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The earliest Phanerozoic carbonate hardground (Cambrian Stage 5, Series 3): Implications to the paleoseawater chemistry and early adaptation of hardground fauna

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ABSTRACT

Carbonate hardgrounds are lithified seafloors formed by synsedimentary cementation of carbonate sediments, which dominantly occur during the period of calcite seas. The earliest typical Phanerozoic hardground known until now was reported from the Furongian of USA, which was suggested to indicate onset of the early Paleozoic calcite sea period. In this study, we report hardgrounds from the early and middle parts of the Cambrian Series 3 (Stage 5 and Drumian) of the North China Platform, which predate previously reported hardgrounds. The hardground surfaces developed on oolitic grainstone, oncolitic wackestone, and microbialite (thrombolite and dendrolite), which sharply truncate the underlying deposits. The radial fibrous calcite cements between the carbonate grains below the hardground surfaces indicate that the cements formed by early marine cementation. EPMA analysis reveals that the fibrous cements typically consist of low-Mg calcite. The hardgrounds are sometimes encrusted by microbialites and coated by hematite, suggesting long exposure to the open seawater after formation of the surface. In addition, detailed review on the sedimentological studies of Cambrian Series 3 to Furongian deposits throughout the world reveals that there may be several other hardgrounds during these times, which could have been overlooked. The abundant occurrence of hardgrounds in Cambrian Series 3 deposits suggests that the general paleoseawater chemistry was suitable to induce synsedimentary cementation of low-Mg calcite, implying that seawater chemistry would have changed from the aragonite to calcite seas during the Cambrian Series 3 or even earlier period. Metazoan encrustors and macroborers possibly could not have adapted to the newly appeared substrate condition yet, until the latest Cambrian Series 3.

1. Introduction

The major seawater chemistry of the oceans oscillated dramatically between aragonite seas (aragonite and high-Mg calcite are dominant precipitant) and calcite seas (low-Mg calcite are dominant precipitant) during the Phanerozoic, which was controlled mainly by changes in Mg/Ca ratio of seawater and temperature (Sandberg, 1983; Hardie, 1996; Balthasar and Cusack, 2015). Although this secular variation in seawater chemistry remains enigmatic, it has been postulated that these changes were influenced by fluctuations in the mid-ocean ridge activity: hot basaltic rocks produced from the mid-ocean ridge removes magnesium from sea water (Hardie, 1996; Müller et al., 2013).

Hardgrounds, synsedimentarily lithified seafloors formed by in situ precipitation of carbonate cement, were widespread during periods of calcite seas (e.g., Ordovician and Jurassic–Cretaceous) when synsedimentary, inorganic precipitation of calcite was dominant (Wilson and Palmer, 1992; Rozhnov, 2001; Palmer and Wilson, 2004). The occurrence of hardgrounds formed by abiotic precipitation of cal- 63 cite therefore has been used as an indicator of the calcite seas in the geo- 64 logical record (cf. Zhuravlev and Wood, 2008). The term hardground often includes biological communities consisting of encrusting and boring organisms which encrust the hardground surface (Wilson and Palmer, 1992; Rozhnov, 2001). Strictly speaking, however, hardgrounds can be formed by abiotic cementation of calcite, which does not require biological communities (Wilson and Palmer, 1992). This notion of the abiotic hardground is used throughout this study.

Until now, it has been thought that the earliest Phanerozoic hardground surface ever reported was from the latest part of the Cambrian Series 3 in Iran, but these are formed by microbial activities which enhanced cementation of underlying substrates (Rozhnov, 2001; Kruse and Zhuravlev, 2008). Hardgrounds formed by abiotic cementation of carbonate cements were known to occur from the Furongian, which are encrusted by echinoderms and some spongiomorphs (Brett et al., 1983). During the Ordovician, hardgrounds became abundant in

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carbonate successions, which were colonized by various encrustors, macroborers, and cryptic dwellers (Wilson et al., 1992; Taylor and Wilson, 2003).

The occurrence of hardgrounds cemented by low-Mg calcite in the Furongian successions, together with other evidences, such as transition in reef-building organisms, increase in shell bed thickness, and increase of flat-pebble conglomerates, was thought to indicate the beginning of calcite sea period that lasted until the Late Ordovician (cf. Zhuravlev and Wood, 2008; Lee et al., 2015). On the other hand, based on the changes in chemical composition of organisms and fluid inclusions, it has been suggested that calcite seas could have initiated during the late Series 2 to early Series 3 of the Cambrian (Wilson and Palmer, 1992; Wilson et al., 1992; Hough et al., 2006; Porter, 2007, 2010; Zhuravlev and Wood, 2008). The time gap between these two scenarios (ca. 12 Myr) remained problematical.

In this study, we report the occurrence of hardground surfaces from Cambrian Series 3 successions in the eastern North China Platform, which are among the earliest Phanerozoic hardgrounds ever described. The occurrence of hardgrounds in Cambrian Series 3 deposits from the North China Platform and other areas may provide an additional evidence for global changes in seawater chemistry during this time interval. It will also help understand early adaptation history of the hardground communities.

2. Geological setting

The North China Platform was a stable epeiric platform during the Cambrian, which was situated near the Indian and Australian margin of Gondwana (Golonka, 2009; McKenzie et al., 2011). According to paleomagnetic analyses, the platform was located near the paleoequator during the Cambrian (Zhao et al., 1992; Huang et al., 2000; Yang et al., 2002). Six lithologic units are identified in the Cambrian succession of Shandong Province, China: the Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian formations, in ascending order (Figs. 1 and 2) (Chough et al., 2010). The siliciclastic-dominant Liguan and carbonate-dominant Zhushadong formations formed the lowermost units of the Cambrian succession and were deposited during the early Cambrian Series 2 (Stage 3?) (Lee et al., 2014). The Mantou Formation, which mainly consists of fine-grained siliciclastic and minor carbonate sediments, conformably overlies the Zhushadong Formation (Lee and Chough, 2011). Some hardground surfaces are recognized from the carbonate-dominant part of the upper Mantou Formation. Trilobite biozones including *Redlichia chinensis*, *Yaojiayuella*, *Santungaspis*, *Hsuchuangia-Ruichengella*, *Ruichengaspis*, *Sunaspis*, *Poriagraulos*, and *Bailiella* suggest that the formation was deposited during the stages 4 and 5 of the Cambrian (Geyer and Shergold, 2000; Peng et al., 2012). During the late Stage 5–early Guzhangian (*Lioparia*, *Crepicephalina*, *Amphoton-Taitzuia*, and *Damesella-Yabeia* zones), the carbonate-dominant Zhangxia Formation was deposited conformably on the Mantou Formation (Woo et al., 2008), which bears abundant hardgrounds. The Zhangxia carbonate platform was drowned during the late part of Cambrian Series 3, resulting in the shale-dominated Gushan Formation (Chen et al., 2011). After a sea-level fall, carbonate platform was re-established and formed a thick carbonate succession (Chaomidian Formation; Furongian) where hardground surfaces develop on flat-pebble conglomerates and grainstones, as well as microbialites (Lee et al., 2010, 2012; Chen et al., 2011).

3. Methods

Ancient hardgrounds are identified based on the existence of features indicating exposure of the cemented seafloor to open seawater. The evidence includes encrusting organisms on hard substrates (e.g., crinoids, bryozoans, and corals), borings (e.g., *Trypanites*), sharp erosional boundaries that truncate underlying substrates, early marine cements, or surfaces coated by iron oxides or phosphate (Brett and Liddell, 1978; Brett and Brookfield, 1984; Wilson and Palmer, 1992; Rozhnov, 2001; Palmer and Wilson, 2004). Due to rare occurrences of

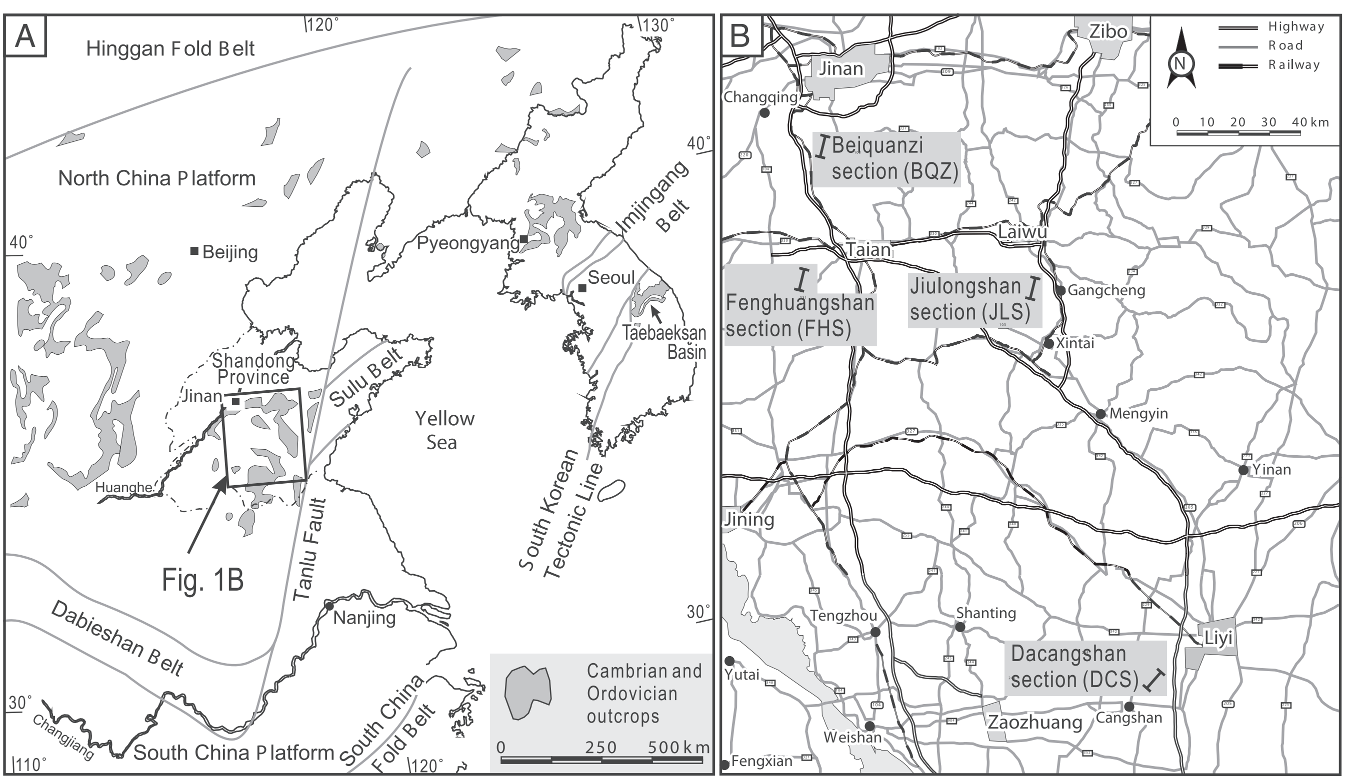

Fig. 1. Location map of the study area. BQZ: Beiquanzi section (36°28′47″N, 116°55′30″E), FHS: Fenghuangshan section (36°09′01″N, 116°54′28″E), JLS: Jiulongshan section (36°04′50″N, 117°44′41″E), DCS: Dacangshan section (34°54′14″N, 118°07′03″E).