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Formative mechanisms, depositional processes, and geological implications of Furongian (late Cambrian) reefs in the North China Platform

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ABSTRACT

The Cambrian Series 3–Furongian successions of the North China Platform contain various microbial–metazoan and microbial reefs. This study focuses on Furongian reefs of the platform in order to understand formative processes and the evolution of the reefs during Cambrian Epoch 3 and the Furongian. Three types of Furongian reefs were differentiated in the Shandong region, China: maceriate reefs, columnar stromatolitic reefs, and small-scale microbial reefs. Maceriate reefs show dm- to m-scale domal or flat-bedded geometry, and consist of cm-scale maze-like maceria structures made of siliceous sponges and microbial components (microstromatolites, *Girvanella*, and *Tarthinia*). Columnar stromatolitic reefs are characterized by stromatolite columns of 10–100 cm in height and 5–50 cm in diameter. They consist dominantly of *Girvanella*, with less conspicuous, poorly preserved sponge spicule networks. Small-scale microbial reefs commonly show cm- to dm-scale, domal macrostructures, and were constructed mainly by calcimicrobes, *Girvanella* and *Renalcis*. These three types of Furongian reefs were deposited in various shallow-marine settings in response to relative sea-level changes.

The Furongian reefs are markedly different, in terms of macro- and micro-fabrics, from the Cambrian Series 3 reefs that are dominated by thrombolites and dendrolites and were constructed mainly by *Epiphyton* in the Shandong region. This difference is also recognized in the Beijing region, ca. 500 km away. The abrupt transition from the Cambrian Series 3-type to Furongian-type reefs, coincidently with a decrease in calcified microbe diversity, was most likely due to global euxinic oceanic conditions and a possible eustatic sea-level drop, rather than the highly diachronous, platform-wide drowning event (i.e., drowning of the Cambrian Series 3 carbonate platform). The abundant occurrence of sponge spicule networks in the Furongian reefs suggests that metazoan reef builders (i.e., sponges) resurged and became actively involved in the reefal systems prior to the Great Ordovician Biodiversification Event. This study may provide an important basis for further investigation into the evolution of reefal systems during the middle to late Cambrian when metazoan reef-builders were known to be scarce.

1. Introduction

The evolution and extinction of organisms significantly affected Early Paleozoic reef-building communities (Wood, 1999; Rowland and Shapiro, 2002). Early Cambrian reefs were mainly constructed by archaeocyaths and diverse calcimicrobes (e.g., Rees et al., 1989; Elicki, 1999; Rowland and Shapiro, 2002). Archaeocyaths went to extinction during the end-Cambrian Epoch 2 extinction event, and many calcified microbes perished as well (Zhuravlev, 1996; Riding, 2001; Lee et al., 2014b). Metazoan reef builders participated only to a limited extent in constructing reefs until the Early Ordovician (Adachi et al., 2011; Wang et al., 2012). It is thus commonly believed that the middle to late Cambrian (Cambrian Epoch 3 to Furongian) was dominated by reefal microbialites (Wood, 1999; Riding, 2006).

The North China Platform contains various microbial and microbial–metazoan reefs that are Cambrian Epoch 3 and Furongian in age (Woo et al., 2008; Chen et al., 2009, 2011; Lee et al., 2010, 2012, 2014a; Woo and Chough, 2010; Chen and Lee, 2014). The reefs of these two intervals are, however, tremendously different with respect to their micro- and macro-scale features. The Cambrian Series 3 reefs are characterized by thrombolites and dendrolites that were constructed mainly by the calcimicrobe *Epiphyton*, with minor metazoan reef-builders (Woo et al., 2008; Woo and Chough, 2010; Park et al., 2011; Hong et al., 2012). On the other hand, the Furongian reefs mainly consist of maze-like, maceriate sponge-microbial reefs and columnar stromatolitic reefs, without any *Epiphyton* (Chen et al., 2011; Lee et al., 2014a). These Furongian reefs, on the whole, are not yet fully investigated,

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except for the maceriate reefs that were recently studied by Lee et al. (2010, 2012, 2014a).

The Furongian reefs are critical with respect to the evolution of reefal systems during the Early Paleozoic since they connect the Cambrian Series 3 reefal systems in the aftermath of end-Cambrian Series 2 extinction event with the Early Ordovician reefs that formed during the Ordovician biodiversification event. In order to examine the geological characteristics of the Furongian reefs, this study focuses on those in the central-eastern part of the North China Platform (Shandong Province, China), which are compared with coeval reefs in the northern part of the platform (Beijing region, China). The main objectives of the present study are thus to (1) illustrate various Furongian reefs and their formative processes, (2) elucidate the nature of reef development in response to relative sea-level changes, and (3) discuss the evolution of Cambrian reef systems by comparing the Furongian reefs with Cambrian Series 3 reefs of the same region.

2. Geological setting

The North China Platform was an extensive epeiric platform (1500 km east–west and 1000 km north–south) that formed on a stable craton, the North China Block (Sino-Korean Block), during the Early Paleozoic (Meyerhoff et al., 1991). It is now bounded by major suture zones, the Hinggan fold belt in the north, the Qinling–Dabieshan fold belt in the south, and a major sinistral strike-slip fault, the Tan–Lu fault, in the east (Chough et al., 2000) (Fig. 1A). Sedimentation on the North China Platform started in Cambrian Series 2 and continued until the Middle to Late Ordovician when the entire platform was subaerially exposed. This resulted in a thick (ca. 1800 m in thickness) succession of mixed carbonate and siliciclastic deposits (Meyerhoff et al., 1991; Meng et al., 1997). After a platform-wide hiatus during the middle Paleozoic (Late Ordovician to Early Carboniferous), coal-bearing, shallow marine and continental deposits accumulated on the platform during the Carboniferous and Permian (Lee and Chough, 2006; Lv and Chen, 2014). Deposition on the platform was terminated in the Early Triassic by regional uplift that resulted from the collision between the North China Block and the South China Block (Lee and Chough, 2006).

The Cambrian strata on the North China Platform contain a thick (ca. 800 m) succession of mixed siliciclastic and carbonate sediments, which were deposited in shallow-marine settings during long-term sea-level rise (Meng et al., 1997). The Cambrian succession in Shandong Province, China consists of six lithostratigraphic units (i.e., the Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian Formations in ascending order), which unconformably overlies Precambrian granitic gneiss or metasedimentary rocks and is conformably overlain by late Furongian–Early Ordovician dolostones (Sanshanzi Formation) (Meng et al., 1997; Chough et al., 2000; Lee and Chough, 2011) (Fig. 2). The dolomitization took place during Middle Ordovician subaerial exposure of the North China Platform, resulting in a highly diachronous lower boundary (Feng and Jin, 1994).

The basal Liguan Formation (laterally discontinuous, 0–30 m thick) consists mainly of quartzose sandstone and mudstone (Fig. 2). It changes both laterally and vertically into the carbonate-dominant Zhushadong Formation (15–40 m thick), which is characterized by stromatolitic and dolomitic lime mudstone, and locally bioturbated wackestone with minor microbial reefs (Lee and Chough, 2011; Lee et al., 2014b). The Mantou Formation (ca. 250 m thick) consists of mixed siliciclastic and carbonate sediments including purple mudstone, sandstone, and various carbonate deposits (Lee and Chough, 2011). The overlying Zhangxia Formation (ca. 180 m thick) is characterized by a variety of microbial-dominant reefs, carbonate deposits, and locally shaly sediments that were deposited during the Cambrian Epoch 3 Changhian Age (*Lioparia*, *Crepicephalina*, *Amphoton–Taitzuia*, and *Damesella–Yabeia* zones; late Cambrian Age 5–early Guzhangian) (Woo, 2009). The Gushan Formation (52–105 m thick) comprises shale-dominated facies deposited during the late Cambrian Epoch 3 Kushanian Age (*Blackwelderia* and *Neodrepanura* zones; late Guzhangian) (Fig. 2). The overlying Chaomidian Formation (190–260 m thick) is dominated by various carbonate facies including thin-bedded limestone-shale/marlstone alternations, wacke- to packstones, grainstones, limestone breccias and

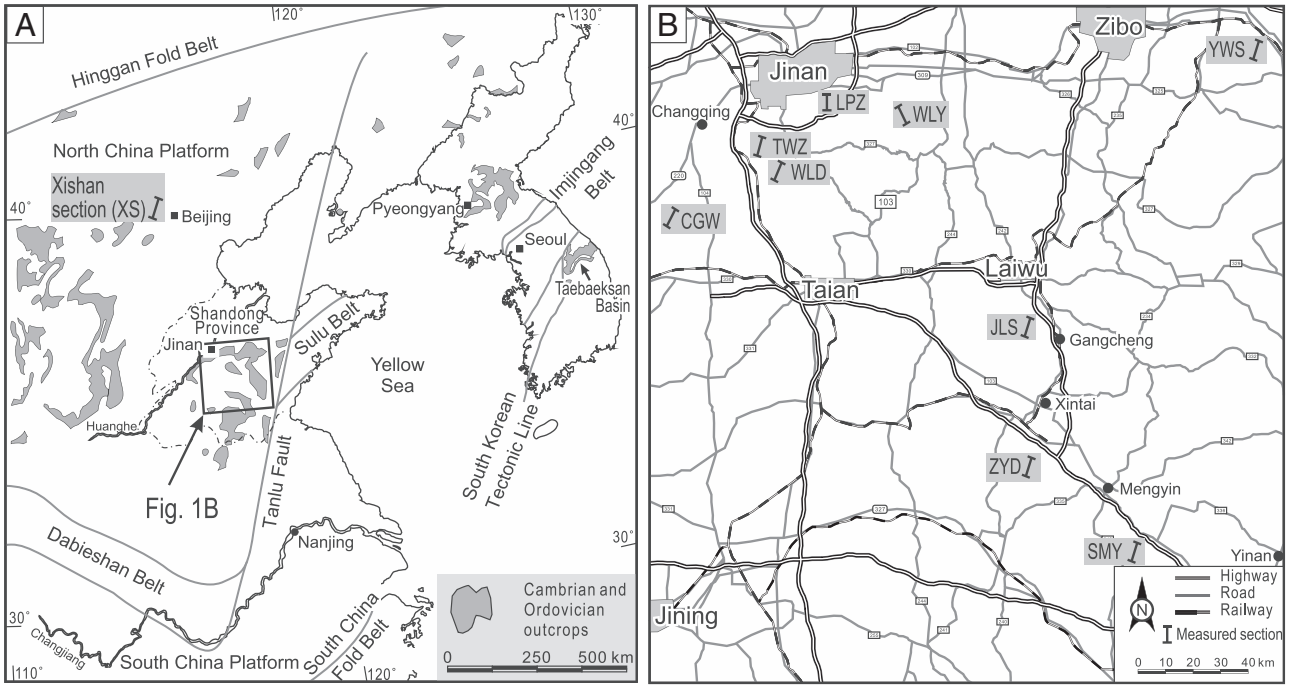

Fig. 1. Brief geological map of the North China Platform and location map of measured outcrop sections. (A) Major tectonic boundaries of the North China Platform and distribution of the Cambrian–Ordovician outcrops, with location of the Xishan section (39°59′38″N, 116°1′18″E). (B) Location map of measured outcrop sections in the Shandong region. CGW: Chengouwan section (36°22′48″N, 116°41′36″E); TWZ: Tangwangzhai section (36°31′00″N, 116°51′39″E); WLD: Wanglaoding section (35°29′5″N, 116°55′53″E); LPZ: Laopozhuang section (36°34′8″N, 117°4′34″E); WLY: Wanliangyu section (36°33′11″N, 117°16′12″E); JLS: Jiulongshan section (36°5′5″N, 117°44′58″E); ZYD: Zhaoyangdong section (35°45′18″N, 117°46′29″E); SMY: Sunmayu section (35°33′40″N, 118°2′11″E); YWS: Yaowangshan section (36°43′02″N, 118°24′58″E).