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Research paper

Multiple controls on the paleoenvironment of the Early Cambrian marine black shales in the Sichuan Basin, SW China: Geochemical and organic carbon isotopic evidence

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ABSTRACT

In order to understand the paleoenvironment of the Early Cambrian black shale deposition in the western part of the Yangtze Block, geochemical and organic carbon isotopic studies have been performed on two wells that have drilled through the Qiongzhusi Formation in the central and southeastern parts of Sichuan Basin. It shows that the lowest part of the Qiongzhusi Formation has high TOC abundance, while the middle and upper parts display relative low TOC content. Redox-sensitive element (Mo) and trace elemental redox indices (e.g., Ni/Co, V/Cr, U/Th and V/(V + Ni)) suggest that the high-TOC layers were deposited under anoxic conditions, whereas the low-TOC layers under relatively dysoxic/oxic conditions. The relationship of the enrichment factors of Mo and U further shows a transition from suboxic low-TOC layers to euxinic high-TOC layers. On the basis of the Mo-TOC relationship, the Qiongzhusi Formation black shales were deposited in a basin under moderately restricted conditions. Organic carbon isotopes display temporal variations in the Qiongzhusi Formation, with a positive excursion of $\delta^{13}C_{org}$ values in the lower part and a continuous positive shift in the middle and upper parts. All these geochemical and isotopic criteria indicate a paleoenvironmental change from bottom anoxic to middle and upper dysoxic/oxic conditions for the Qiongzhusi Formation black shales. The correlation of organic carbon isotopic data for the Lower Cambrian black shales in different regions of the Yangtze Block shows consistent positive excursion of $\delta^{13}C_{org}$ values in the lower part for each section. This excursion can be ascribed to the widespread Early Cambrian transgression in the Yangtze Block, under which black shales were deposited.

1. Introduction

The Yangtze Block in southern China contains successive sediment sequences from the Neoproterozoic to Early Paleozoic, and records several episodes of glacial and interglacial periods (Jiang et al., 2010, 2011, 2012). Within this period, the Ediacaran–Cambrian (E–C) transition was a key period for the understanding of one of the most important transitional intervals in Earth's history, as it recorded the explosive radiation of metazoans and coeval sharp shifts in the ocean geochemistry (Kaufman et al., 1993; Grotzinger et al., 1995; Knoll and Caroll, 1999; Amthor et al., 2003). A prolonged global oceanic anoxia period occurred after the Ediacaran–Cambrian bio-radiation, producing deposition of organic-rich black shales worldwide (Kimura and Watanabe, 2001).

Three main depositional settings existed in the Yangtze Block in the Ediacaran and Early Cambrian intervals, including shallow water facies in the platform interior, transitional facies, and deep water slope and basinal facies from northwest to southeast (Fig. 1b; Steiner et al., 2001; Guo et al., 2007a, b). During the Early Cambrian, global sea-level rise and extensive transgression promoted the deposition of black shale over the entire Yangtze Block (Chen et al., 2009).

The Lower Cambrian organic-rich black shales in the Yangtze Block have been studied extensively in terms of depositional environments and stratigraphy using trace elements, stable carbon and sulfur isotope chemostratigraphic and biostratigraphic approaches (e.g., Shields and Stille, 2001; Steiner et al., 2001; Chen et al., 2003; Pan et al., 2004; Guo et al., 2007a, b, 2013; Chen et al., 2009). Most of these studies were carried out in focus on

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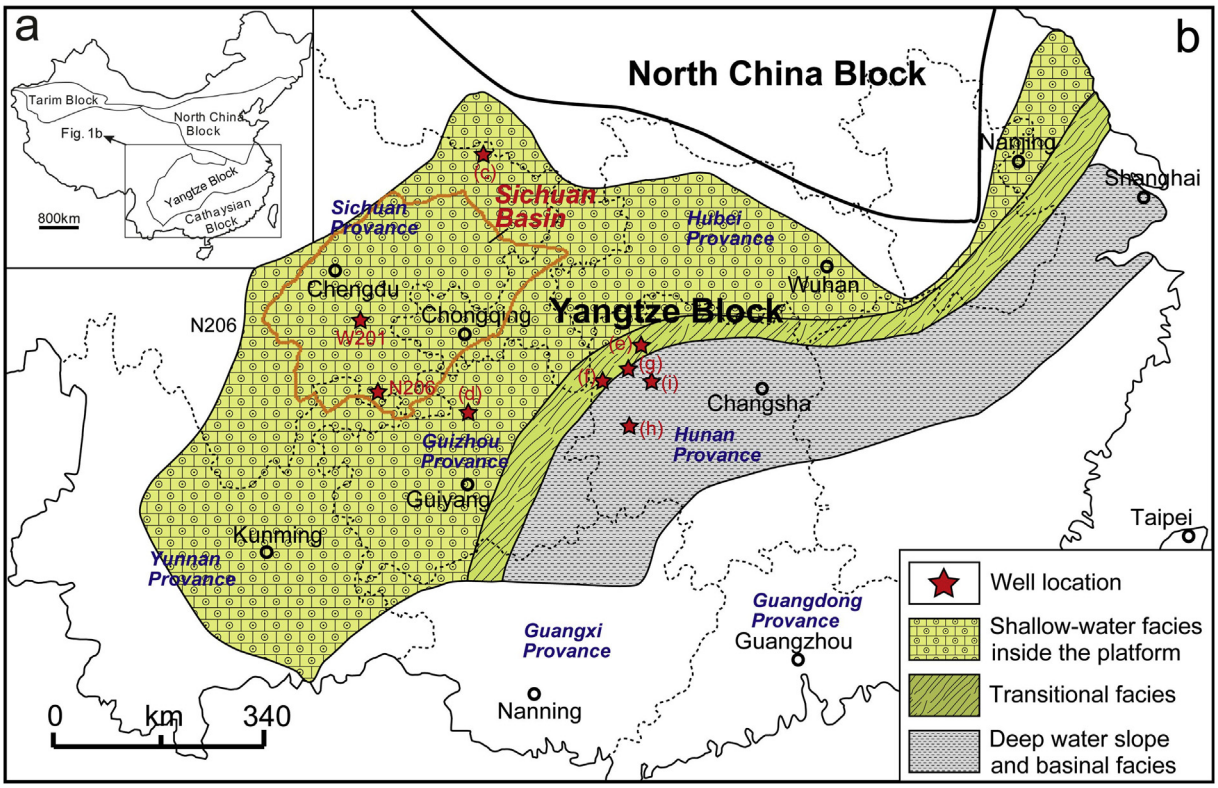

Fig. 1. (a) Map of China showing the location of the Yangtze Block. (b) Simplified paleogeographic map of the Yangtze Block around the Sinian-Cambrian boundary interval (modified after Steiner et al., 2001 and Zhu et al., 2003). The location of two studied wells are marked by stars. The Lower Cambrian Qiongzhusi Formation black shales were deposited above the platform shallow water limestone.

the Guizhou and Hunan provinces where the Lower Cambrian strata were well exposed (Fig. 1b). However, the Lower Cambrian black shales in the Sichuan Basin (northwestern Yangtze Block) have not been systematically studied due to the extensive coverage by Mesozoic sediments. Fortunately, as their significant shale gas potentials, a number of wells were drilled in the central and southern Sichuan Basin, which offers an opportunity to study the Lower Cambrian black shales in the Sichuan Basin.

Metal enrichment is an important feature for all organic-rich shales (black shales), which is usually related to warm periods in Earth history and anoxic depositional environment, e.g. in the Cambrian, late Devonian–Carboniferous, mid-late Permian and Cretaceous Periods (e.g., Guo et al., 2007a and references therein). As there is a systematic association between redox-sensitive metals and carbon abundance in black shales, it seems that anoxia caused by biological productivity and organic decay played a major role in most metal enrichment (Rimmer, 2004; Guo et al., 2007a; Xu et al., 2012). Therefore, recently, numerous studies have used these redox-sensitive trace elements and carbon isotopic proxies to determine the depositional conditions, and their relation to the total organic carbon accumulation.

Here, we present trace elements, total organic carbon (TOC), and organic carbon isotope studies on fresh core samples of two wells of the Lower Cambrian Qiongzhusi Formation black shales wells in the central (Well W201) and southern (Well N206) Sichuan Basin, and compare them with previous findings from the Yangtze Block. Previous studies were mainly performed on outcrops, which are often affected by subtropical weathering in South China. Hence, this study presents the first dataset from fresh subsurface samples from the Sichuan Basin.

2. Geological setting

After the Neoproterozoic rift events, the Yangtze Block evolved into a passive continental margin basin during the Ediacaran–Cambrian transition (Steiner et al., 2001; Wang and Li, 2003; Guo et al., 2007a). The basin accommodated the carbonate platforms, surrounded by narrow marginal transitional zones to the south and southeast, where shallow-water carbonates abruptly changed basin-wards into black chert-shale successions (Fig. 1b; Chen et al., 2009). The sharp shift from the shallow-water carbonates (e.g. Dengying Formation dolostones) to deep-water chert-shales (e.g., Liuchapo Formation cherts) has been identified along the southeastern platform margin, where chert deposits occurred as stratal wedges embedded in the carbonate successions, and thicken rapidly into the complete chert successions in the deep basin region (Chen et al., 2009). Due to the Early Cambrian global sea-level rise, black shales were deposited almost over the entire Yangtze Block, which unconformably covered the Ediacaran-lowermost Cambrian platform carbonates or conformably overlay the coeval black chert-shale successions basinwards (Guo et al., 2007a, b; Chen et al., 2009). Both of our studied wells were located on the paleo-carbonate platform (Fig. 1b). During Late Sinian and Early Cambrian, “Deyang–Anyue” paleo-taphrogenic trough was successively developed in the western part of the Sichuan Basin, whereas a relative uplift occurred in the eastern part (Fig. 2; Zou et al., 2014; Li et al., 2014; Wei et al., 2015; Xing et al., 2015). The trough controlled the distribution of the Early Cambrian black shales in the Sichuan Basin (Fig. 2). Both two studied wells are from the deep-water trough area (Fig. 2). The Lower Cambrian Qiongzhusi Formation black shales