Precambrian Research 245 (2014) 1–12

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Fluctuation of shelf basin redox conditions in the early Ediacaran: Evidence from Lantian Formation black shales in South China

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ARTICLE INFO

Article history:
Received 3 March 2013
Received in revised form 4 December 2013
Accepted 8 January 2014
Available online 28 January 2014

Keywords:
Lantian biota
Redox condition
Pyrite framboid
Redox-sensitive trace element
Southern Anhui Province

ABSTRACT

Finely laminated, pyrite- and organic-rich black shales that bear a euxinic interpretation dominate the Ediacaran Lantian Formation in southern Anhui, South China. However, these black shales preserve benthic sessile algae and possible metazoans *in situ*, suggesting that the Lantian shelf basin may have had at least episodically oxidized bottom water during the early Ediacaran Period. Redox conditions of the fossiliferous Lantian black shales were examined by petrological analysis, pyrite framboid and $\delta^{34}S$ measurements, and redox-sensitive trace element (RSTE) analysis. Lamina-by-lamina pyrite framboid measurements show that Lantian black shales were deposited under fluctuating redox conditions. The $\delta^{34}S$ values of pyrites range from −20.5‰ to 2.3‰ for different laminae and display less negative values than the earliest Ediacaran black shales, supporting a return to a relatively low seawater sulfate concentration after the early Ediacaran oxidation event. Similarly, the Lantian black shale RSTE concentrations (*e.g.*, Mo, U, and V) are low compared to previously published results from the early Ediacaran and constant from lamina to lamina, suggesting a drop in ocean wide RSTE concentrations occurring independently of frequent local redox condition changes. These frequent redox condition changes in the Lantian shelf basin may have facilitated the productivity and preservation of macroscopic Lantian biota.

1. Introduction

The Ediacaran Period is an important transitional time in Earth history, during which pronounced changes occurred in the biosphere and ocean (Butterfield, 2007; Narbonne, 2011). Previous world-wide paleontological investigation indicates that after the Marinoan glaciation (~635 Ma), the early Ediacaran marine community was characterized by micro-eukaryotes such as the Doushantuo-Pertatataka type acritarchs, whereas after the Gaskiers glaciation (~580 Ma), the late Ediacaran marine ecosystem was occupied by macroscopic Ediacara organisms (Xiao and Laflamme, 2009). This biological transformation may have been accompanied by an increasingly oxic ocean as macroscopic and complex Ediacara biota replaced the former microscopic marine inhabitants (Fike et al., 2006; Canfield et al., 2007; McFadden et al., 2008).

This Ediacaran biological evolutionary pattern has recently been challenged by the discovery of an early Ediacaran macrofossil Lagerstätte – the Lantian biota in southern Anhui Province, South China (Yuan et al., 2011). Lantian biota comprises diverse benthic sessile algae and possible metazoans with tentacles comparable to those of modern metazoans (Van Iten et al., 2013). Regionally integrated stratigraphic correlation suggests that Lantian biota may have existed in the early Ediacaran Period (Yuan et al., 2011). Lantian macrofossils are preserved as carbonaceous compressions on the bedding surfaces of lower Lantian Formation black shales that show millimeter-thick laminations without sedimentary structures indicative of strong hydrodynamic activity. The presence of holdfasts in most Lantian fossils, combined with the lack of evidence for fossil transport, suggests that the Lantian macroorganisms were preserved *in situ* and lived below maximum wave base but within the photic zone. Because free oxygen is required to maintain the metabolism of complex macroeukaryotes, the *in situ* preservation of complex macroorganisms in the early Ediacaran indicates that free oxygen was at least locally available below storm wave base (Yuan et al., 2011). This inference, however, is inconsistent with previous geochemical studies that indicate that many early Ediacaran basins, including the Lantian shelf basin, were regionally anoxic or even euxinic (Canfield et al., 2007, 2008; Shen et al., 2008; Li et al., 2010; Johnston et al., 2012; Sahoo et al., 2012).

To reconcile this conflict, Yuan et al. (2011) proposed that the Lantian basin was largely anoxic but punctuated by brief oxic episodes. These oxic episodes were opportunistically capitalized by benthic macroeukaryotes that were subsequently killed and preserved by frequent oscillations to anoxic conditions (Yuan et al., 2011). To test this model, we carried out petrologic and geochemical studies on the fossiliferous Lantian black shales. We measured

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http://dx.doi.org/10.1016/j.precamres.2014.01.003

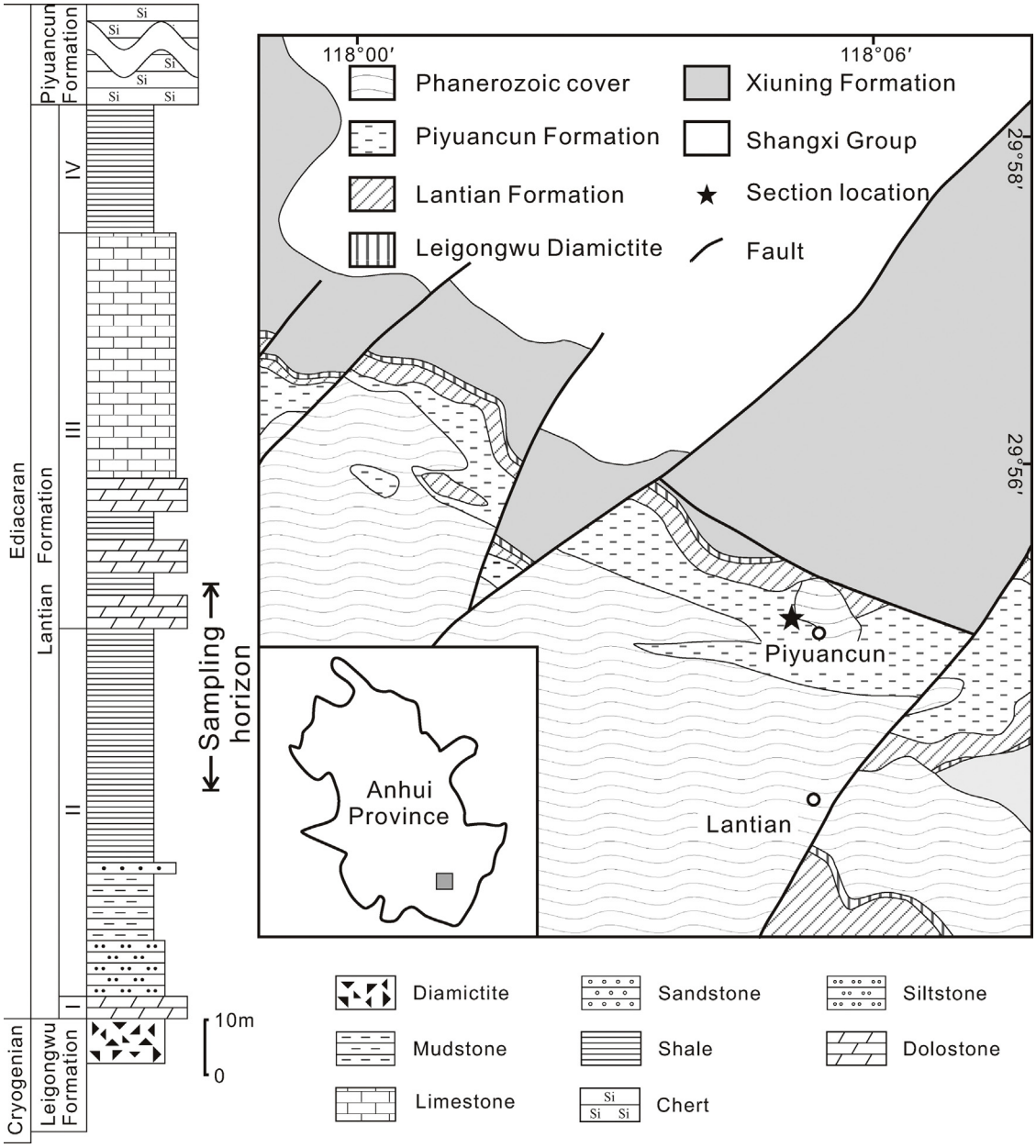

Fig. 1. Geological map of the studied area and Ediacaran stratigraphy of the studied section.

the size distribution of pyrite framboids within individual mm-scale laminae using scanning electron microscopy, and measured the concentration of redox-sensitive trace elements in both bulk rock samples and at the scale of a few laminae. Our data indicate that frequent changeover in redox condition did occur in the early Ediacaran shelf basin environment, and that the use of geochemical proxies on bulk rock samples, as opposed to lamina-scale pyrite framboidal analysis, may not accurately resolve fluctuating bottom water redox conditions.

2. Lithostratigraphy and sedimentary background of the Lantian Formation

The Ediacaran System in southern Anhui Province, South China, consists of Lantian and Piyuancun formations (Fig. 1) that can be correlated with the Doushantuo and Dengying formations in the Yangtze Gorges area, respectively (Yuan et al., 1999). Overlying the Leigongwu Formation diamictite (Nantuo diamictite equivalent) at Lantian in Xiuning County, the Lantian Formation can be subdivided lithologically into four members. Member I is an ~4-m-thick dolostone (cap dolostone). The lower part of Member II is ~24-m-thick gray fine sandstone, siltstone, and mudstone, with the number of black shale interbeds increasing up section. The upper part of Member II is characterized by an ~40-m-thick black shale unit that yields the Lantian biota (Fig. 2a and b). The shales have high total organic carbon (TOC) content (average 5.7%, Wang, 2004). Our sedimentary observations indicate that millimeter-scale fine parallel laminations dominate in the Member II black shales (Fig. 2c and d). Discontinuous fine pyrite laminations and centimeter-sized pyrite clusters are common in the studied black shale (Fig. 2e and f). Sedimentary structures indicative of high-energy environments, such as ripple marks and cross-beddings, are completely absent in Member II of the Lantian Formation. Member III is characterized by an ~26-m-thick gray dolostone interbedded with black shale in the lower part, and an ~40-m-thick limestone in the upper part. The limestone has wavy bedding structure and is composed