et al., 2011). Criticism of this work has centered on the coarse sampling intervals and the argument that oversampling of event beds has "diluted" the trace element signal (Gaines and Droser, 2010; Gaines, 2014). The methodology of this study addresses these criticisms through fine-scale sampling and incorporation of both background and event beds in its samples. The paleoredox geochemistry dataset presented here is therefore the highest resolution thus far collected from any BST deposits.

2. Geologic setting

2.1. Maotianshan shale

The early Cambrian (Series 2, Stage 3) Maotianshan Shale is the middle member of the lower Cambrian Yuanshan Formation of Yunnan Province, southwestern China (Chen and Zhou, 1997). The Yuanshan Formation is a 150 m thick sequence of shallowing upward siliciclastics that likely represents deposition in a shallow, tidally influenced marine shelf setting (Chen and Zhou, 1997; Babcock et al., 2001). The Maotianshan Shale preserves BST fossils and features many storm-generated sedimentary structures such as graded bedding, ripple marks, tool marks, and flute casts (Hagadorn, 2002). Exceptional fossils in the Maotianshan Shale are generally preserved in beds composed of very thin (1–3 mm thick) graded gray-green to yellow mud layers sharply overlain by a thin layer of clay (Babcock et al., 2001; Hagadorn, 2002).

2.2. Wheeler Shale

The middle Cambrian (Series 3, Stage 5) Wheeler Shale of central Utah, USA is a fine-grained siliciclastic unit that was deposited within a fault-controlled trough that developed during the middle Cambrian known as the House Range Embayment (Rees, 1986). The development of the House Range embayment created two broad depositional settings: a relatively shallow carbonate shelf to the east and a deep-water trough to the west (Rees, 1986; Elrick and Snider, 2002). The Wheeler Shale is preserved both in the trough and on the platform. The trough-deposited black shales are sparsely fossiliferous, preserving mostly agnostic trilobites, while the deep ramp platform-deposited carbonaceous shales preserve a greater diversity of fossils including the BST fauna (Rees, 1986; Brett et al., 2009).

2.3. Spence Shale

The middle Cambrian (Series 3, Stage 5) Spence Shale of southern Idaho-northern Utah, USA is the middle member of the Langston Formation (Liddell et al., 1997). The Langston Formation was deposited on a carbonate ramp, with the Spence Shale deposited in the outer detrital belt of the distal portion of the ramp (Liddell et al., 1997). Liddell et al. (1997) identified seven parasequence sets, each a shallowing upward sequence transitioning from fine-grained shales to a carbonate cap, and distinguishable based upon changes in diversity, size, and taphonomic grade of trilobites. The Spence Shale contains a diverse BST fauna (Robison, 1991; Briggs et al., 2008).

2.4. Shared depositional characteristics

These three shales were all deposited in generally calm marine paleoenvironments below normal wave base, wherein background sedimentation slowly accumulated thinly bedded or laminated fine-grained siliciclastic sediment (Rees, 1986; Chen and Zhou, 1997; Liddell et al., 1997). These calm conditions were periodically punctuated by higher energy influxes of coarser-grained siliciclastic sediment, resulting in thicker graded event beds. Exceptionally preserved fossils are typically buried under these obrution deposits (Chen and Zhou, 1997). Both of these microfacies were sampled in this study.

3. Methods

3.1. Field sampling

Samples were collected from the early Cambrian Maotianshan Shale of Yunnan Province, China (core sample), the middle Cambrian Wheeler Shale of Utah, USA, and the middle Cambrian Spence Shale of Idaho and Utah, USA. Continuous samples were collected from short stratigraphic intervals with documented BST preservation; composite sections were created when necessary to avoid weathered beds. A total of 1.7 m of strata of the Wheeler Shale was collected from the Antelope Springs locality, Utah. Approximately 4.0 m of strata of the Spence Shale was collected from four localities in Idaho and Utah—High Creek, Miner's Hollow, Oneida Narrows, and Spence Gulch. For Miner's Hollow, care was taken to sample localities corresponding to the parasequences of Liddell et al. (1997) in order to compare the results of this study with previous paleoenvironmental interpretations. Core samples through the exceptional fossil-bearing interval of the Maotianshan Shale were utilized for geochemical analysis of this unit.

3.2. Laboratory analysis

A total of 96 samples (34 samples from three sections at the Antelope Springs locality of the Wheeler Shale, 57 from four localities in the Spence Shale, and 5 samples from a single core from the Maotianshan Shale) were prepared for geochemical analysis. The sample interval was ~5 cm (5 cm +/- 1 cm). X-radiography of slabbed samples and petrographic thin sections were analyzed to ensure that graded event bed and laminated background microfacies were both included in our geochemical database. Strata from the Spence Shale series LMH2 (Lower Miner's Hollow 2) were sampled at two intensities: one at ~5 cm scale, and another at ~1 cm scale. This was done to test the hypothesis proposed by Gaines and Droser (2010) that the scaling intensity (i.e. m-scale) of geochemical analysis was not accurately portraying bed (mm-to-cm) scale variations in redox conditions in Cambrian shales. For comparison to the multiple-meter scale analyses of previous studies, the LMH2 locality was also sampled at a course multiple-meter scale.

Concentrations of V, Ni, Cr, and Zn were measured using X-ray Fluorescence (XRF), and normalized for paleoredox analysis through the use of paleoredox indices V/Cr and V/(V + Ni) (Jones and Manning, 1994; Schovsbo, 2001). Enrichment factors (EF) (Tribovillard et al., 2006) were also calculated, but do not directly correlate with paleoredox conditions. These trace elements were chosen due to their redox-sensitivity, their wide use in paleoredox geochemical analyses of marine shales, including those of Cambrian age, their detectability in these rocks (e.g. Calvert and Pederson, 1993; Powell et al., 2003; Tribovillard et al., 2006; Powell, 2009; Zhou and Jiang, 2009; McKirdy et al., 2011), and the lower limits of detection of the equipment and calibration procedures (McHenry, 2009). V is reported with statistical error $<12\%$; all other elements reported have statistical errors $<10\%$. Other redox-sensitive trace elements, such as Mo and U, were not detectable on the XRF. Other informative paleoredox proxies, such as Corg/P ratios and Fe speciation, are beyond the scope of this study. Future studies using these indicators will test the multi-proxy results presented here.

For V/Cr, the Paleoredox Index (PI) ratio is correlated to redox zones: values of <2.00 characterize the oxic zone, values between 2.00 and 4.25 characterize the dysoxic zone, and values >4.25 characterize the anoxic zone (Jones and Manning, 1994). V/(V + Ni) ratios cannot discriminate between oxic and dysoxic conditions, but values >0.84 indicate anoxic conditions (Schovsbo, 2001). For EFs, enrichments occur when $EF > 1$, and depletions when $EF < 1$, as compared to average global shale (AGS) concentrations (Tribovillard et al., 2006).