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Early Cambrian oxygen minimum zone-like conditions at Chengjiang

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ABSTRACT

The early Cambrian succession at Chengjiang contains the most diverse Cambrian fossil assemblage yet described, and contributes significantly to our understanding of the diversification of metazoans in the Cambrian "explosion". The Cambrian Period occupies a transitional episode of global ocean chemistry, following the oxygenation of the surface ocean and of shallow marine environments during the Ediacaran Period, but prior to the establishment of a predominantly oxygenated deep ocean in the mid-Paleozoic. Despite recent attention, a detailed understanding of the chemical conditions that prevailed in early Cambrian marine settings and the relationship of those conditions to early metazoan ecosystems is still emerging. Here, we report multi-proxy geochemical data from two drill cores through the early Cambrian (Series 2) Yu'anshan Formation of Yunnan, China. Results reveal dynamic water-column chemistry within the succession, which progressively shifted from euxinic to oxic conditions during deposition of the Yu'anshan Formation. The Chengjiang biota occurs in strata that appear to have been deposited under an oxygen-depleted water column that may have supported denitrification, as in modern oxygen-minimum zones. The oxygenated benthic environments in which the Chengjiang biota thrived were proximal to, but sharply separated from, the open ocean by a persistent anoxic water mass that occupied a portion of the outer shelf. Oxygen depletion in the lower water column developed dynamically in response to nutrient availability and possibly at lower thresholds of productivity due to lower atmospheric oxygen concentrations in Cambrian. These findings suggest that the frequent development of oxygen-limiting conditions in continental margin settings provided an environmental barrier that may have affected biogeographic, ecological and evolutionary development of early metazoan communities.

1. Introduction

The dramatic appearance of most animal phyla during the Cambrian Period is captured in a unique fossil record characterized by exceptional preservation of soft-bodied organisms (Knoll and Carroll, 1999). Among exceptional fossil deposits of the Cambrian Period, the Chengjiang and Burgess Shale biotas exhibit the highest taxonomic richness (>100 taxa) (Gaines, 2014) and form the foundation for understanding large scale evolutionary patterns of the radiation of the Metazoa.

In what geochemical environment, however, did these earliest Metazoan ecosystems proliferate and flourish? There is geochemical evidence of water-column oxygenation (Canfield et al., 2007; Fike et al., 2006) together with widespread marine anoxia, during the time when animal ecosystems first emerged during the Neoproterozoic Era, together indicating much lower atmospheric oxygen concentrations than those of today (Canfield et al., 2008a; Johnston et al., 2013; Sperling et al., 2015). During the Cambrian period, geochemical evidence also points to the occurrence of oxygenated but also widespread anoxic marine conditions (Dahl et al., 2010; Gill et al., 2011; Sperling et al., 2015), while modeling of geochemical data suggests that low atmospheric oxygen prevailed well into the Paleozoic Era (Lenton et al., 2016 and references therein). If relatively low atmospheric oxygen prevailed at the Precambrian–Cambrian boundary followed by more extensive marine anoxia than today, how might have the distribution of water-column oxygen impacted the Cambrian "radiation" and emerging animal ecosystems, such as those at Chengjiang?

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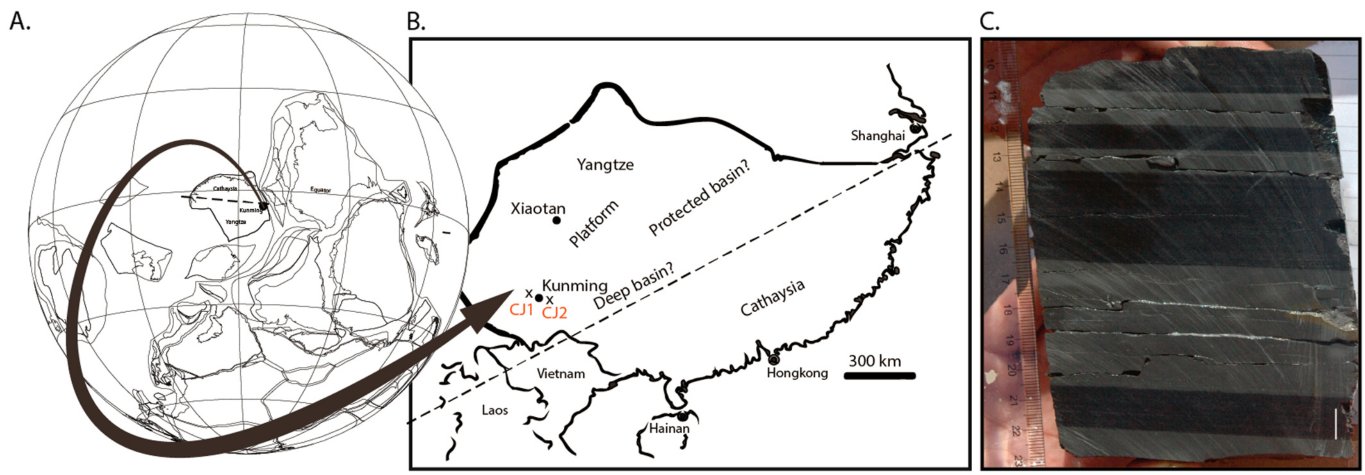

Fig. 1. A. The Cambrian globe and Yangtze platform at ∼520 Ma (Cocks and Torsvik, 2002) were constructed in the software Bugplates (Torsvik, 2009) visualizing the now joined (dotted line) South China and Cathaysia blocks. B. Location map of the study area. C. A segment of core (11 cm diameter) from the fossiliferous interval in lower member 3, showing alternation of event deposited claystones (light gray) and intervals dominated by pelagic background sedimentation (black) from ∼21 m in CJ1. Scale = 1 cm (white bar).

Studies of the early Cambrian Yangtze platform have resulted in several reports of marine anoxia (Canfield et al., 2008a; Chen et al., 2015; Feng et al., 2014; Li et al., 2015; Och and Shields-Zhou, 2012; Och et al., 2013; Wen et al., 2015). Previous efforts to determine water column and benthic redox conditions for the interval hosting the Chengjiang biota using data from trace element concentrations (Forchielli et al., 2014; Zhu et al., 2001), ichnology (Gaines et al., 2012a), and taphonomy (Zhang and Hou, 2007; Zhao et al., 2009), have produced conflicting interpretations. Therefore, the redox conditions surrounding the living environments of the Chengjiang biota and those that favored its exceptional preservation have remained unclear.

In this study, we apply a multi-proxy, high-resolution geochemical approach to two newly drilled successions of the early Cambrian (Series 2) Yu'anshan Formation of Yunnan Province, China to determine the nature of water column chemistry during the proliferation of the Chengjiang biota. This continuous subsurface record from Chengjiang holds potential for reconstructing the conditions in which the earliest Phanerozoic ecosystems thrived.

2. Geological setting and depositional history

The Chengjiang biota occurs in the Yu'anshan Formation, which was deposited at low latitude (Evans, 2000) in offshore slope and shelf environments adjacent to the Yangtze platform (Fig. 1) at ∼520 Ma (Hu, 2005; Zhu et al., 2001). The Yu'anshan Formation is comprised of four members that grade upwards from condensed black siltstone and shale through a succession of mudstones with intercalated sandstones into a sand-dominated upper member. Together, these four members have been interpreted to represent a single depositional sequence with deep-water environments, conducive to organic accumulation near the base, transitioning upwards into shallower, wave-dominated sedimentary environments at the top (Zhu et al., 2001). Exposure of the Yu'anshan Formation is relatively poor in the study area owing to a humid climate and high degree of cover by vegetation; nevertheless, our subsurface study of sedimentary features and general geochemistry is in agreement with previous estimates of approximately 170 m of stratigraphic thickness (Hu, 2005; Zhu et al., 2001).

The lowermost black siltstone member of the Yu'anshan Formation (member 1) is associated with rapid flooding across an erosive surface that separates the Yu'anshan from the underlying Shiyantou Formation. Organic-rich black shales of member 2 are interpreted to represent calm, deep-water environments that were widely spread across the region during sea-level highstand. The transition to member 3 is marked by the onset of distal claystone turbidite deposition in a deep basin that continued to accumulate black claystones representing pelagic "background" sedimentation between turbidite events (Hu, 2005; Zhao et al., 2009; Zhu et al., 2001). Member 3 records gradual basin filling and progradation of the shelf towards the study area, facilitating the delivery of turbidites that increase in frequency, maximum grain size, and thickness upsection across more than 90 m of member 3. The Chengjiang biota occurs in distal claystone turbidites (Hu, 2005; Zhao et al., 2009; Zhu et al., 2001) within the lower 27 m of member 3 (Fig. 2), the thickest and most lithologically complex member of the Yu'anshan Formation. The fossiliferous part of the unit is also known as the "Maotianshan Shale" (Hou et al., 2017). In core, the event-deposited claystone turbidites range from 0.5 to 8.0 cm in thickness and are readily recognized by their light gray color and massive fabric, which lacks the laminated character typical of the "background" pelagic/hemipelagic claystones (Gaines et al., 2012b; Hu, 2005; Zhao et al., 2009; Zhu et al., 2001). Graded turbidites in member 3, with silt or laminated or rippled sand bases become increasingly prevalent upsection, commensurate with a decline in the influence of pelagic sedimentation. The silt and fine sand dominated member 4 reflects shallowing and a transition from a turbidite-driven sedimentation to a storm wave-influenced shelf or distal shoreface setting (Zhu et al., 2001).

We recovered drill cores from the two primary fossil-bearing localities at Haikou (CJ1) and Maotianshan (CJ2; see details in SI), which span the fossil-bearing interval in the lower part of member 3, and include underlying strata. In the Haikou area, the Yu'anshan Formation is truncated by a Mid-Paleozoic erosion surface near the top of the fossil-bearing interval, but the Maotianshan core (CJ2) includes all four members of the Yu'anshan Formation. The core localities are separated by ∼40 km, and are similar in lithology and stratigraphic architecture (Hu, 2005; Zhu et al., 2001).

3. Methods

We applied multi-proxy geochemical analyses to 298 samples collected from the two cores at an average spacing of 100 cm, with samples collected at higher resolution (∼20 cm) within the fossil-bearing interval of member 3. Samples were analyzed at University