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Geochemical changes in the Early Cambrian interval of the Yangtze Platform, South China: Implications for hydrothermal influences and paleocean redox conditions

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ABSTRACT

The possible triggering mechanisms of the Ediacaran–Cambrian transition in South China have been debated for many years. In this study, 80 samples from Liuchapo, Niutitang and Mingxinsi Formations were collected from Well YK-1, located in southeastern Chongqing. A high-resolution chemostratigraphic study, including evaluation of rare earth elements (REEs) and trace elements, was used to elucidate the paleoenvironments of the Upper Yangtze Platform margin. The Mingxinsi gray shale and the Liuchapo Formation exhibit flat Post-Archean Australian-normalized REE patterns with weakly negative Ce anomalies, which is typical of detritus. Obvious positive Eu anomalies in chert samples of the basal Niutitang Formation imply a short-term influence of hydrothermal fluid. The REE patterns of the basal Niutitang phosphatic rocks show significant enrichment of heavy REEs, significantly negative Ce anomalies, and positive Y anomalies, similar to the REE-distribution pattern in seawater, demonstrating that these sediments were produced under oxic seawater conditions. Moderately positive Eu anomalies and positive Y anomalies of the lower Niutitang shales may indicate mixing of hydrothermal fluids and seawater. The flat REE patterns with weak Eu anomalies of the upper Niutitang shale may have been generated by hydrothermal inputs diluted by detrital materials. Dramatic increases of Ce anomalies in the basal Niutitang Formation reveal a significant decrease of the oxygen level in seawater. Trace elements, such as Ba, U, V, U, Cu, Cr, Zn, Ni and Sr, are commonly enriched in these formations compared to the upper continental crust. Authigenic abundances of Al-normalized U and Al-normalized V as well as ratios of Th/U and V/Sc are used as indicators of redox conditions. These distributions demonstrate that the redox conditions of the bottom water during the Ediacaran–Cambrian transition abruptly changed from oxic in the Nemakit–Daldynian age to anoxic in the early Tommotian age, and gradually became less reducing in the late Tommotian age and the Atdabanian age. A strong correlation between total organic carbon (TOC) concentrations and ratios of U/Al and V/Al in the entire section (except in the phosphatic rocks) implies non-sulfidic conditions. Most trace elements cannot be used as proxies for redox conditions associated with the phosphatic rocks in the basal Niutitang Formation because abundant trace elements were especially absorbed in apatite. The TOC concentrations correlated well with the redox conditions of bottom water. We infer that the section deposited in the platform margin was influenced by episodic hydrothermal activities that began at the beginning of the Tommotian age, and these activities may have terminated at the beginning of the Atdabanian age. Enrichments of organic matter that were mainly derived from the photic zone were controlled by the redox conditions of the bottom water.

1. Introduction

The Ediacaran–Cambrian transition was a key period in Earth's history, as it recorded simultaneously remarkable shifts in

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geobiology, ocean geochemistry and redox conditions (Amthor et al., 2003; Grotzinger et al., 1995; Huerta-Diaz and Morse, 1990, 1992; Kaufman et al., 1993; Kimura and Watanabe, 2001; Knoll and Carroll, 1999; Morse and Luther Iii, 1999; Schroder and Grotzinger, 2007), during which major tectonic blocks amalgamated with attendant volcanic activities (Doblas et al., 2002; Kirschvink et al., 1997; Veevers et al., 1997). Because of controversies regarding the triggering mechanisms of these coeval processes and extreme enrichment of polymetallic Ni–Mo–PGE–Au in these successions, numerous studies in geobiology, geochemistry and petrology have been conducted out. The Yangtze Platform in South China is a type-area for the study of the transition from Ediacaran to Cambrian (e.g., Braun and Chen, 2003; Chen et al., 2009; Guo et al., 2007; Jiang et al., 2007a; Lott et al., 1999; Shields and Stille, 2001; Steiner et al., 2001; Wang et al., 2012a). However, most previous studies reported geochemical data from the Yangtze Platform and the basin belt, but rarely from the platform to basin transitional zone in the Upper Yangtze Platform. In addition, most previous geochemical data were collected from sections of weathered outcrop. Recently, geochemical data collected from drill cores in the Three Gorges area (Hunan Province) have been published (Ishikawa et al., 2008, 2013, 2014; Isozaki et al., 2014; Kikumoto et al., 2014; Okada et al., 2014; Sawaki et al., 2008, 2010, 2014; Shimura et al., 2014; Yamada et al., 2014). However, more reliable data from drill cores of wells in the transitional zone have not been analyzed.

The Niutitang Formation (or equivalents), which is composed of lower siliceous successions and upper black shales successions, was extensively deposited around both the northern and southern flanks of the Yangtze Platform, South China (Zhu et al., 2003). Despite numerous studies on the basal metalliferous (Ni–Mo–PGE–Au) black shales of the Lower Cambrian in South China, the origin of the black shales succession has been debated for decades. Possible origins proposed by previous studies include seafloor hydrothermal venting (Chen et al., 2009; Jiang et al., 2007a; Lott et al., 1999; Shields and Stille, 2001; Steiner et al., 2001; Wang et al., 2012a) and marine (biogenic) origins (Braun and Chen, 2003; Guo et al., 2007; Lehmann et al., 2003, 2007; Mao et al., 2002; Wille et al., 2008; Xu et al., 2012, 2013). In addition, very few studies have focused on the mechanism of organic carbon accumulation during the Ediacaran–Cambrian transition (e.g., Goldberg et al., 2007; Pi et al., 2013). In this paper, we present the results of a high-resolution chemostratigraphic study, including an evaluation of major elements, rare earth elements and trace elements, in the Early Cambrian successions in the Upper Yangtze Platform (Fig. 1) to elucidate the remarkable environmental and oceanic changes and their influences on the accumulation of organic carbon.

2. Geological setting

During the Ediacaran–Cambrian transition, the Yangtze Block, which is surrounded by two narrow margin-slope zones in the northern flank and south-southwest flank (Chen et al., 2009), was affected by two continental events: the rifting of Laurentia from western Gondwana (Meert, 2003) and the amalgamation of Australia with East Antarctica and eastern Gondwana, coinciding with the collision between East and West Gondwana (Kirschvink, 1992; Meert, 2003). Both these events had effects on the sedimentation on the Yangtze Platform (Goldberg et al., 2007). During this time, a large segment of the Yangtze Block was covered by carbonate platforms that were subsequently drowned by a deep muddy shelf system at the beginning of the Early Cambrian as a result of a worldwide transgression called the "Niutitang Event" (Steiner et al., 2001).

This worldwide transgression event, accompanied with a greenhouse climate and volcanic activities, led to a hiatus at the lithostratigraphic boundary during the Ediacaran–Cambrian transition. Biostratigraphically, the fossil evidence of a hiatus between the Precambrian–Cambrian boundary is provided the occurrence of *Cloudina*, reflecting a terminal Neoproterozoic age and the appearance of Cambrian small shelly fossils (SSF) (Goldberg et al., 2005a).

This study focuses on the Ediacaran–Cambrian successions in the marginal zone of the Upper Yangtze Platform (Fig. 1). A section of the Yuke-1 well, located at Youyang County in southeastern Chongqing, was selected for the chemostratigraphic study. The "shallow-water" Ediacaran–Cambrian successions in southeastern Chongqing include the Dengying Formation (composed of dolostone) and the overlying Liuchapo Formation composed of a basal chert and siliceous shale layer and an upper interbedded muddy dolostone and shale, overlain by the Niutitang Formation (composed of a basal chert and siliceous shale layer, as well as phosphate-rich horizon, and an upper thick organic-rich black shale succession), which in turn is overlain by gray shale of the Mingxinsi Formation (Fig.2). These successions located at the platform marginal zone are well correlated in terms of lithostratigraphy with the deep-water slope-basin setting (e.g., Longbizui, Hunan Province) and the marginal facies (e.g., Ganziping, Hunan Province) in western Hunan (Chen et al., 2009; Wang et al., 2012b). However, in the shallow-water setting of the platform interior in northern Guizhou (e.g., Zunyi, Guizhou Province) (Jiang et al., 2006, 2007a, 2009; Steiner et al., 2001, 2005) and northern Hunan (e.g., Sansha, Hunan Province) (Steiner et al., 2001), the Niutitang black shales directly overlie the dolostone of the Dengying Formation rather than the Liuchapo Formation. Bypassing the Liuchapo Formation is caused by a sharp shift from the shallow-water Dengying dolostones to the Liuchapo chert successions taking place along the platform margin, where the chert deposits occur as the stratal wedges embedded in the carbonate successions, which thicken rapidly into the complete chert successions over a short distance (Chen et al., 2009). The chronological constrains of the Niutitang Formation can be determined by the radiometric age. A SHRIMP U–Pb age of 532.3 ± 0.7 Ma for a volcanic ash bed just beneath the phosphorite bed of the Niutitang Formation in Guizhou Province was proposed (Jiang et al., 2009), which is clearly younger than the Ediacaran–Cambrian boundary age of 542.0 ± 0.3 Ma (Amthor et al., 2003; Shergold and Cooper, 2004). Additionally, a Re–Os age of 521 ± 5 Ma for the polymetallic sulfide ores a few meters above the phosphorite bed was determined (Xu et al., 2011), which is similar to the SHRIMP U–Pb age of 518 ± 5 Ma for the tuff at the bottom of the lower Niutitang Formation (Zhou et al., 2008). These data are consistent with the biostratigraphic Tommotian age of approximately 530 Ma. Based on biostratigraphic and lithostratigraphic evidence (Chen et al., 2009; Goldberg et al., 2005a; Steiner et al., 2005), the Niutitang Formation belongs to the Tommotian age, which is equivalent to the 3rd SSF-Assemblage Zone and the poorly fossiliferous interzone. Compared to the deep-water slope-to-basin setting where the Ediacaran–Cambrian boundary is placed at a level within the Liuchapo Formation (Chen et al., 2009; Wang et al., 2012b,a), the Ediacaran–Cambrian boundary is placed near or at the base of the Liuchapo Formation toward the carbonate platform marginal zone (Chen et al., 2009). Therefore, the Liuchapo Formation corresponds to the Nemakit–Daldynian age.

3. Material and methods

Eighty selected samples from the Yuke-1 well (Tables 1–4) were analyzed for major elements and trace elements (include REE), from the siliceous Liuchapo, Niutitang and Mingxinsi Formations.