Trace element and mineral composition of Ediacaran-early Cambrian strata in South China and their geochemical implications

Q Deng1,2, J B Xu1,2, Z W Wei1,2, B Cheng1, O L Faboya1,3 and Z W Liao1
1 State Key Laboratory of Organic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, China
2 University of Chinese Academy of Sciences, Beijing, 100049, China
3 Department of Chemical Sciences, Afe Babalola University, Ado-Ekiti, Ekiti-State, Nigeria

Email: liaozw@gig.ac.cn

Abstract. Ediacaran-early Cambrian is a critical interval in the evolution of atmosphere-ocean environment and biodiversity. The continuous Ediacaran-Cambrian strata in South China provide a good opportunity for investigating the associated environment with its ecological evolution. In this study, outcrop sedimentary rock samples collected from the Dongkanshang and Fengtan sections on the Yangtze Block were analyzed for their mineral and trace element compositions. The results showed some heterogeneity in the geochemistry of the Ediacaran-early Cambrian ocean in South China. Based on the U/Th, V/(V+Ni), V/Cr, and Ni/Co ratios, the middle-deep water was predominated by anoxic or euxinic condition with interferences from several transient oxidation events. The basinal Fengtan section indicates a more reduced depositional environment when compared with the slope Dongkanshang section. This shows that the seawater oxygenation was a gradual process that expanded from shallow to deep water.

1. Introduction
Throughout geological history, the Ediacaran-Cambrian transition is the most critical interval, during which dramatic changes occurred in seawater chemistry and biological evolution. Abundant geochemical studies on Ediacaran-Cambrian strata have been conducted to discuss the co-evolution between life and the environment. For instance, a stratified redox model [1] and wedge-shaped oxygen minimum zones [2] have been proposed as two models for characterizing the structure of the Ediacaran-Cambrian oceans. However, more high-resolution geochemical work is still required to study the temporal and spatial evolution of redox condition during Ediacaran-Cambrian, which will be helpful in understanding the marine environment at the dawn of complex life. In this study, mineral composition and trace elements geochemistry of two sections having different sedimentary settings on Yangtze Block were evaluated in order to provide more insight into the reconstruction of redox dynamics at the basinal scale during Ediacaran-early Cambrian.

2. Geological setting and analytical methods
The Yangtze Block evolved from a rifted basin to a passive continental margin during the Ediacaran-Cambrian transition [3]. The paleogeographic study suggests a shallow-water platform to the northwest, a deep-water basin to the southeast, and a transitional slope in between [4, 5].
The two studied outcrop sections (Dongkanshang and Fengtan) are located in Hunan Province, South China. According to the paleogeographic reconstruction, the Dongkanshang and Fengtan sections were deposited in the slope and basinal settings, respectively (figure 1). The slope Dongkanshang section has 220 m thickness of sedimentary rock which includes the Ediacaran Doushantuo, Dengying, and the Cambrian Niutitang Formations, and consists mainly of carbonates and black shales. The basinal Fengtan section is approximately 160 m thick and includes the Doushantuo, Liuchapo and the lower part of the Niutitang Formations. The Fengtan section comprises dolostones, cherts, and black shales. The Dengying and Liuchapo Formations were regarded as time-equivalent generally.

![Figure 1. The locations of the two studied sections](image)

A total of 141 fresh outcrop sedimentary rock samples collected from the Dongkanshang and Fengtan sections of the Yangtze Block were analyzed for their mineral and trace element compositions. The mineral composition was determined using OLYMPUS Innova-X BTX X-ray diffractometer. Trace elements analyses were carried out on an Agilent 7700x ICP-MS after the digestion with HNO₃-HClO₄-HF-HCl mixture.

3. Results and discussion

3.1. Mineral composition
The mineral composition of sedimentary rocks from the two sections is displayed in figure 2. The chief minerals of the Doushantuo Formation in the Dongkanshang section are dolomite and quartz, whose relative content is greater than 80%. Other minerals include feldspar, calcite, pyrite, illite, and a small amount of zeolite. At the same stratigraphic unit of the Fengtan section, there are additional...
minerals including kaolinite, apatite, but no feldspar. At the Dengying Formation in the Dongkanshang section, calcite, dolomite, and quartz are the three primary minerals. While at the Liuchapo formation in the Fengtan section, there is an almost pure siliceous deposition. The lower Niutitan Formation in both sections consists of black shales which are composed mainly of quartz, feldspar, and illite.

![Figure 2. Mineral composition of the Dongkanshang section (left) and the Fengtan section (right)](image_url)

The rock type and mineral composition of the two sections are different and seem to be related to the various water depths and environmental settings. From the northwest to the southeast, along with
the deeper water, the Ediacaran sediments transformed from carbonate- to siliceous-dominated. Compared with the Fengtan section, there are more feldspars in the sediments at the Dongkanshang section probably due to the more susceptibility of the slope to receiving terrigenous debris. Besides, phosphorous deposit in the middle of the Doushantuo Formation in the Fengtan section was identified, with relative apatite content up to 50% (figure 2). Similarly, the massive phosphorous deposit has been found in the Doushantuo Formation at Hubei and Guizhou Provinces which is currently under exploitation [6]. During the early Cambrian, there was an occurrence of large-scale transgression, leading to the widespread deposition of the Niutitang black shale [7].

3.2. Trace element ratios
Redox-sensitive trace element ratios are valid proxies for assessing the paleo-redox condition. For example, $\text{U}/\text{Th}>1.25$, $\text{V}/(\text{V}+\text{Ni})>0.54$, $\text{V}/\text{Cr}>4.25$, and $\text{Ni}/\text{Co}>7$ could serve as indicators of anoxic condition, whereas these ratios decrease with the increased oxidation of the depositional environment [8, 9]. Moreover, euxinic condition (presence of $\text{H}_2\text{S}$) can be distinguished from anoxic condition (without $\text{H}_2\text{S}$) when $\text{V}/(\text{V}+\text{Ni})=0.84$.

![Figure 3. Paleo-redox conditions according to trace element ratios (Cb-Cambrian; Ntt-Niutitang)](image)

The $\text{U}/\text{Th}$, $\text{V}/(\text{V}+\text{Ni})$, $\text{V}/\text{Cr}$, and $\text{Ni}/\text{Co}$ proxies display overall strong variations throughout the two studied sections. However, their patterns of variation are not the same as they provide different hints on the paleo-redox condition at some particular beds. For example, at the lower Niutitang Formation from the Dongkanshang section, the $\text{U}/\text{Th}$ ratio indicates a suboxic state while the $\text{V}/(\text{V}+\text{Ni})$ ratio indicates a euxinic state, and both $\text{V}/\text{Cr}$ and $\text{Ni}/\text{Co}$ ratios indicate an anoxic condition. The conflicting redox interpretations are likely to be, in part, the consequence of the differing sensitivities of the employed proxies to high-frequency redox variation in the Ediacaran-early Cambrian oceans [10]. On the other hand, these proxies have multiple controlling factors besides benthic redox condition, such as organic matter accumulation, sedimentation rate, and diagenetic process [11, 12].

Nevertheless, the comprehensive evaluation of paleo-redox conditions of these two sections is displayed in figure 3. The results show a significant spatial and temporal variation in redox condition from the slope to basin area across the Yangtze Block. The Ediacaran-early Cambrian oceans were
predominated generally by anoxic-euxinic conditions, while occasionally interrupted by suboxic-oxic variations. The seawater reflects a more reduced condition in the basin area as compared to the slope area. This suggests that the oxygenation process expanded from the shallow to deep water, but could not be completed during the early Cambrian.

4. Conclusion
The mineral and trace element compositions of outcrop sedimentary rock samples collected from the Dongkanshan and Fengtan sections reflect significant spatial-temporal heterogeneity of ocean chemistry within Ediacaran-early Cambrian strata on Yangtze Block. From the slope to basinal area, the Ediacaran sediments changed from carbonate- to silicicaceous-dominated, and the depositional environment got more reduced. Fluctuant redox conditions prevailed in the Ediacaran-early Cambrian oceans, and the deepwater was yet to be fully oxidized during the early Cambrian.

Acknowledgments
The authors are grateful to Dr. L L Wu from SKLOG for help in the field trip work. This research work was financially supported by the National Natural Science Foundation of China (grant no. 41772117) and the Oil and Gas Special Project of China (2017ZX05008002).

References
[1] Li C, Love G D, Lyons T W, Fike D A, Sessions A L and Chu X 2010 A stratified redox model for the Ediacaran ocean Science 328 80-83
[2] Hammarlund E U, Gaines R R, Prokopenko M G, Qi C, Hou X G and Canfield D E 2017 Early Cambrian oxygen minimum zone-like conditions at Chengjiang Earth Planet. Sci. Lett. 475 160-168
[3] Wang J and Li Z X 2003 History of Neoproterozoic rift basins in South China: implications for Rodinia break-up Precambrian Res. 122 141-158
[4] Steiner M, Li G. X, Qian Y, Zhu M Y and Erdtmann B D 2007 Neoproterozoic to Early Cambrian small shelly fossil assemblages and a revised biostratigraphic correlation of the Yangtze Platform (China) Palaeogeogr. Palaeoclimatol. Palaeoecol. 254 67-99
[5] Zhu M Y, Zhang J, Steiner M, Yang A, Li G and Erdtmann B D 2003 Sinian-Cambrian stratigraphic framework for shallow- to deep-water environments of the Yangtze Platform: an integrated approach Prog. Nat. Sci. 13 951–960
[6] Gao Y P, Zhang X L, Zhang G J, Chen K F and Shen Y N 2018 Ediacaran negative C-isotopic excursions associated with phosphogenic events: evidence from South China. Precambrian Res. 307 218-228
[7] Goldberg T, Strauss H, Guo Q J and Liu C 2007 Reconstructing marine redox conditions for the early Cambrian Yangtze platform: evidence from biogenic sulphur and organic carbon isotopes Palaeogeogr. Palaeoclimatol. Palaeoecol. 254 175-193
[8] Jones B, Manning D A C 1994 Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones Chem. Geol. 111 111-129
[9] Rimmer S M 2004 Geochemical paleoredox indicators in Devonian–Mississippian black shales, Central Appalachian basin (USA) Chem. Geol. 206 373-391
[10] Jin C S, Li C, Algeo T J, O’Connell B, Cheng M, Shi W, Shen J and Planavsky N J 2018 Highly heterogeneous “poikiloredox” conditions in the early Ediacaran Yangtze Sea Precambrian Res. 311 157-166
[11] Algeo T J and Maynard J B 2004 Trace-element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems Chem. Geol. 206 289–318
[12] Tribouillard N, Algeo T J, Lyons T and Riboulleau A 2006 Trace metals as palaeoredox and paleoproductivity proxies: an update Chem. Geol. 232 12–32