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Depositional environment and organic matter accumulation of Upper Ordovician–Lower Silurian marine shale in the Upper Yangtze Platform, South China

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ABSTRACT

The main controlling factors of organic matter accumulation in the Upper Ordovician Wufeng–Lower Silurian Longmaxi Formations are complex and remain highly controversial. This study investigates the vertical variation of total organic carbon (TOC) content as well as major and trace element concentrations of four Ordovician–Silurian transition sections from the Upper Yangtze Platform of South China to reconstruct the paleoenvironment of these deposits and to improve our understanding of those factors that have influenced organic matter accumulation in these deposits.

The residual TOC content of the Wufeng Formation averages 3.2% and ranges from 0.12 to 6.0%. The overlying lower Longmaxi Formation displays higher TOC content (avg. 4.4%), followed upsection by consistent and lower values that average 1.6% in the upper Longmaxi Formation. The concentration and covariation of redox-sensitive trace elements (Mo, U and V) suggest that organic-rich intervals of the Wufeng Formation accumulated under predominantly anoxic conditions. Organic-rich horizons of the lower Longmaxi Formation were deposited under strongly anoxic to euxinic conditions, whereas organic-poor intervals of the upper Longmaxi Formation accumulated under suboxic conditions. Positive correlations between redox proxies and TOC contents suggest that organic matter accumulation was predominantly controlled by preservation. Barium excess (Ba_{xs}) values indicate high paleoproductivity throughout the entire depositional sequence, with an increase in the lower Longmaxi Formation. Increased productivity may have been induced by enhanced P recycling, as evidenced by elevated C_{org}/P_{tot} ratios. Mo–U covariation and Mo/TOC values reveal that the Wufeng Formation was deposited under extremely restricted conditions, whereas the Longmaxi Formation accumulated under moderately restricted conditions. During the Late Ordovician, the extremely restricted nature of ocean circulation on the Upper Yangtze Platform in tandem with enhanced stratification of the water column promoted anoxic conditions favorable for the preservation of organic matter. During Early Silurian time, organic matter accumulation was principally controlled by changes in sea level, which affected terrigenous flux, redox conditions, and the degree of nutrition recycling.

1. Introduction

The Ordovician–Silurian transition was a critical interval in Earth history marked by large-scale glaciation, marine mass extinction, extensive volcanism, and sea level and global environmental change (Brenchley et al., 2003; Fan et al., 2009; Delabroye and Vecoli, 2010; Munnecke et al., 2010; Yan et al., 2010, 2012; Melchin et al., 2013; Zhou et al., 2015; Algeo et al., 2016; Davies et al., 2016). The sedimentary record of this transitional period is characterized by widespread organic-rich marine shales that accumulated in a wide range of paleogeographic settings, ranging from deep shelf to base of continental slope (Melchin et al., 2013). Many of these shales are regarded as the important petroleum source rocks (Lüning et al., 2000, 2005; Finney et al., 2007; Armstrong et al., 2009; Vecoli et al., 2009; Yan et al., 2012). The Wufeng–Longmaxi Formations preserve a continuous stratigraphic record of Upper Ordovician–Lower Silurian black shale sequence in South China, mainly on the Upper Yangtze Platform (Chen et al., 2004; Su et al., 2007). The very thick Wufeng–Longmaxi shale succession contains abundant organic matter, experienced high levels of thermal stress and related natural gas generation, and is conducive to hydraulic fracture stimulation. Thus, these formations are thought to be excellent targets of shale-gas exploration and development in China (Zou et al., 2010; Liang et al., 2012; Dai et al., 2014).

Several hypotheses, including enhanced preservation due to anoxic conditions (Wang et al., 2008), restricted basin conditions (Mu et al.,

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2011), changes in sea level (Li et al., 2008; Z.H. Liu et al., 2016; Y. Liu et al., 2016), high paleoproductivity (Tenger et al., 2006), or/and any combinations of these factors (Yan et al., 2012, 2015; Zhang et al., 2012) have been proposed as controls on organic matter accumulation during the deposition of the Wufeng–Longmaxi succession. Among these models, the most prominent and widely accepted is that accumulation of Wufeng–Longmaxi shale was associated with watermass restriction and consequent development of anoxic or euxinic conditions in a silled basin (Chen et al., 2004; Su et al., 2007; Zhang et al., 2012). However, no direct geochemical evidence for watermass restriction has been provided. Though recent studies have indicated that sediment composition and depositional conditions significantly changed from the Late Ordovician to Early Silurian (Su et al., 2009; Liang et al., 2012; Y. Liu et al., 2016), it has long been assumed that the Wufeng and Longmaxi marine shales share a similar mechanism of organic matter enrichment (Li et al., 2008; Chen et al., 2016).

Major and trace element geochemistry has been used to elucidate paleoenvironmental conditions of deposition of shale successions (Algeo and Maynard, 2004; Algeo and Lyons, 2006; Tribovillard et al., 2006; Calvert and Pedersen, 2007). Redox-sensitive trace elements (e.g., Mo, U and V) tend to be highly enriched under reducing conditions, making elemental concentrations and ratios thereof useful proxies for paleo-redox reconstruction (Tribovillard et al., 2006; Algeo and Tribovillard, 2009; Algeo and Rowe, 2012; Tribovillard et al., 2012). Biogenic elements such as phosphorus and barium show significant correlation with productivity variations in different ocean basins, and have therefore been used to evaluate changes in primary productivity (Dymond et al., 1992; Tribovillard et al., 2006; Calvert and Pedersen, 2007). In addition, recent studies have shown that patterns of Mo–U covariations and Mo/TOC values can provide information concerning a wide range of paleoenvironmental parameters, including redox condition and watermass restriction (Algeo and Lyons, 2006; Rowe et al., 2008; Algeo and Tribovillard, 2009; Tribovillard et al., 2012).

This study addresses vertical variations in TOC content and major and trace-element concentrations of four Ordovician–Silurian sections from the Upper Yangtze Platform, China. The main objectives include the reconstruction of the depositional environment of these deposits and enhanced understanding of organic matter accumulation during deposition of the Upper Ordovician Wufeng and Lower Silurian Longmaxi marine shale succession. This study specifically addresses (1) geochemical characteristics of Upper Ordovician–Lower Silurian marine shale deposits; (2) terrigenous flux, redox conditions, productivity, and watermass restriction during accumulation of marine shale; and (3) factors that were crucial to organic matter accumulation of the studied deposits.

2. Geological setting

South China was a separate plate during the Paleozoic, but was still attached to the margins of Gondwana during the Late Ordovician to Early Silurian (Fig. 1A) (Metcalfe, 1994). South China was comprised of the Yangtze Platform in the northeast and the Cathaysia continental blocks in the southeast (Su et al., 2009; Yan et al., 2009). The Yangtze Platform was covered by a broad epeiric sea, the Yangtze Sea, and was bordered to the southeast by the Southeast China Sea (Pearl River Sea), which was probably connected to the global ocean (Wang et al., 1997). It was surrounded by Cathaysian Land, Dianqian Uplift and Chengdu Uplift, forming a semi-enclosed bay that opened northwards during Late Ordovician (Fig. 1B; Chen et al., 1987). The Yangtze Sea was divided by the Jiujiang Strait into a western Upper Yangtze Sea and an eastern Lower Yangtze Sea (Chen, 1984). From the Late Ordovician, the Caledonian movement reached the highest intensity, placing the Upper Yangtze Platform under compression and resulting in the formation of Chengdu Uplift in the northwest of the Upper Yangtze Platform, Dianqian Uplift in the south of the Upper Yangtze Platform and Jiangnan-Xuefeng Uplift in the southeast of the Upper Yangtze Platform (Fig. 1C; Liang et al., 2009). Surrounded by these uplifts, the Upper Yangtze Sea evolved to a generally enclosed basin (Wang et al., 1997; Chen et al., 2004; Su et al., 2007). At the same time, affected by the large-scale transgression, the Chuanbei, Chuandong and Chuannan depocenters developed on the Upper Yangtze Platform during the Ordovician–Silurian transition (Fig. 1C; Liang et al., 2009; Guo, 2013).

The shale succession that accumulated during the Ordovician–Silurian transition in South China is composed of two lithostratigraphic units: the Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation (Fig. 2). The Wufeng Formation comprises the lower Graptolite Shale Member and the upper Guanyinqiao Member (Liang et al., 2012). The Graptolite Shale Member is composed of organic-rich

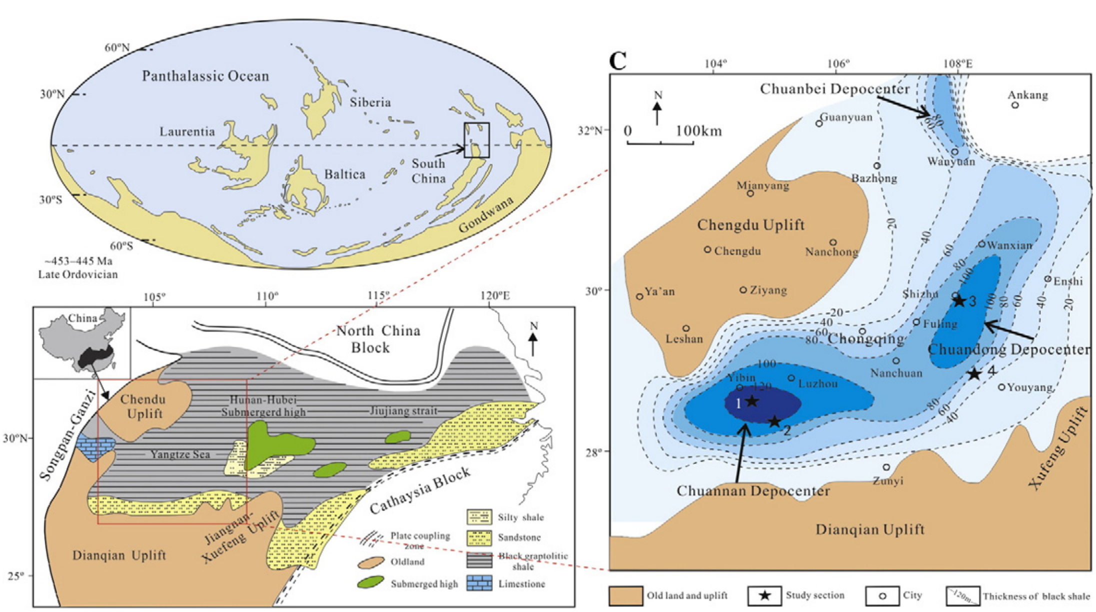

Fig. 1. (A) Global paleogeographic map (~453–445 Ma) showing the location of the South China (modified from Zhou et al., 2015); (B) paleogeographic map of the Yangtze Platform during Late Ordovician to Early Silurian (modified from Chen et al., 2004 and Zhou et al., 2015), and (C) isopach of Upper Ordovician Wufeng–Lower Silurian Longmaxi marine shale in Upper Yangtze Platform (modified from Liang et al., 2009 and Guo, 2013). Study sections (★): 1 = Changning, Yibing, Sichuan; 2 = Xingwen, Yichang, Sichuan; 3 = Shizhu, Chongqing; 4 = Qianqian #1 well, Xiushui, Chongqing.