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Paleo-environmental cyclicity in the Early Silurian Yangtze Sea (South China): Tectonic or glacio-eustatic control?

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ABSTRACT

The Yangtze Sea of the South China Craton experienced strong environmental perturbations during the first ~5-6 Myr of the Silurian. The Lower Silurian Lungmachi Formation in the Jiaoye-1 drillcore (Chongqing, China) records three sea-level cycles (stratigraphic sequences) characterized by rapid deepening at the base of each cycle followed by slow shallowing. Each deepening event was associated with shifts toward higher marine productivity, more intensely reducing bottomwater conditions, reduced watermass restriction, lower detrital input, and enhanced siliciclastic weathering intensity. We infer control by glacio-eustasy, in which deglacial sea-level rises and concurrent climatic warming triggered the observed environmental changes. Shallowing was associated with renewed glaciation and characterized by the opposite set of conditions. The results of this study thus provide evidence in support of continued continental glaciation during the Early Silurian, i.e., following the termination of the major end-Ordovician Hirnantian glaciation. The study core also exhibits a long-term shallowing trend through the entire Lower Silurian, the origin of which may have been tectono-epeirogenic uplift of the South China Craton during the Kwangsian Orogeny.

1. Introduction

The Ordovician-Silurian (O-S) transition was a time of global climatic and biotic perturbations. Cooling during the Middle to Late Ordovician culminated in a brief (~0.5-Myr) but intense episode of continental glaciation during the Hirnantian, the final stage of the Ordovician (Brenchley et al., 2003; Chen et al., 2004; Zhang et al., 2009, 2010; Young et al., 2010; Gorjan et al., 2012; Dronov, 2013; Algeo et al., 2016), which was accompanied by a two-stage mass extinction eliminating 86 % of extant species (Jablonski, 1991; Rong et al., 2002, 2007; Chen et al., 2005; Fan et al., 2009; Melchin et al., 2013; Harper et al., 2014). Global climate conditions ameliorated rapidly at the termination of the Hirnantian glaciation but remained somewhat disturbed during the Rhuddanian (early Early Silurian), which was characterized by higher-than-background rates of turnover among conodonts (Aldridge et al., 1993) and graptolites (Chen et al., 2000, 2005; Fan et al., 2013; Harper et al., 2014).

The climatic conditions of the Early Silurian remain under debate. Some workers have inferred global greenhouse conditions (Brenchley et al., 1994; Armstrong and Coe, 1997; Sheehan, 2001; Munnecke et al., 2010; Finlay et al., 2010) whereas others have suggested renewed continental glaciation, although less extensive than during the Hirnantian (Jeppsson and Calner, 2003; Melchin and Holmden, 2006; Cramer and Saltzman, 2007; Munnecke et al., 2010; Finnegan et al., 2011; Trotter et al., 2016). Many of the latter studies have provided evidence for three to four episodes of expansion and contraction of continental icesheets during the Early Silurian, yet there is little agreement among published sea-level curves for this interval (Fig. 1; Munnecke et al., 2010).

The Yangtze Platform of the South China Craton preserves a continuous record of sedimentation through the O-S transition (Chen et al., 2004). A number of studies have reconstructed environmental conditions within the Yangtze Sea (Yan et al., 2009, 2010, 2012; Zhou et al., 2015; Li et al., in review; Liu et al., in review), although most have focused on the Upper Ordovician rather than the Lower Silurian. In the most thoroughly investigated sections, Wangjiawan and Nanbazi, only a few meters of the Lower Silurian Lungmachi Formation is exposed in outcrop, corresponding to the *Akidograptus ascensus* to *Coronograptus cyphus* graptolite zones of the Rhuddanian stage (Yan et al., 2009,

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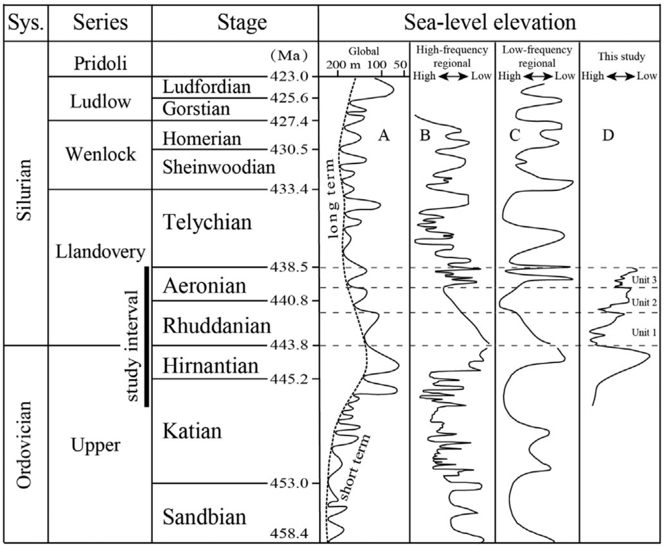

Fig. 1. Stratigraphy and sea-level variation for the Late Ordovician to Late Silurian. (A) High-frequency ("short term") and low-frequency ("long term") eustatic (global sea-level) curves of Haq and Schutter (2008). (B) High-frequency sea-level curves of Ross and Ross (1995) for the Ordovician (of North America) and Loydell (1998) for the Silurian (of Europe). (C) Low-frequency sea-level curves of Kanygin et al. (2010) for the Ordovician (of Russia) and Johnson (2006, 2010) for the Silurian (of North America). (D) High-frequency sea-level variation during the latest Ordovician-Early Silurian in South China (this study). Units 1-3 are defined in Sections 4.2 and 5.1.

2010; Zhou et al., 2015). As a consequence, these studies have not recognized third-order (~1-3-Myr-long) cycles in this formation. In contrast, the Jiaoye-1 drillcore spans a much longer interval, through the *Stimulograptus sedgwichii* Zone, comprising the full Rhuddanian and Aeronian stages of the Lower Silurian. The Jiaoye-1 drillcore was studied recently by Chen et al. (2015b), who analyzed conditions within the Early Silurian Yangtze Sea on the basis of petrographic data. However, the geochemistry of the Jiaoye-1 drillcore has not been investigated to date. Here, we report total organic carbon (TOC), major and trace element, $\delta^{13}C_{org}$, and pyrite framboid size data, as well as new graptolite biostratigraphic data, for a ~85-m interval of mostly Lower Silurian strata in the Jiaoye-1 drillcore. Our goals are (1) to reconstruct environmental changes within the Early Silurian Yangtze Sea, and (2) assess the tropical marine environmental record of possible climatic perturbations in the aftermath of the end-Ordovician Hirnantian glaciation.

2. Geological background

2.1. Location and paleogeographic setting

The South China Craton was located close to the paleo-equator, in a tectonically active region along the northwestern margin of Gondwana, during the Early Paleozoic (Fig. 2A) (Metcalfe, 1994). During the Ediacaran to Early Ordovician, the Nanhua Basin (a failed intracratonic rift) opened between the Yangtze and Cathaysia blocks, producing a broad shelf on the northeastern (present-day southeastern) margin of the Yangtze Block (Fig. 2A; Liu and Xu, 1994; Macouin et al., 2004; Li et al., 2009; Zhang et al., 2013) (note: all further references to compass directions are paleo-orientations for the Late Ordovician, when South China was rotated ~90° counter-clockwise relative to its modern position). The Nanhua Basin began to close in the Middle Ordovician (~ 460 Ma) along the Wuyi-Yunkai orogenic belt, resulting in suturing of the Yangtze and Cathaysia blocks to form a unified South China Craton by the Early Silurian, an event known as the "Kwangsian Orogeny" (Wang, 1985; Wan and Zhu, 1990; Faure et al., 2009; Charvet et al., 2010; Li et al., 2010). As a consequence, the northeastern margin of the Yangtze Block was transformed from an extensional shelf margin to a compressional foreland basin, with continued tectonic activity until the Early Devonian (Li et al., 1998; Su et al., 2007; Huang et al., 2011).

The study area is located in the western part of the Yangtze Block, in the Jiaoshiba shale gas field, which is in Jiaoshi Town, Fuling District of Chongqing Municipality (Fig. 2B). The study material was collected from the Jiaoye-1 drillcore, which was acquired by the China Petroleum and Chemical Corporation in 2012 and is now curated by the Exploration Southern Company of Sinopec. The Jiaoye-1 drillcore consists of 84.8 m of Upper Ordovician and Lower Silurian strata from 87.1 m of borehole (Fig. 3), representing a core recovery rate of ~97 %. This drillcore is from the crest of an anticline, and the intersected strata are nearly horizontal (Fig. 2B, inset). The thermal maturity of the study section is moderately high, as shown by *Ro* (vitrinite reflectance) values from 2.2 % to 3.1 % (mean 2.6 %), which correspond to the post-maturation stage of hydrocarbon generation (Table S1).

Semi-restriction of the shallow Yangtze Sea developed during the Late Ordovician to Early Silurian as a result of far-field stresses of the Kwangsian Orogeny, which caused relative uplift of the Chengdu and Hunan-Hubei submarine highs and Yunnan-Guizhou Oldland on the western Yangtze Block (Chen et al., 2004). The study site was located in the middle of the western Yangtze Sea, approximately equidistant from these uplifts (Fig. 2A). Beginning in the late Katian, the Yangtze Sea accumulated siliciclastics, primarily black shales of the Wufeng Formation, owing to a combination of weathering of uplifted orogens and restriction of the interior of the Yangtze Sea (Wang, 1985; Chen et al., 2004). A major eustatic fall during the Hirnantian glaciation (Brenchley, 1988; Chen et al., 2004) led to widespread deposition of calcareous mudstone and limestone of the Kuanyinchiao Bed (Zhang et al., 2016). A post-glacial transgression led to renewed deposition of black shales, now assigned to the Lungmachi (= Longmaxi in Pinyin) Formation of latest Ordovician to Early Silurian age.

2.2. Stratigraphy and sedimentology

The Wufeng Formation, which disconformably overlies limestones of the Upper Ordovician Linhsiang Formation, consists of 4.26 m of black carbonaceous shale and dark gray silty shale (Fig. 3). This unit is conformably overlain by the Kuanyinchiao Bed, which consists of ~0.1 m of light-colored argillaceous limestones. According to regional correlations, the Kuanyinchiao Bed is equivalent to the upper part of the *M. extraordinarius* Zone and the lower part of the *M. persculptus* Zone of the lower to middle Hirnantian Stage (Fan et al., 2009). It contains the Hirnantia Fauna, a cool-water shelly fauna that spread rapidly at the onset of the Hirnantian glaciation and disappeared abruptly at its termination (Rong et al., 2002; Zhan et al., 2010). The Lungmachi Formation, which conformably overlies the Kuanyinchiao Bed, consists of >79 m of dark gray to black silty shale (Fig. 3; note that the minimum thickness cited here represents the cored interval in the Jiaoye-1 drillcore). In the study core, we subdivided the Lungmachi Formation into three units (Unit 1, 2408.5-2390 m; Unit 2, 2390-2353 m; Unit 3, 2353-2330 m) that have sequence stratigraphic significance (see Sections 4.2 and 5.1).

The Wufeng and Lungmachi black shales contain many well-preserved graptolite specimens (Fig. 4, Appendix 1) that permit correlations to international biozonation schemes. On this basis, the *Dicellograptus complexus*, *Paraorthograptus pacificus*, and *Metabolograptus extraordinarius* biozones of late Katian to early Hirnantian age were recognized in the Wufeng Formation (Fig. 3). The lowermost 3.24 m of the Lungmachi Formation is assigned to the *M. persculptus* Zone of the late Hirnantian Stage. The remainder of the Lungmachi Formation is of Early Silurian age and assigned to the *Akidograptus ascensus-Parakidograptus acuminatus*, *Cystograptus vesiculosus*, *Coronograptus cyphus* zones of the Rhuddanian Stage, and the *Demirastrites triangulatus*, *Lituigraptus convolutus*, and *Stimulograptus sedgwickii* zones of the Aeronian Stage (Fig. 3).