J.C. Gutiérrez-Marco, I. Rábano and D. García-Bellido (eds.), *Ordovician of the World.*
Cuadernos del Museo Geominero, 14. Instituto Geológico y Minero de España, Madrid. ISBN 978-84-7840-857-3

DEMISE OF EARLY ORDOVICIAN OOLITES IN SOUTH CHINA: EVIDENCE FOR PALEOCEANOGRAPHIC CHANGES BEFORE THE GOBE

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Keywords: Ooids, GOBE, global cooling, carbonate saturation, Ordovician.

INTRODUCTION

The "Great Ordovician Biodiversification Event" (GOBE) was one of the largest biodiversification events of marine life in Phanerozoic (Webby et al., 2004; Harper 2006). However, the primary causal mechanisms of the GOBE remain the subject of considerable debate (see Servais et al., 2010, and reference therein). Although previous studies expected dichotomically either intrinsic macroevolutionary dynamics (e.g., Sepkoski, 1979) or extrinsic physicochemical changes might have been responsible for the GOBE, more and more researches suggested that both biological and geological factors mutually controlled the onset and consequent development of the GOBE.

The Early to Mid Ordovician has been long regarded as a period of a super-greenhouse world on the basis of modeled atmospheric pCO_2 levels ranging from 14x to 18x PAL (the preindustrial atmospheric level) (Berner, 2006), high sea-level (Haq and Schutter, 2008), as well geochemical proxies (e.g., Shields et al., 2003). In contrast, a gradually global cooling through the Early Ordovician has been recently argued from the oxygen isotope data of conodonts, and consequently considered as the main trigger of the GOBE (Trotter et al., 2008).

Ooids are a kind of coated grains having spherical or ellipsoidal shapes with nuclei encompassed by calcareous cortices. They could be constructed by aragonite and/or magnesium calcite with concentric (tangential) and/or radial microfabrics (Tucker and Wright, 1990). Ooids are commonly regarded as an index of agitated, shallow-water tropical sedimentation. Moreover, the microfabrics, mineralogy and abundance of ooids appear to vary during Phanerozoic, which are well-known proxies for the changes in Phanerozoic seawater chemistry, and paleoclimatic conditions (Sandberg, 1983; Wilkinson et al., 1985; Wilkinson and Given, 1986). Wilkinson et al. (1985) distinguished marked depositional peaks of ooids in the Cambrian, Early Carboniferous, Late Jurassic. However, the temporal changes in abundance of ooids have seldom been documented from the Ordovician of South China.

This study documents the temporal distribution of ooids in the Lower Ordovician of South China. Concerning also other lines of circumstantial evidences, we propose that the decreasing and final demise of ooid precipitation and the concurrent increasing of skeletal accumulation in Early Ordovician were probably induced by the decreasing carbonate saturation state of sea water, which was caused by a fall of atmospheric pCO_2 as well as the resultant global cooling. The global cooling event just opened a window for metazoan reefal constructors, and still remained the induced calcification of cyanobacteria, which were eventually ceased by the further declining carbonate saturation in early Floian of South China.

GEOLOGICAL SETTINGS

The South China paleoplate comprises mainly the Yangtze Platform, the Jiangnan Slope, and the Zhujiang Basin in most of the Early Palaeozoic (Chen and Rong, 1992). During the Early and Mid Ordovician, South China was situated in a middle latitude (Cocks, 2001), and covered by a vast epeiric sea on the Yangtze Platform. In the Tremadocian, extensive shallow-marine carbonates prevailed in the offshore area, with terrigenous clastic input in the inshore areas close to the western oldlands (Zhan and Jin, 2007). The shallow-marine carbonate deposits were shut down in the early Floian, owing to rapid sea-level rise, and the Middle and Lower Yangtze regions were overwhelmed by deeper water, carbonate-siliciclastic mixed deposits (Liu, 2006).

In this study, the Gudongkou section, located at Gudongkou village, about 2 km north of Xingshan County town, northwestern Hubei Province, South China (for the detailed locality map refer to Liu, 2009), is selected to investigate the temporal distribution of ooids in the Early Ordovician. The Early Ordovician strata at this section include the Nantsinkuan (26 m thick), Fenhsiang (21 m), Hunghuayuan (19 m), and lower Dawan formations (> 6 m) (Fig. 1), overlying conformably on the Cambrian strata, and are assigned to the Tremadocian and early Floian age, based chiefly on conodont biozones (Liao et al., in prep.) (Fig. 1).

The lower Tremadocian Nantsinkuan Formation consists of thin- to medium-bedded peloidal packstone/grainstone and oolitic grainstone, with intercalated beds of flat-pebble conglomerate and small amount of stromatolite, which were primarily deposited in a shallow subtidal environment. The upper Tremadocian Fenhsiang and basal Hunghuayuan formations are characterized by increasing deposition of medium-bedded skeletal packstone/grainstones and greenish gray shales, deposited in deep subtidal and shallow subtidal settings. Flat-pebble conglomerate is abundant in this interval. The lower Floian part of the Hunghuayuan Formation is characterized by thick-bedded skeletal packstone and skeletal peloidal packstone with patched sponge-microbial reefs as well as flat-pebble conglomerate, deposited in a shallow subtidal setting. The lower Floian part of the Dawan Formation is dominated by dark gray shales and thin-bedded nodular skeletal wackestone deposited in deep subtidal to basinal environments, due to a major rise of sea level through the Yangtze Platform (e.g. Liu, 2006).

LITHOLOGICAL CHARACTERISTICS OF OOIDS

Most ooids in the Lower Ordovician have well-developed radial microfabrics, composed of calcite, and some ooids have faintly concentric laminae with microcrystal (Fig. 2B). These radial ooids range in diameter from 0.1 to 1.2 mm and have relatively thick cortices up to 0.5 mm. The nuclei of the ooids are mostly micritic peloids and subsidiary skeletal grains. The radial cortices are composed optically of radial-fibrous calcite, and exhibit poorly developed extinction crosses. Single crystals of calcite usually extend to the periphery of the ooid. Between these crystals is microcrystalline calcite exhibiting a vague banding (Fig. 2B).

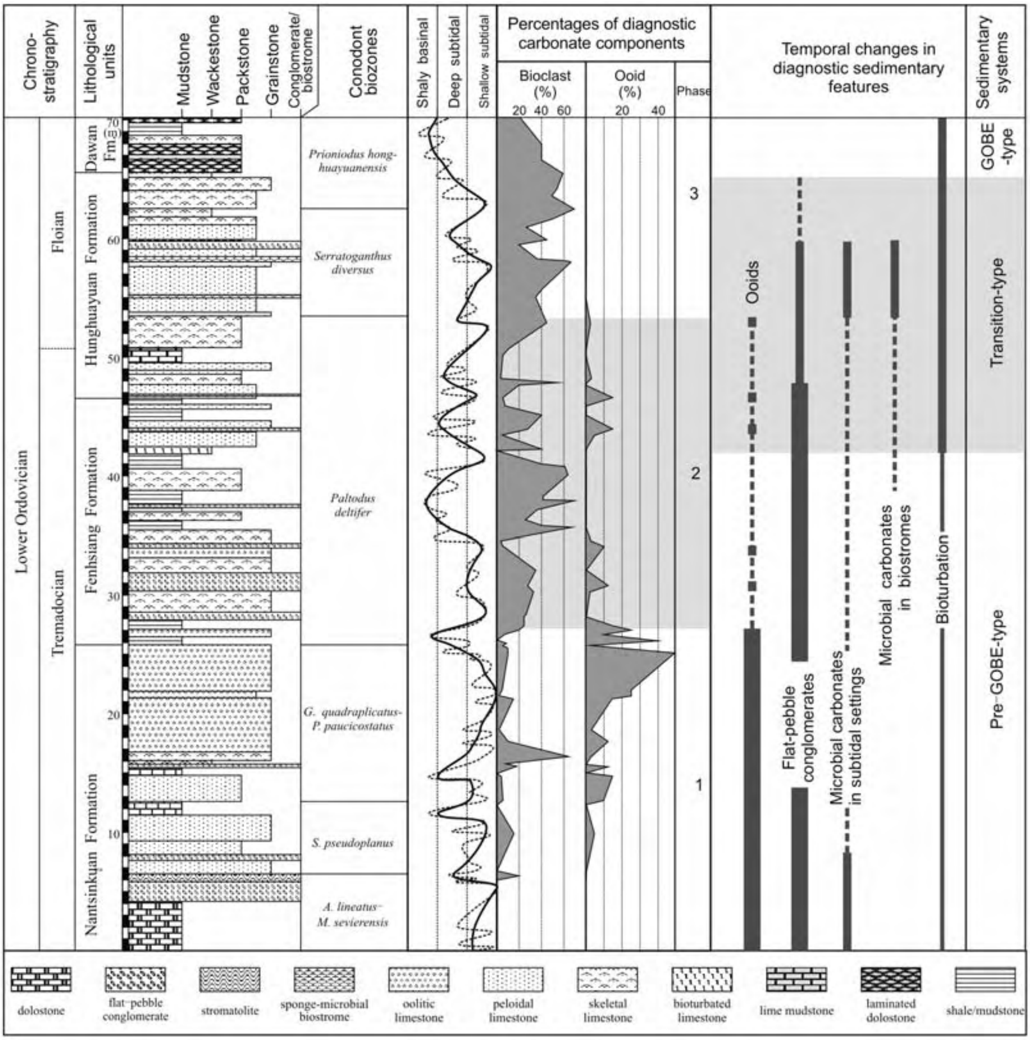

Figure 1. Lithofacies changes, relative sea-level fluctuations, temporal distributions of bioclastics, ooids, and diagnostic sedimentary fabrics of the Lower Ordovician in the Gudongkou section of Xingshan, Hubei Province.

Some other types of ooids occurred at the studied section. For example, superficial ooids with thin, radial cortices occur only in a few stratigraphic intervals, and are accompanied with radial ooids. Composite ooids are much rare, consisting of interior with two or several ooids amalgamated together and a relatively thin cortical layer (Fig. 2B). Sparry radial ooids are composed of neomorphic calcite with relics of originally radial microfabrics retained by the alignment of dark inclusions (Fig. 2C). This kind of ooids is rare, with a limited distribution in the Fenhsiang and the lowermost Hunghuayuan formations.

The ooids mainly occur in thin-bedded to massive packstone and grainstone, but also behave as a minor components of grains with round to irregular peloids and/or bioclastics in wackestone. Ooid grainstone/packstone lithofacies commonly exhibit structureless, graded-, and tabular cross-beddings.

Oolitic intraclasts are common in some oolites and flat-pebble conglomerate units. The ooids and other grains are cemented by equant calcite spar in grainstone.

Well-preserved radial microfabric of the radial ooids indicates an original calcite mineralogy, which resists disruptive structural alteration (Sandberg, 1983; Wilkinson et al., 1985). Sparry radial ooids, although consisting of equant interlocking crystals of calcite, are likely the result of aggrading neomorphic, recrystallization of calcite indicated by the alignment of inclusions. Intensive recrystallization of calcite in the cortices of sparry ooids suggests an early diagenetic stage of dissolution happened after precipitation of ooids.

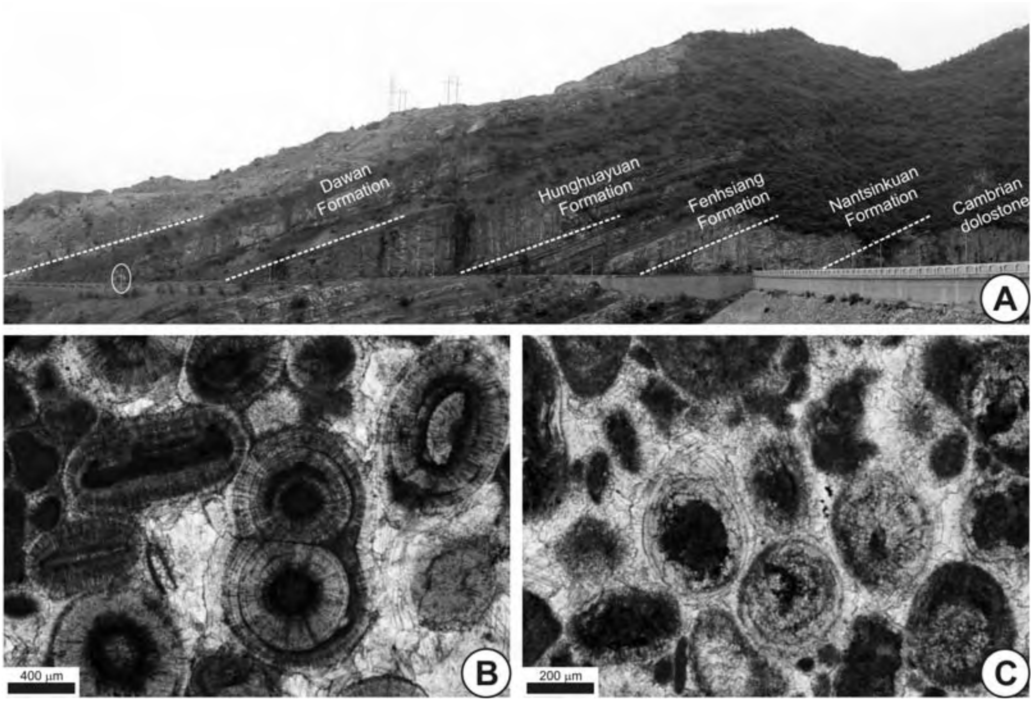

Figure 2. A, Outcrop of the Lower Ordovician in the Gudongkou section, Xingshan County. Telegraph pole (the while bar in ellipse) is about 8 m high. B, Plain light micrograph of radial ooids within oolitic grainstone of the Nantsinkuan Formation. C, Plain light micrograph of sparry radial ooids within oolitic grainstone of the Fenhsiang Formation.

TEMPORAL AND SPATIAL DISTRIBUTIONS OF OOIDS

The percentages of ooids and bioclastics are established with comparison charts for visual estimates (Fig. 1). In general, the frequency of ooids increases from the lower Nantsinkuan Formation, and reaches its acme (~40%) at the top of the formation (Phase 1). A sharp decline in deposition of ooids occurs in the lower Fenhsiang Formation; only 5 ooid-containing beds with frequencies less than 25% are distinguished from the overlying Ordovician strata (Phase 2). The formation of ooids in the Lower Ordovician vanishes eventually from the lower Hunghuayuan Formation, and does not reappear in the rest of the Ordovician (Phase 3). Viewed from their microfabrics, most ooids in Phase 1 have well-preserved radial microfabrics, whereas majority of the ooids in Phase 2 are sparry radial ooids (Figs. 2B, 2C). Composite ooids occur only in Phase 1, and superficial ooids in both Phase 1 and Phase 2.

The temporal distribution of ooids at the Gudongkou section shows a reversed trend for that of bioclastics (Fig. 1). The Nantsinkuan Formation commonly contains rare bioclastics (Phase 1). From the base of the Fenhsiang Formation, the frequency of bioclastics increases gradually and shows two peaks in the middle Fenhsiang Formation (Phase 2) and the middle and upper Hunghuayuan Formation (Phase 3). Additionally, the construction of sponge-microbial reefs apparently follows the disappearance of ooids formation (Fig. 1).

Such a relationship between the temporal distribution of the ooids, bioclastics, and reefs in the Early Ordovician has been observed from wide area (Liu et al., 2010; Liu, unpublished data) across the Yangtze Platform and beyond. Oolites are abundant in Early Ordovician successions (Opdyke and Wilkinson, 1990). The Tremadocian contains abundant stromatolites, oolitic grainstones, and flat-pebbled conglomerates, which become rare in the following Floian of Siberia (Kanygin et al., 2010; Zhuravlev and Wood, 2009). Accumulation of ooids was commonly associated with microbialites in the Lower Ordovician of the Appalachians (Pope and Read, 1998) and the Michigan Basin of Laurentia (Smith, 1996). James et al. (1989) documented a decline of oolite accumulation and an increase in bioclastic carbonate production in the Middle Ordovician of Laurentia, and only localized occurrences of oolites are recorded from the Katian metazoan-dominated reef on several palaeoplates (Webby, 2002). Evidently, multiple changes in carbonate factories occur successively in Early Ordovician world: (1) a decline of ooids deposition; (2) a coeval increase in skeletal mass, and (3) a subsequent inception of construction of metazoan-microbial reefs. Although these changes occurred at slightly different time according to individual regions, the overall succession of changes and their attributes are strikingly similar with each other.

DISCUSSION

A growing body of field and laboratory evidences suggest that ooids are formed by directly chemical precipitation (Davies et al., 1978; Sandberg, 1983; Morse and Mackenzie, 1990), and microbial activity does not necessarily play an essential role in the ooids formation (Schlager, 2003; Duguid et al., 2010). Modern ooids are commonly distributed in a shallow, warm, high-energy environment above a normal wave base (Hine, 1977). The formation of ooids is controlled by (1) existence of nuclei, (2) supersaturated water for carbonate minerals, (3) agitating bottom water, and (4) minimal amount of grain degradation (Flügel, 2004). Accordingly, a rapid sea-level rise or a drowning of carbonate platform may diminish ooids precipitation. However, the Early Ordovician demise of ooids on Yangtze Platform represented the change in factors apart from the facies shifts or long-term sea-level rise, since agitating setting still prevailed on the carbonate platform even after the demise of the ooids formation (Fig. 1).

Supersaturation state, as well as elevated pH, total alkalinity of sea water, is considered to be essentially controlling factors on the modern ooids production (Rankey and Reeder, 2009). Temporal changes in ooids abundance during Phanerozoic likely reflect the fluctuation of the carbonate saturation state in the ocean (Sandberg, 1983; Wilkinson and Given, 1986). During the Ordovician, a sharp decrease in pCO2 as calculated from the GEOCARB and MAGic models (Berner, 2006; Guidry et al., 2007), which were approved independently by the oxygen isotope data of conodonts (Trotter et al., 2008). However, Trotter et al. (2008) further asserted that a global cooling and decrease in atmospheric pCO_2 possibly elevated the carbonate saturation of seawater, and may have triggered widespread carbonate biomineralization and reef growth in the Ordovician. In fact, lower temperature tends to decrease the fluxes of calcium, DIC and total alkalinity from the continents to the ocean, and then decrease carbonate saturation over long time-scales (Riding, 2006); whereas high saturation commonly promotes ordinarily inorganic $CaCO_3$ precipitation (e.g., ooids, carbonate mud, etc.) (Zeebe and Westbroek, 2003). For example, when atmospheric pCO_2 declined in the Cretaceous, skeletal carbonate factory overwhelmed non-skeletal carbonate factory in neritic areas (Pomar and Hallock, 2008). Therefore, the demise of ooids deposition and increase in skeletal accumulation in the Lower Ordovician of South China and elsewhere were controlled by a probable decline of carbonate saturation induced by the decrease in pCO_2 and resultant global cooling event. The limited distribution of sparry radial ooids just after a decline of ooids precipitation in the late Tremadocian provides another line of evidence for a decline rather than a elevation of carbonate saturation during Early Ordovician.

In the Early Ordovician, cyanobacteria (e.g., *Girvanella*) are well-preserved in microbial sediments in South China (Cao et al., 2009; Adachi et al., 2011) and other palaeoplates (Webby, 2002; Riding, 2005). That is to say, the carbonate saturation of seawater, although beginning its decline to some extent from mid Tremadocian, still remained relatively high to induce the calcification of cyanobacteria and the construction of metazoan-microbial reefs in the late Tremadocian and earliest Floian in South China. From mid Floian, metazoan-microbial reefs disappeared on Yangtze Platform, and bioclastics became the major contributor to the carbonate factory, implying a further decline of carbonate saturation.

Late Tremadocian to mid Floian was a pivotal period for the biodiversification processes in South China. Brachiopod of the Paleozoic Evolutionary Fauna began its radiation from early Floian and exhibited its diversity zenith in mid Floian at generic ranks (Zhan and Harper, 2006). Bulk biodiversity trajectories of trilobites and dichograptid graptolites were also executing radiations at early Floian (Chen et al., 2006; Zhou et al., 2007), which was much earlier than the first global-scale diversification at the beginning of Darriwilian (Zhan and Harper, 2006).

Prior to the rapid biodiversification of the Paleozoic Evolutionary Fauna, the sedimentary systems had started their substantial changes (Liu, 2009). The transition-type sedimentary systems were developed in the late Tremadocian to earliest Floian, exhibiting a decrease in subtidal microbialite and flat-pebble conglomerate, and an increase in the extent of bioturbation as compared with pre-GOBE sedimentary systems (Fig. 1). In addition, a replacement of the Cambrian-type shellbeds by Paleozoic-type shellbeds occurred while the transition-type sedimentary systems were developed (Liu et al., 2010). All these changes happened prior to the rapid diversity of the Paleozoic Evolutionary Fauna in South China. According to the temporal distribution of ooids in Early Ordovician of South China, the development of the transition-type sedimentary systems were preceded by the decline of ooids precipitation in mid Tremadocian.

CONCLUSIONS

This study has documented the temporal distribution of ooids in the Lower Ordovician of South China, and recognized the decline and demise of ooids precipitation in mid and late Tremadocian respectively. Concerning also other lines of evidence, we found multiple changes in carbonate factories during the declining process of ooids: (1) a decline of ooids deposition; (2) a coeval increase in skeletal mass, and (3) a subsequent inception of the construction of metazoan-microbial reefs. We propose that the demise of ooids precipitation and the concurrent rise of skeletal accumulation were probably induced by the decrease in the carbonate saturation of sea water, chiefly due to a fall of atmospheric pCO_2 as well as the resultant global cooling. This global cooling event just opened a window for the bloom of metazoan-reefal constructors until mid Floian in South China. The onset of the Ordovician radiation in South China might be due to the decrease in carbonate saturation of neritic seawater, subsequent turnover of carbonate factories, and mutual interactions between physical and biological processes under a long-term global cooling condition.

Acknowledgements

We thank Cao Jun and other graduate students of Peking University for field assistance and helpful discussions. Financial supports for this study were provided by the National Natural Science Foundation of China (40972020, 40825006), the State Key Laboratory of Palaeobiology and Stratigraphy (113104), and the Scientific Research Fund of the Japan Society for the Promotion of Science (21340154).

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