Indian Journal of Geo Marine Sciences
Vol. 50 (09), September 2021, pp. 743-758

Ooid distribution and fabric in the Miaolingian of Xiaweidian Section, Beijing (North China Platform)

A A A Hussein[a,b,c], K Latif*[,b,d], K Shehzad[e], K K Khaing[b], M Riaz[f,g,h] & M U Khan[b]

[a]State Key Laboratory of Marine Geology, Tongji University, Shanghai – 200 092, China
[b]School of Earth Sciences and Resources, China University of Geosciences, Beijing – 100 083, China
[c]Department of Geology and Environment, Thamar University, Thamar – 87246, Yemen
[d]National Centre of Excellence in Geology, University of Peshawar, Peshawar – 25130, Pakistan
[e]Khushal Khan Khattak University, Karak – 27200, Pakistan
[f]Centre for Geographical Information System, University of the Punjab, Lahore – 54590, Pakistan
[g]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu – 610 059, China
[h]College of Energy Resources, Chengdu University of Technology, Chengdu – 610 059, China

*[E-mail: khalidlatif@uop.edu.pk]

Received 25 August 2019; revised 02 December 2021

This study is an attempt to describe the distribution and fabric of the Cambrian ooids from the Xuzhuang, Zhangxia and Gushan formations at the Xiaweidian section. The oolitic banks occupy the upper parts of the 3rd order depositional sequences recognized for these formations. Petrographical techniques were applied to describe the sedimentary features of ooid grains. Different characteristics of ooids including size distribution, composition, morphology and the internal and external cortical architecture were taken into consideration. Radial-concentric, micritic, superficial, composite, pseudo-ooids, neomorphosed and geopetal ooids are properly studied under the microscope. Different fabrics of ooids have been linked to their different depositional settings, and a variety of sub-environments has been established. The oolitic grain banks are composed mainly of calcite, with noteworthy presence of aragonite and dolomite. The two-fold role of microorganisms during and after the formation of ooids can be recognized under the microscope. The mechanism of ooids fabric modification has been elaborated in detail. Firstly, the dark laminae in several ooids most probably show the remains of filamentous cyanobacteria taking part in the construction of ooids. Secondly, they destroy the cortex through boring, which is then subsequently filled by aragonite. In order to apprehend the sedimentological features of the Miaolingian strata in the Xiaweidian section, this research highlights the distribution of oolites and their resultant fabric in response to relative sea-level variations. The Miaolingian ooids in the Xiaweidian section provide a good reference example of the depositional pattern of oolitic grain banks.

[**Keywords**: Cambrian, Miaolingian, North China platform ooids, Xiaweidian**]**

Introduction

Among the coated grains, ooids served as a significant paleoenvironmental proxy for appraising the water depth, chemical composition, salinity, temperature, and water energy[1,2]. They are found in almost entire geological record since Precambrian[3-5]. Oolites are mostly attributed to shallow-water, regularly agitated environments, where ooidal laminae is chiefly controlled by the water chemistry and energy[2,6]. Their growth needs repeated stages of agitation subsequently followed by resting stages[7]. This growth mechanism is widely regarded as a product of the activity of microbes in numerous studies[3,5,8].

Ooids develop oolitic packstone and grainstone[4], which are formed in a high energy setting where these grains frequently move in order to develop their spherical shape specifically in tidal deltas[5], beaches and offshore bars[2]. They can also form at inner carbonate ramp associated with calcareous tempestites, as well as in the washover fans suggesting a high energy environment for their formation[9]. If moved to low energy zones, microbially mediated calcite precipitation on relatively less mobile grains[3,10] may lead to asymmetric ooids[10] or aggregate grains[6].

During the Cambrian time, ooids-dominated carbonate platforms were present across the globe, like in North America, Europe, Australia, Middle East, and Antarctica[4]. In a similar fashion, the Miaolingian carbonates in the north China are characterized by widespread distribution of oolite[4,5,11], having different ooidal fabrics. Prior to the onset of Ordovician radiation event, there were massive carbonate deposition during Cambrian Period in the north China, which resulted in formation of several types of coated grains on North China carbonate platform[4,5,8,12,13].

The current research provides a comprehensive insight into ooids morphology and associated sedimentological features. The Cambrian carbonates in the North China Platform have been extensively studied, however most of the published work is in Chinese[14-16]. This study is an attempt to provide a new view of the oolite beds in the Cambrian strata of the North China Platform. In order to apprehend the sedimentological characteristics of the Cambrian strata in Xiaweidian section, this research highlights the distribution of oolites and their resultant fabric in response to relative sea-level fluctuations. The Miaolingian ooids in Xiaweidian section provides a good reference for studying the depositional pattern of oolitic grain banks in the mature stage of the carbonate platform.

Materials and Methods

The Xiaweidian section, situated at a distance of 20 km west of Beijing, was systematically measured and sampled for petrographic study. The oolitic beds were focused, and all the visible features were recorded during the field. Then the best representative samples were collected and packed in polythene bags, marked with location and appropriate sample number, and sent to the laboratory for further processing. About 220 thin sections were prepared from whole rock fragments. The larger sample was cut down into about 4 – 5 cm thick slabs by the rock cutting machine. The slabs were polished with 400 and 600 mesh size grits for removing cutting marks. After drying and hardening, the samples were cut and polished. Microscopic imaging was carried out for determining the constituent grains, their morphology, and depositional and diagenetic textures using a polarizing microscope at the China University of Geoscience (Beijing). All the geological description, facies variations, features and characteristics were created in digital form using Corel Draw X7 software. While the text and figures of the manuscript were organized in Microsoft Office 2007.

Study area

The Xiaweidian section lies in northeastern part of Beijing and comprises a part of the North China Platform (NCP; Fig. 1a, b), which extends 1000 km north-south and 1500 km east–west. The platform covers Cambro-Ordovician successions, mainly

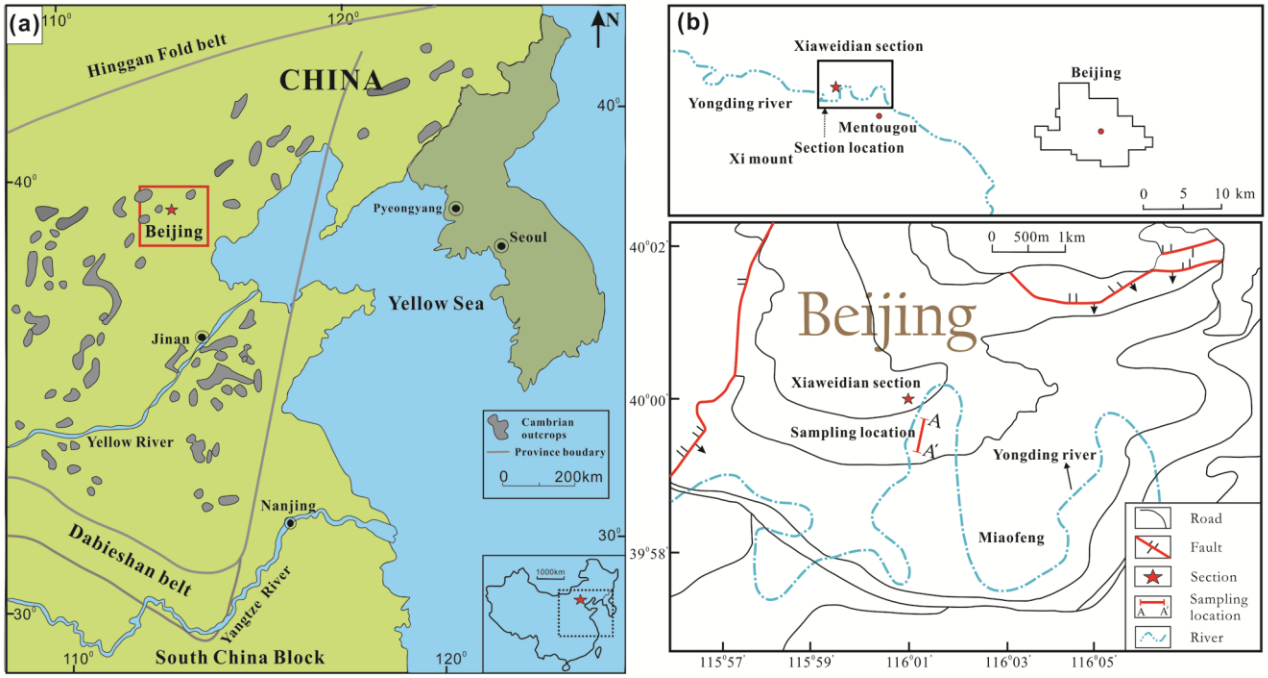

Fig. 1 — Geological setting of the study area: (a) Distribution of the Cambrian outcrops and major tectonic boundaries in the North China platform; and (b) Geological map of Beijing western hills. The star is showing the study area (Modified after Chough *et al.* 2010)

shallow-marine carbonates and siliciclastics[17]. Sedimentary deposition in the NCP started during the early Cambrian and sustained up till the early Ordovician, until the platform was sub-aerially exposed[17]. The Miaolingian succession from bottom to top in Xiaweidian section can be divided into four 3rd order depositional sequences (1 – 10 m.y.), and is bounded at the top and bottom by type one sequence boundaries (SB_1), (Figs. 2 & 3). The whole sequence exhibits a retrogradational facies set deposited during Transgressive Systems Tract (TST) and a progradational facies set deposited during Highstand

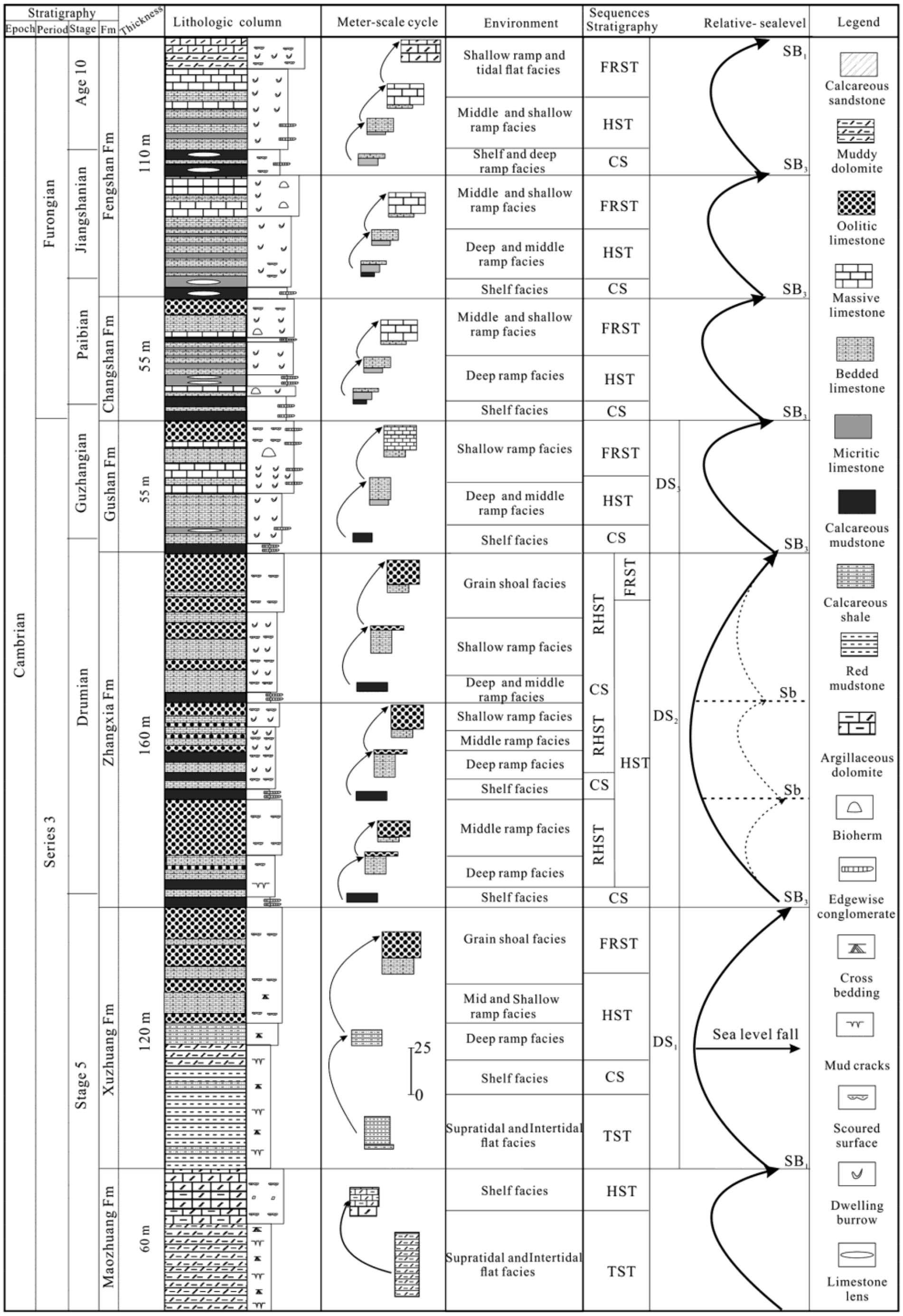

Fig. 2 — Lithostratigraphy of the exposed Cambrian succession along the Xiaweidian section. Abbreviations: *Fm* - Formation; *DS* - Depositional Sequence; *SB* - Sequence Boundary; *TST* - Transgressive System Tract; *CS* - Condensed Section; *HST* - Highstand System Tract; and *FRST* - Forced Regressive System Tract

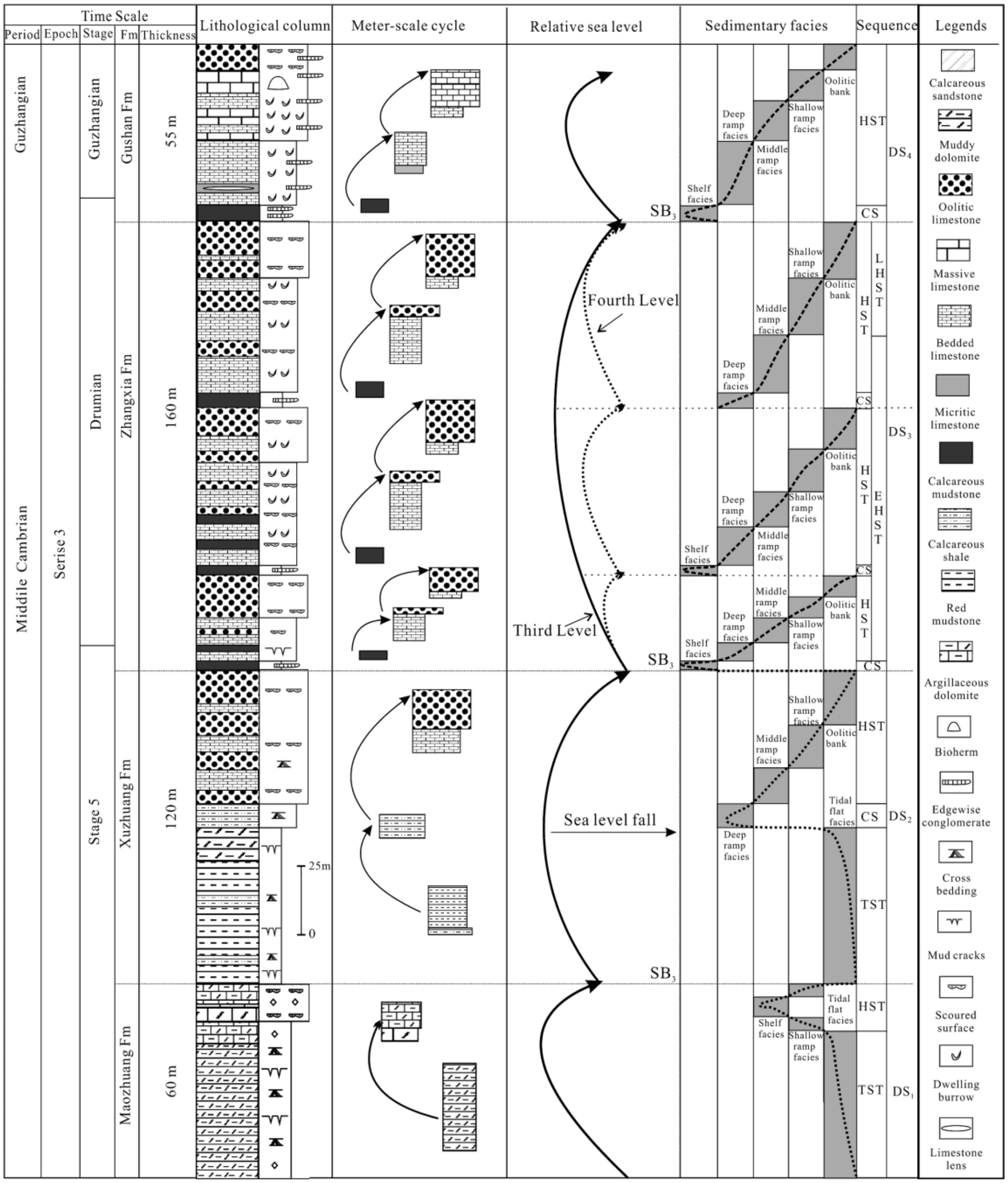

Fig. 3 — Lithostratigraphy of the exposed Miaolingian strata along the Xiaweidian section. Key for abbreviations is same as for Figure 2

Systems Tract (HST). The lithostratigraphic units include: Maozhuang (not sampled, because of lacking ooids), Xuzhuang (depositional sequence 1: DS_1), Zhangxia (depositional sequence 2: DS_2) and Gushan (depositional sequence 3: DS_3) formations. The main lithology of Maozhuang Formation is silty mudstone (Fig. 2). It is purplish red in color and contains salt psuedomorphs. Its thickness is 60 m in the Xiaweidian section. This formation was deposited in a sabkha playa. The overlying two units comprise of dolomite and contain intraclasts and microbial laminites. The Xuzhuang Formation (DS_1) contains a condensed section, which is a shelf facies marking the base of HST. The upward evolution from red beds to thick carbonate deposits shows the maturity of platform in regards to carbonate sedimentation, depositing oolitic grain banks and microbialites. This is indicative of type 3 sequence boundary (SB_3), a drowning unconformity, formed as a result of global sea-level rise. Meanwhile, the whole system is submerged further down the photic zone. This rapid sea-level rise reduced the subsidence at the shelf edge and at the shoreline[18,19]. The oolitic grainstones in the 3rd order sequences of Xuzhuang, Zhangxia and Gushan formations mainly occupy the shallow ramp during HST, with or without microbialites[4,5]. The variable-fabric ooids are distributed throughout the Miaolingian strata in the study section, representing high-energy oolitic-grain banks during regression in the Late Highstand System Tract (LHST)[19,20].

Results

Depositional sequences and lithology

In Xiaweidian section, the paleogeography of middle-late Cambrian interval is represented by ramp type carbonate platform[21]. The oolitic section represents a retrograding to prograding facies pattern from bottom to top. The lack of accommodation space and cessation of carbonate factory led to rapid forced regression[20]. The relative sea-level fall was promoted by regional tectonics and normal faulting in rift system which caused the platform's tilt towards north[17]. The standard sequence stratigraphic model is bypassed as carbonates deposited during forced-regression are analogous to the littoral facies sandstone progradation in muddy continental shelf[22].

A detailed account of the distribution and fabric of ooids have been provided as under:

Depositional sequence 1 (DS$_1$): The Xuzhuang Formation

DS$_1$ starts with a drowning unconformity (Type-1 sequence boundary: SB$_1$), at the bottom of the Xuzhuang Formation. It is represented by a sudden change in lithology from the underlying red beds and dolomites at the base of the Xuzhuang Formation to the oolitic carbonate deposits of shallow ramp facies (Figs. 2 & 3) in the upper part. The base of TST in sequence 1 is marked by clastic sediments containing red beds (58 m thick). These sediments were deposited in supratidal to intertidal settings[4]. On the top of these red beds, shelfal facies comprising of calcareous shale are present, which marks the CS (Fig. 4a) occupying the middle part of the formation (2 m thick)[4,23,24]. The strata above CS is comprised of meter-scale cycle (25 m thick) in a ramp setting (Fig. 4b). A conformable contact exists between the underlying Xuzhuang and the overlying Zhangxia formations (Fig. 4c). The top part of the 3rd order sequence contains thin-bedded mud-intercalated micrite and massive oolitic grainstone (35 m thick; Fig. 4d) of oolitic grain bank facies which constitutes HST.

The uppermost part of Xuzhuang Formation is represented by thin- to thick-bedded massive oolitic grainstone with interbeds of mudstone. They indicate shallow ramp to grain shoal depositional environment[4,9]. The ooids are characterized by different morphologies. Radial-concentric ooids (Fig. 5a) contain pellets as nuclei, and are representative of high energy settings. The elliptical ooids (Fig. 5a, b) have trilobite or brachiopod cores. Their core is enveloped by micrite and the cortices are composed of radial crystals of calcite/aragonite. The micritic envelope is the result of calcification of bacterial biofilm[4]. Superficial ooids (Fig. 5b) have bigger nuclei than the other ooid types and one to two thin aragonite cortices comprised of sparite cement[4,9]. Radial-fibrous calcite film and micritic nucleus cemented by sparite are associated to the calcification of bacterial biofilm, and are believed to have formed in moderate to low-energy environments (Fig. 5b). Composite ooids (Fig. 5c) are composed of several ooids cemented together by sparite. Their sticking pattern indicate that they are probably formed by the reworking of oolites, which have already undergone some lithification. Pseudo-ooids (Fig. 5d) appear without traces of concentric laminae, produced by the dissolution of aragonite and are transformed into dolomite crystals. They specify dolomitization following a calcitization stage, which were later on agglomerated by calcified bacterial biofilms[25]. The dolomite crystals were formed after calcite cementation occurred in tidal limestone. They lack evidence of compaction before the development of dolomitic crystals. Neomorphosed ooids (Fig. 5e) show replacement by sparite, and have possibly undergone dissolution of cortices and cores that were later on filled by sparite cement. The partially dolomitized ooids (Fig. 5f) are shown in a matrix of bladed calcite.

Depositional sequence 2 (DS$_2$): The Zhangxia Formation

The Zhangxia Formation (160 m thick) conformably overlies the Xuzhuang Formation. This formation mainly contains oolitic or skeletal grainstones and microbialites[4]. It was deposited in one 3rd order depositional sequence DS$_2$, bounded by Type 3 sequence boundaries (of drowning unconformity type) at top and bottom[24]. The DS$_2$ starts from the lower shelf facies of calcareous mudstone to the upper

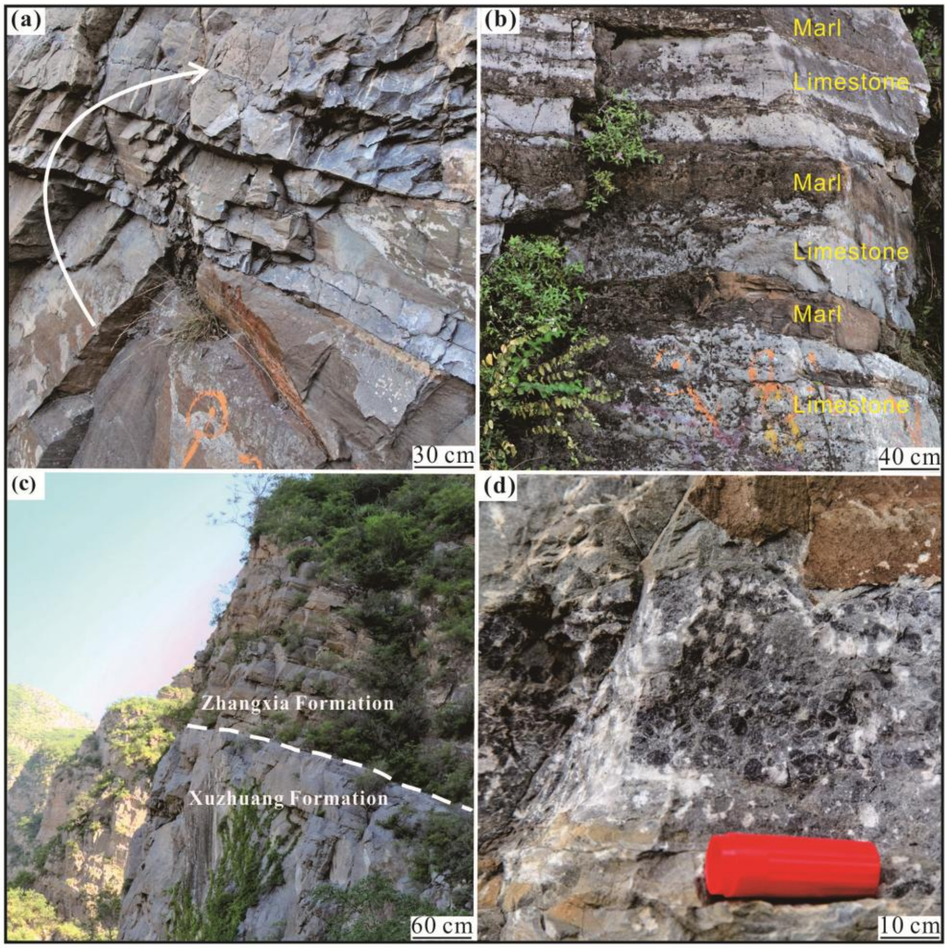

Fig. 4 — Field photographs of the Miaolingian Xuzhuang Formation at Xiaweidian section: (a) Transformation from thick to thin-bedded oolitic limestone; (b) Meter-scale cycle in middle to shallow ramp setting in the Xuzhuang Formation; (c) Oolite in the Xuzhuang Formation overlain by the shelf facies of the Zhangxia Formation; and (d) Upper part of massive oolitic-grainstone of the Xuzhuang Formation

oolitic grain bank facies and reflects a gradually shallowing upward sedimentary sequence (Figs. 2 & 3). The whole sequence is divisible into three 4th order sequences bounded by marine flooding surfaces[4,23,24].

The first 4th order sequence contains calcareous mudstone (Fig. 6a) of shelf facies with lenses of edgewise calcirudite (4 m thick), forming CS (Fig. 6c). Above this bed, thick-bedded calcareous mudstone and thin-bedded micrite is present, which constitute an L-M subtidal meter-scale cycle (Fig. 6b; 15 m thick). This succession marks the bottom of HST, occupied by MFS from bottom and top[13,23]. Middle ramp facies in the form of calcareous mudstone[4,23,24], thin bedded micrite (10 m thick) and thick-bedded oolite (15 m thick) constitutes the upper portion (HST) of the first 4th order sequence.

The second 4th order sequence begins with the calcareous mudstone containing lenses of edgewise calcirudite (3 m thick; Fig. 6c) and micritic limestone at its base (*i.e*. condensed section; Figs. 2 & 3). Deep ramp facies includes thick-bedded calcareous mudstone and intercalated thin-bedded micritic limestone (15 m thick) while the middle ramp facies contains thick-bedded greenish gray calcareous mudstone with edgewise calcirudites and thin-bedded oolites (10 m thick). The overlying shallow ramp facies comprises of massive oolites with thin interbeds of micritic limestone (30 m thick).

The third 4th order sequence is marked by deep to middle ramp facies (20 m thick) at its base, forming a condensed section of this subsequence[18]. From bottom to top, the sequence comprises of thick-bedded calcareous mudstone, thin-bedded micrites and thick-bedded to massive oolites with intercalated micrites (Figs. 2 & 3). The shallow ramp facies consists of thin-bedded micrite and thick beds of oolite

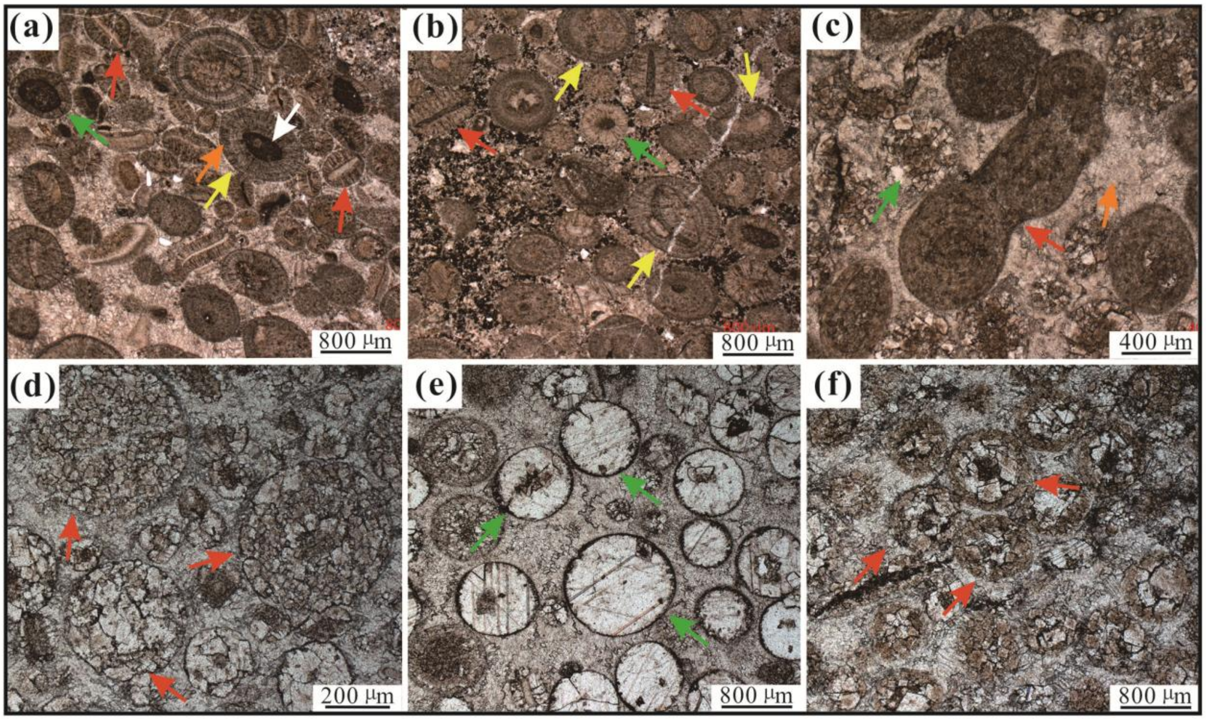

Fig. 5 — Images showing microscopic features of oolitic-grain bank in upper part of the Xuzhuang Formation: (a) Radial-concentric ooid (yellow arrow) with pellets nuclei surrounded by micrite (white arrow), superficial ooids with big nuclei (green arrow), and elliptical ooids with trilobite or brachiopod cores (red arrow); (b) Superficial ooids with big nuclei (yellow arrow) cemented by sparite reflecting high-energy condition, radial ooids (green arrow) with micrite nuclei and cortices composed of calcite spare which are formed in moderate to low – energy environments, elliptical ooids with trilobite or brachiopod cores (red arrow); (c) Composite ooids cemented together, crystals; (e) Different size of neomorphosed ooids (green arrow) cemented by sprite without nuclei; and (f) Partially dolomitized ooids (red arrow) in a matrix of bladed calcite

(8 m thick). A bioherm that pinches out with thin mudstones of the shelf facies occurs in the central part of the Zhangxia Formation (Fig. 6d). A subtidal carbonate meter-scale cycle represented by both the deep-ramp muddy banded marls (5 – 10 cm thick) and the massive oolitic grainstones (5 m thick) is also present (Fig. 6e). They are overlain by oolitic grain bank facies (30 m thick) comprising of massive oolites (Fig. 6f) interbedded with thin micrite.

The oolitic grain banks are observed in the top beds of the 4th order depositional sequences in the Zhangxia Formation (Fig. 6d). In the first 4th order sequence, two distinct ooid type were examined under the microscope, completely neomorphosed ooids (Fig. 7a) and circular ooids with or without core (Fig. 7b). The latter type displays a radial structure of microbial accretion if seen under high magnification, where no distinct separation occurs between the core and the cortex. The possible reason of such without-core ooids is that their formation involves the calcified bacterial biofilms, having cyanobacteria and sulfate reducing bacteria as their predominating microbes. The biofilm accretes together to form an amalgamation, where the microbes provide a microenvironment as the locus of $CaCO_3$ precipitation, and provide a pathway for ooid formation[3,26]. In the second sequence, three ooid types were recorded under the microscope, 1) pseudo-ooids, formed by dissolution of aragonitic grains that transformed into tiny calcite grains, which were bonded together by bacterial biofilms at some later stage (Fig. 7b), 2) composite ooids, formed by aggregation of multiple ooids, and 3) geopetal ooids, containing mixed mineralogy and are probably produced during meteoric diagenetic stage[2]. They might have formed from the solution of aragonite and were subsequently replaced in associated rocks[7] (Fig. 7c).

The oolitic grain bank deposited in the third 4th order sequence as deep to middle ramp facies comprises of various ooid types. Figure 7(d) is showing normal ooids formed of blocky calcite, and embedded in a matrix of bladed calcite. The Neomorphosed ooids (Fig. 7e) might experience

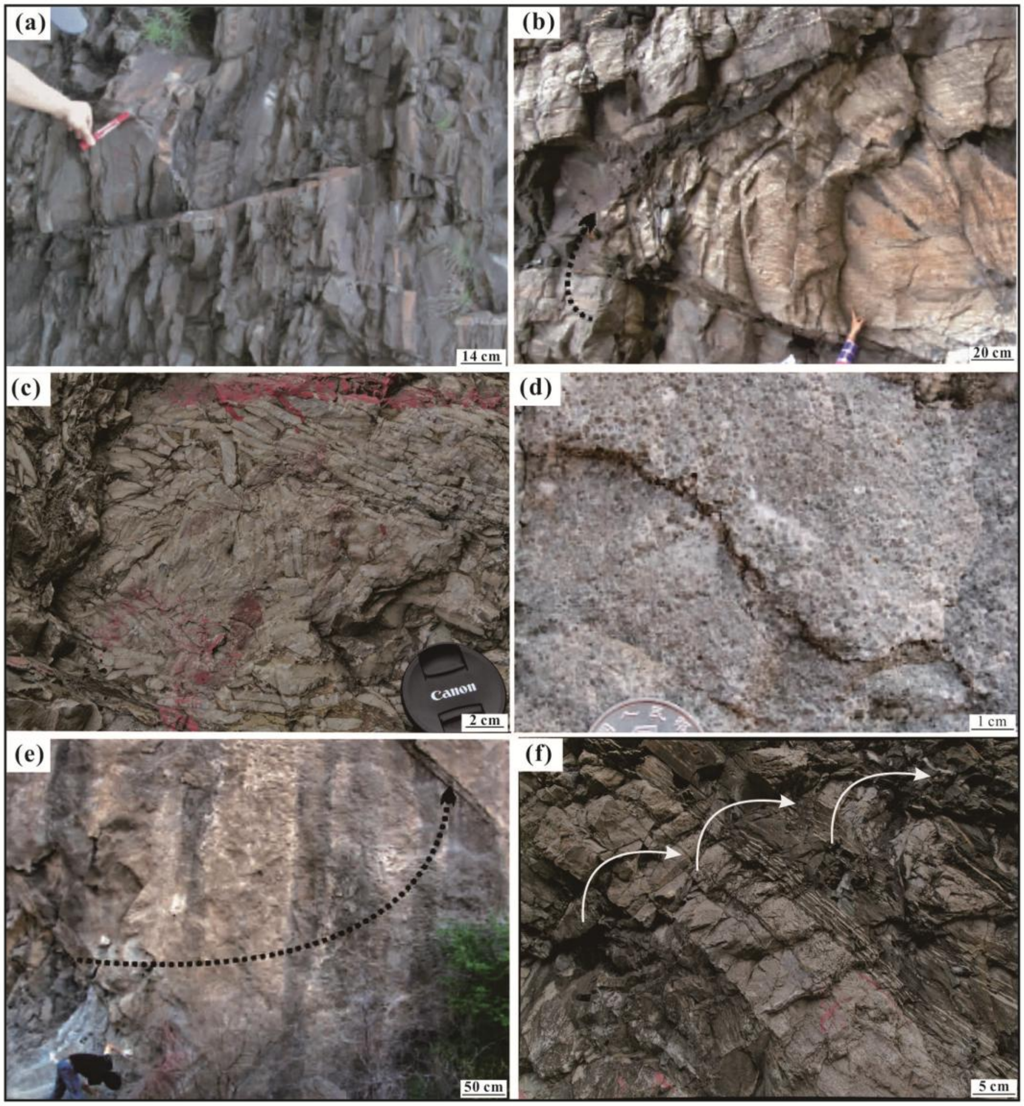

Fig. 6 — Field photographs of the Cambrian strata at the Xiaweidian section for the Zhangxia Formation: (a) Mudstones of the shelf facies in the bottom part of the Zhangxia Formation; (b) Meter-scale cycles in the first fourth-order sequence in Zhangxia Formation; (c) Storm deposits that are marked by flat-pebble calcirudite in the middle part of the Zhangxia Formation; (d) Deep-water bioherm that pinches out (the arrowed) with thin mudstones of the shelf facies in the middle part of Zhangxia Formation; (e) Subtidal carbonate meter-scale cycle (the arrowed) constituted by both the deep-ramp muddy banded marls with the thickness of 5-10 cm and the massive oolitic grainstones with thickness about 5 m; and (f) Upper part of massive oolitic grainstone of the Zhangxia Formation. The arrows shows cyclicity between oolites and thin micrites

dissolution of coatings and cores, which were filled by sparite cement at later stage[4]. The Radial-concentric ooids (Fig. 7f) display an alternation of laminae with radial and concentric fabrics. The radial fabric entirely cross-cuts the other fabrics, and is probably, a diagenetic feature[2]. The radial ooids (Fig. 7h) with pellets as nuclei and cortices of calcite spar composition, possess a cortical fabric comprised of radial-fibrous crystals and formed in moderate to low-energy environments[2]. The superficial ooids (Fig. 7i) have thin cortices around a micritized bioclast, representing a short period in high-energy environment. These ooids are found mainly in domal microbialites, with a smaller proportion associated with sandy oodolarenite facies[27].

Depositional sequence 3 (DS_3): The Gushan Formation

The Gushan Formation (DS_3, 55 m thick) is a sequence of alternating fine-grained mudstone and shale, lime mudstone, and thick-bedded oolite (Figs. 2 & 3). The base of 3rd order sequence (DS_3) is marked by shelf facies of calcareous mudstone (Fig. 8a), edgewise calcirudite (Fig. 8b), and thin-

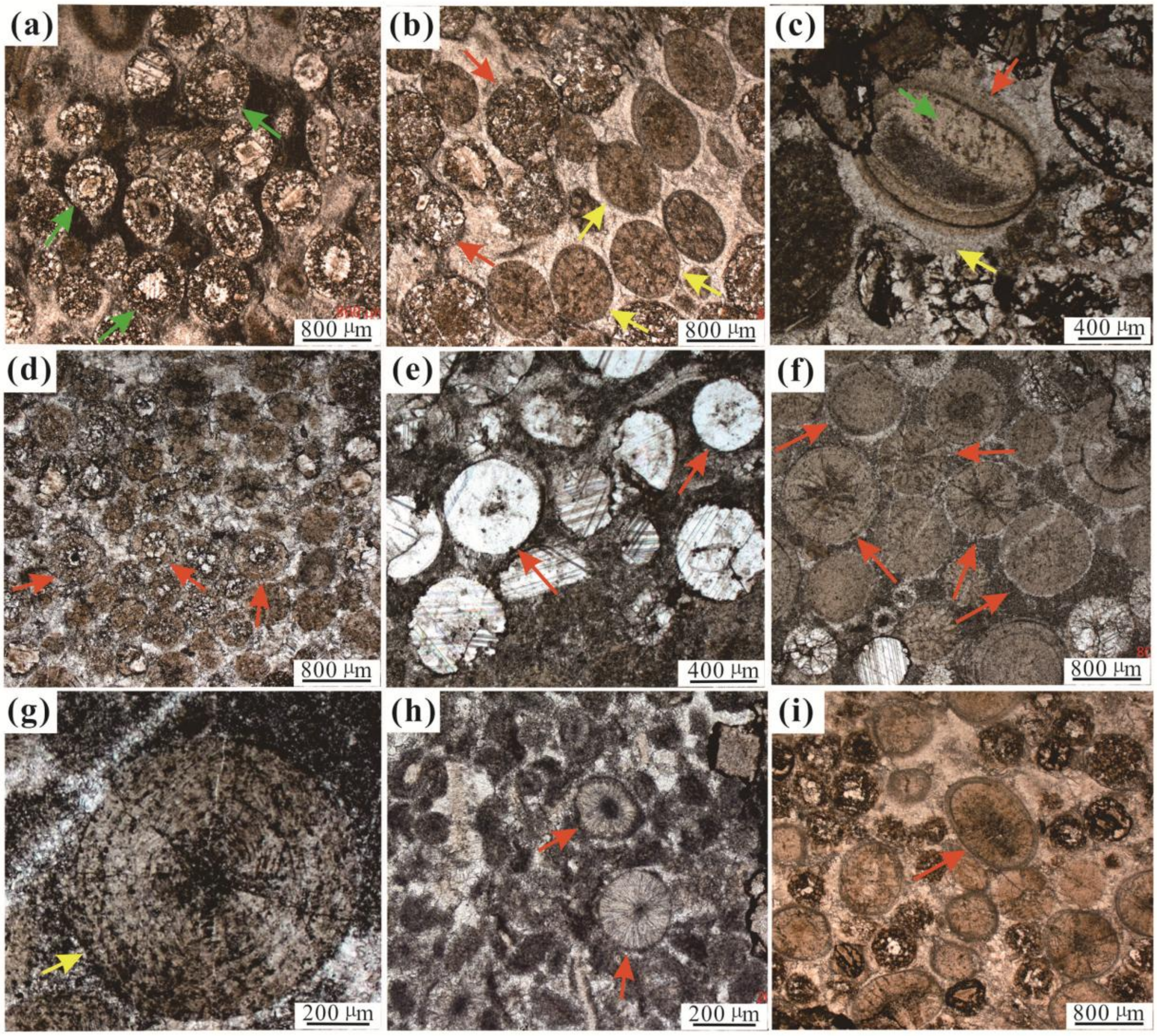

Fig. 7 — Images showing microscopic features of oolitic-grain bank in upper part of Zhangxia Formation: (a) Completely neomorphosed ooids (green arrow) cemented by micrite; (b) Pseudo-ooids cemented by sprite (red arrow) and formed by dissolution of aragonite which alters into tiny crystal of calcite, rounded ooids without cores (yellow arrow); (c) Geopetal ooid (red arrow), contains mixed mineralogy, probably formed from solution of aragonite and subsequently replaced in associated rocks; blocky calcite (yellow arrow), dolomite (green arrow); (d) Normal ooids (red arrows) formed of blocky calcite, embedded in a matrix of bladed calcite; (e) Neomorphosed ooids (red arrow) these grains have probably undergone dissolution of coatings as well as cores and later filling by spary cement; (f) Radial concentric ooids (red arrow) with and without micrite nuclei and surrounding by micrite lamina, is generally related to the clacification of bacteria- films; (g) Radial concentric ooids (yellow arrow) with micrite nuclei and surrounding by micrite lamina; (h) Radial ooids (red arrow) with pellets nuclei and cortices composed of calcite spare; and (i) Superficial ooids (red arrow) with thin cortex around a micritized bioclast, showing the low period in a high-energy environment

bedded micrite forming CS (8 m thick). The middle ramp facies (4 m thick) overlie the CS, and comprises of thin- to medium-bedded micrite. The bioherm-bearing massive limestone with interbedded micrite forms shallow ramp facies (3.5 m thick) in the formation, which is overlain by massive oolitic grainstone (6 m thick) in the top part of this sequence[4,23,24] (Fig. 8e & f).

The Gushan Formation deposited its oolitic-grain bank as shallow ramp facies of Forced Regressive System Tract (FRST) or LHST during relative sea-level fall. Similar oolitic grain banks are also reported from the modern sediments in Bahamas[28]. The recovered ooids include pseudo, radial, superficial and neomorphosed types. Pseudo-ooids (Fig. 9a) resulted from dissolution of aragonite or calcite, altering it into dolomite crystals that were agglomerated by calcified bacterial biofilms at some later stage. The preserved organic matter and their related iron compounds mark the initial outline of

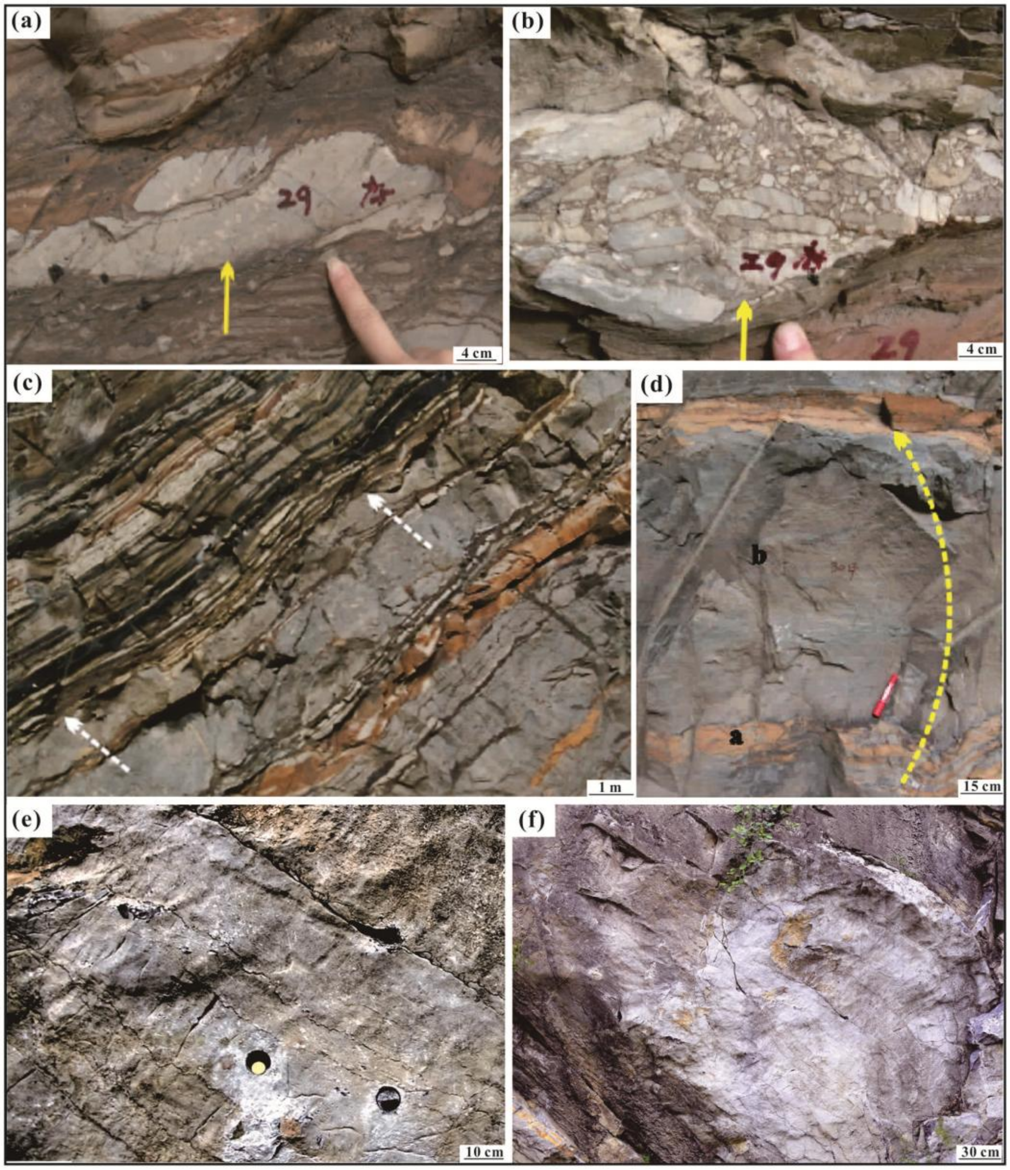

Fig. 8 — Field photographs of the Cambrian strata at Xiaweidian section for Gushan Formation, Miaolingian: (a) Small micritic bioherm (the arrowed) developed within shelf calcareous mudstones in the bottom part of Gushan Formation; (b) Lens of edgewise calcirudite (the arrowed) developed with thin shelf calcareous mudstones in the bottom part of the Gushan Formation; (c) Sequence boundary of the drowning unconformity type (the arrowed) in the top of the Gushan Formation; (d) Sub-tidal meter-scale cycle (the arrowed developed in the upper part of the Gushan Formation , which is composed of both the thin-bedded deep-ramp micrite with muddy bands a and the thick-bedded oolitic grainstone; and (e) & (f) Shallow water bioherms (the arrowed) made up of column stromatolites within massive oolitic grainstone in the upper part of the Gushan Formation

ooids. However, they were significantly disturbed and forced to occupy the inter-crystal spaces between the adjacent dolomite rhombs. Radial concentric ooids (Fig. 9b) appear in alternating dark and light lamina with micritic nuclei, a basic feature of ooids formed in low energy environment[2]. Superficial ooids have a relatively larger nucleus, and single or multiple thin coatings of aragonite (Fig. 9c). This is due to the availability of increased time and energy at their part, which facilitate their migration from low- to high-energy settings, leading to formation of thick cortices[4,16]. Broken ooids (Fig. 9d) exhibits alternating dark and light lamina. Broken ooids show alternate shift in heating and cooling in the subaerial environment, thus causing expansion and contraction[2]. Also the head-on collision of grains

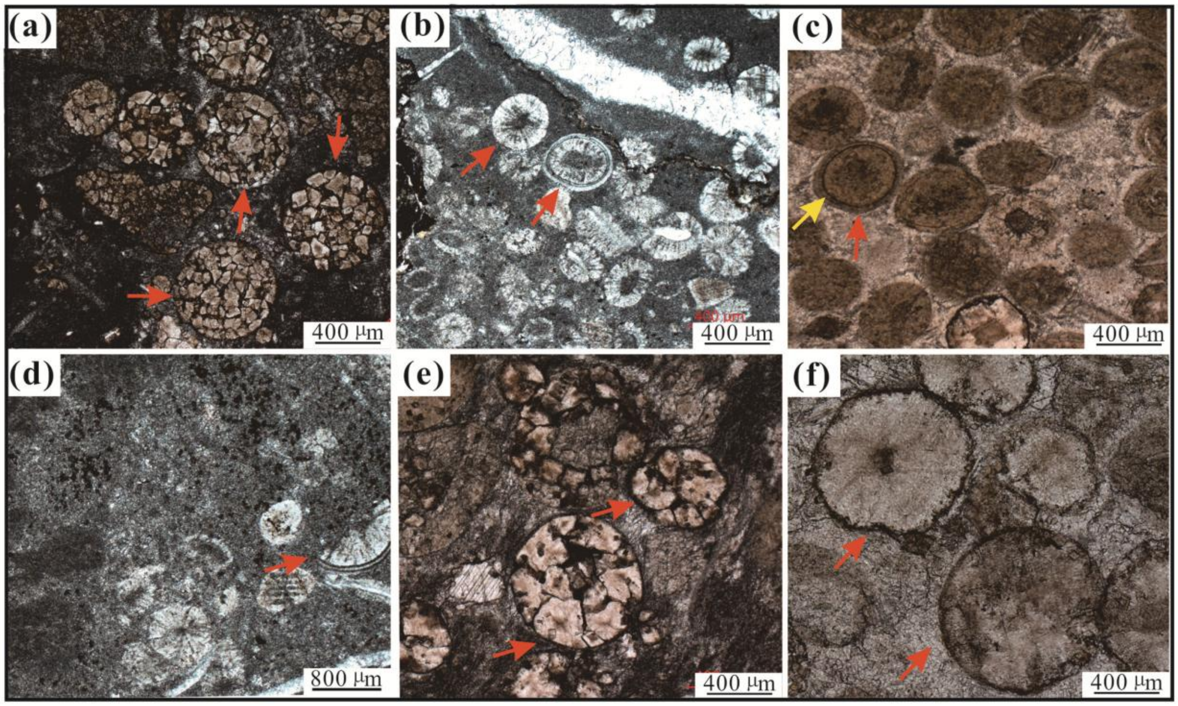

Fig. 9 — Images showing fundamental microscopic features of oolitic-grain bank in upper part of Gushan Formation: (a) Pseudo- ooids (red arrow) cemented by micrite which were formed by dissolution of aragonite/calcite, which alters into dolomite crystals; (b) Radial - concentric ooids with or without micrite nuclei (red arrow) and cemented by sprite; (c) Superficial ooids (red arrow) enclosed by dark micrite (yellow arrow); (d) Broken ooids (red arrow) cemented by micrite; (e) Pseudo- ooids (red arrow) cemented by sparite and destruction of fabrics during burial diagenesis in this ooid coatings were selectively replaced by saddle (baroque) dolomite - the coarse crystals with curved faces; and (f) Neomorphosed ooids (red arrow) single crystal, without nuclei and cemented by sparite

during eolian transport may break the ooids. These ooids may, therefore, represent their deposition in a supratidal environment of pond shores, or the subsequent dehydration of ponds[10]. Figure 9(e) shows variety of pseudo-ooids cemented by sparite, most likely showing destruction of fabrics during burial diagenesis. The coatings were selectively substituted by coarse crystalline saddle (also called baroque) dolomite, shown as coarse crystals with curved faces. Single crystal neomorphosed ooids (Fig. 9f) are composed of aragonite without nuclei, and are cemented by sparite.

Description of ooids

Ooids are nuclei bearing grains of calcium carbonate that fall in a sand size range *i.e.* 0.25 – 2 mm in diameter. They are spherical to elliptical in shape and consist of radiating or concentric rings around a nucleus[2]. Nuclei may consist of bioclasts, rock fragments, peloids and siliciclastic detritus. The crystals are arranged in various patterns around the nucleus[2]. Peripheral arrangement in the form of rings around a nucleus leads to the development of a concentric fabric, whereas radial orientation of calcite crystals around a nucleus leads to radial fabric[6,27]. The number of surrounding laminae also counts in classification of ooids. Smaller radius and a number of laminae in the cortex forms a normal ooid. On the other hand, larger nucleus as compared to cortex thickness is specific to superficial ooids[2]. The chemical composition of ooids is dependent upon the environment where they develop. Water chemistry, depth, energy conditions are some influential factors in their formation[29,30]. The primary shape of nucleus contribute to the ultimate shape of ooid, with spherical shape as the most common one[2].

Ooids prefers to precipitate in shallow marine environment[2]. They develop in the regions of active carbonate and evaporite formation as like in the Arabian Gulf[2,31]. Currently, warm shallow waters are the favorable sites for their deposition where CO_2 is released from water[10]. Ancient rock record as well as some modern high energy water contain high amount of oolitic sediments[32]. Nowadays, they occur mostly in shallow marine, freshwater and saline lake settings[27].

They can occur solitary or combined with one another (Fig. 10). Some ooids have preserved their

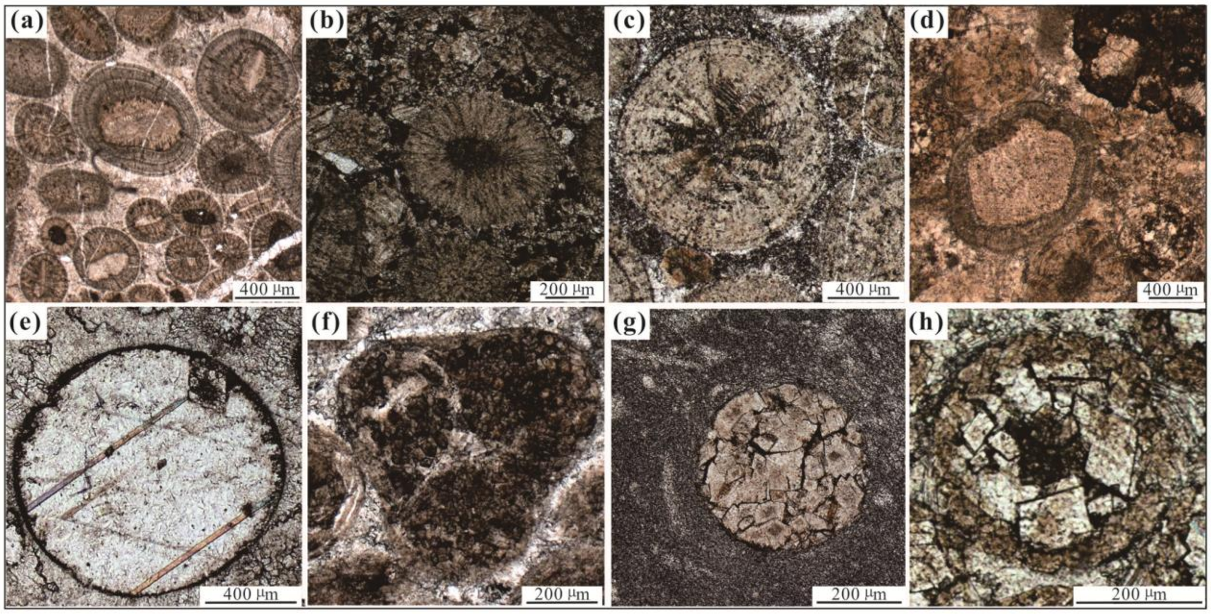

Fig. 10 — Photomicrographs showing the features of Miaolingian oolitic-grain banks in Xiaweidian section: (a) Concentric ooids, showing alternation of laminae; (b) Radial-fibrous ooid; (c) Radial-concentric ooid showing alternation of laminae with radial and concentric fabrics; (b) Radial ooids with micritic nucleus; (d) Superficial ooids with thick cortices cemented by sparite reflecting high-energy condition; (e) Neomorphosed ooids composed of a random mosaic of subequant anhedral spar crystals without nuclei; (f) Composite ooids consist of three ooids cemented together by micrite; and (g, h) Pseudo-ooids made up of dolomite crystals

concentric or radial inner fabric while others have undergone intense alteration to form featureless spheroids. Moreover, superficial, pseudo-ooids, composite ooids, neomorphosed ooids and geopetal ooids can also be seen. The size of ooids is independent of its fabric type. Nucleus in some ooids consists of peloidal fragments, bioclasts of trilobite or brachiopod and, occasionally of quartz grains[27]. The brown-colored carbonaceous matter is distributed among all types of constituent grains.

Concentric ooids

These type of ooids comprise of circular rings surrounding a nucleus. The rings are micritic in composition (Fig. 10a). The thickness as well as number of laminae varies for individual ooid. The cortex of these ooids contains 2 to 5 concentric laminae (Fig. 10a). They are specific to high energy marine environment such as oolitic shoals, tidal bars and beaches, mid- and outer ramp settings[2]. Carbonaceous matter (dense brown) is thoroughly distributed inside concentric laminae while heterogeneously distributed in the inner and outer cortex.

These ooids are usually aragonitic in composition and like to precipitate in agitated sea-water conditions, supersaturated with respect to aragonite[6,27]. Modern day example is the great Bahama bank where such type of ooids are very common. They contain two varying kinds of laminae in their cortices: 1) peripherally oriented aragonite crystal without organic matter indicative of agitated environmental conditions, and 2) Non-oriented tiny crystals of aragonite related with organic matter. Such ooids are the result of interstitial recrystallization and precipitation linked to organic matter combined in the grain[33]. The interpretations here follow Davies *et al*.[7], where he experimentally produced ooids with tangentially arranged crystals in turbulent water conditions without involvement of organisms from a supersaturated solution. While the organic matter accumulated in the low energy stage provides a new substrate for further growth. The mineralogical composition also affects the fabric to a greater extent. According to Medwedeff & Wilkinson[34], the primary aragonitic composition favors the development of concentric ooids. All these statements reveal that the development of concentric ooids involve biotic as well as abiotic factors. The concentric ooids in the studied section were formed in high energy agitated water. However, the extent of influence of hydrodynamic conditions is not that much obvious. While the ooids with structure-less cortices may be the result of chemical precipitation in agitated water abiotically and/or micritization of primary unstable minerals during diagenesis. The concentric fabric suggests prolonged high-energy setting that prevailed during the formation of these ooids[2]. Previous studies suggest that cortical layers are formed by tangential, anhedral rod-like crystals, or subhedral crystals with pointed ends having their average dimensions are 1 – 0.2 µm[10]. The formations of cortical envelopes are also possible from subspherical anhedral (random) crystals (0.25 µm) that change into typical tangential laminae due to continuous washing in the shallow high-energy setting. Several researchers have reported that organisms like algae are primarily associated to the layers of subspherical anhedral crystals[33].

Radial-fibrous ooids

Radial fibrous ooids (Fig. 10b) are characterized by different sizes, cemented by micrite or sparite. Their cortices are composed of calcite spar with micritic nucleus. The arrangement pattern is radial in outer laminae. They are characteristic of moderate to low energy settings, probably in marginal marine environments with higher or lowered salinities[2]. Unlike concentric ooids, the carbonaceous matter is more evenly distributed in radial-fibrous ooids.

The composition does affect the fabric construction here. High Mg-calcite favors the development of radial fabric[6] and is distinctive to some hypersaline lacustrine aragonitic ooids[29]. Aragonitic ooids of marine origin do not exhibit this fabric[7,35]. Radial ooids tend to develop in a feebly agitated, protected marine environments[30]. The presence of abundant humic acid induces the production of radial ooids in calm water[7], where they are precipitated from supersaturated seawater. Such ooids display the alternation of organic rich and carbonate layers, and the radial orientation is displayed by carbonate crystals. The fabric and features of radial ooids in Xiaweidian section reflect some close similarities to ancient and modern-day examples, indicating their deposition in similar conditions with more stable mineralogy[3,10,27].

Radial-concentric ooids

The petrographic studies reveal the presence of several radial-concentric ooids (Fig. 10c); with or without nuclei surrounded by micrite. They show more varied distribution of carbonaceous matter and possess alternation of laminae. They represent an enhanced view of a modern day ooid specified by a radial aragonitic structure with strong traces of concentric lamination[3]. While the coarse, radial aragonite rays seem to have cross-cut the original fabric (also regarded as a product of recrystallization), nevertheless they are primary features in these modern grains. Some of the partially dissolved radial cores also contain micrite rays. Here the radial fabric completely cross-cut the other fabrics and can be regarded as a diagenetic feature (Fig. 10c). These ooids originate in moderate to low energy conditions unlike concentric ooids which develop in high-energy settings[2].

The development of two distinct fabric type in laminae (radial and concentric; Fig. 6a, c) is contributed to compositional differences of the respective layers. Concentric fabric is dominated by aragonite while radial fabric prefers High-Mg-calcite[36]. Although, they may occur together in a single ooid grain with alternating laminae[37]. This feature can be seen in Precambrian[6] as well as in Phanerozoic strata. The combined precipitation of these two is affected by temperature and/or salinity[37]. Organic acids also play an active role here, as High-Mg-calcite precipitates in manifestation to some organic acids while their absence will play the opposite role[26]. Another explanation to this fabric is the variable hydrodynamic conditions[30]. While researchers suggest that microbial growth causes a radial fabric to develop and concentric laminae are attributed to the function of waves and currents[4,5,37,38].

Superficial ooids

A comparatively larger nuclei and thick cortices are characteristic of superficial ooids (Figs. 5b &10d). The outer rim is surrounded by organic matter[2,28] (Fig. 5b). They indicate quiet and calm water conditions and are usually present in domal microbiolites[4,27].

Superficial ooids form within featureless microbiolites associated with other sediments including quartz grains, peloids and intraclasts. This possibly specifies that all these particles were stuck within microbiolites, an unusual phenomenon regarding present-day microbiolites[2,39]. The larger size of the nucleus (Figs. 7i & 10d) is responsible for thin cortex, as the movement of the particle is impeded and the growth is hindered[40], making conditions suitable for microbes to grow and colonize.

Neomorphosed ooids

Completely neomorphosed ooids are present in the studied formations. Their fabric indicates that they were deposited as aragonite cement and afterwards transformed to neomorphosed calcite (Figs. 5e & 10e). Perhaps, these grains have experienced dissolution of cortices as well as nuclei and later filling by spary cement. Their fabric is so much altered that it is difficult to confirm these grains as ooids but their appropriate size, high degree of roundness and significant sorting indicate that they are probably linked to ooidal origin. The burial pressures probably deformed the neomorphosed ooids to differentially elongated outlines[2].

Composite ooids

Composite ooids are the result of more than two ooids (Figs. 5c & 10f). As shown in these figures, two or more smaller ooids were cemented together and surrounded by concentric rings making a larger size grain. Finally, a composite ooid is formed, which is different from other aggregate grains (e.g., grape stones, thrombolites, etc.). Furthermore, this amalgamation reveals the basic feature of a rebirth ooid[2,10]. These ooids are the result of two or more than two ooids, surrounded by concentric layers of calcium carbonate[6]. These nuclei grains have a variable size and fabric. Other equivalent size grains, for example quartz and peloids, may have cemented together by micrite and/or calcite while the thick cortical coatings surround the composite smaller ooids (Fig. 5c & 10f).

Geopetal ooids

Geopetal ooids contain mixed mineralogical composition (Fig. 7c). Originally, these ooids were of aragonitic composition. Selective dissolution of the aragonitic cortical layers and transformation to the seemingly less soluble calcitic composition took place. Consequently, a gravitational collapse of the undissolved material to the bottoms of the ooid molds occurred that produced an obvious geopetal fabric. Later spar infilling of the moldic pores took place. It can be inferred that the primary calcite was partly replaced by dolomite, and the secondary (leached) pores were filled with blocky calcite at some later stage[2].

Dolomitic ooids (Pseudo-ooids)

These type of ooids were entirely replaced by dolomite crystals. The difference in composition of the parent mineral (*i.e*., aragonite, or low or high Mg calcite) is responsible for varied intensity in dolomitization. The dolomite is euhedral to subhedral in shape. Some of the pseudo-ooids (Figs. 9a & 10g, h) are also formed by the dissolution of aragonite which transformed into small crystals of calcite bonded by the calcified bacterial-films[4,6,25]. The calcite was subsequently transformed to dolomite during diagenesis.

Discussion and Conclusions

Diaz & Eberli[3] attributed the genesis of ooids to many factors, including: (i) physio-chemical factors, which facilitate the abiotic processes, and result in super-saturation of water with respect to calcite, and are characterized by currents, waves and storms, (ii) biogenic factors, triggered by microbial Extracellular Polymeric Substances (EPS) that precipitate $CaCO_3$ directly and/or indirectly, and (iii) microbes, which alter their geochemical environment through their metabolic processes, and change alkalinity and calcium availability therein.

Organisms show important part to regulate the mineralogy of ooids skeletons by two methods: (i) their organic templates favor a specific crystal structure[41], (ii) regulate medium chemistry from which skeletal material is derived[42]. The tangential ooids of calcitic or aragonitic fabric usually exist in higher energy environments. Several researchers demonstrate in their studies that tangential structure in ooids develop in agitation condition *i.e*., broken crystal[35], needle-shaped crystals originate from the influence of shocks between the particles[7], and radial structure ooids develop in quiet water condition. Moreover, radial fibrous ooids grow principally in poorly agitated and quiet environmental settings. But these tangential and radial fibrous ooids are also present in both high- and low energy environments.

The studied Miaolingian ooids of the NCP are inferred to have formed in different energy settings, which show particular characteristics of size, shape, fabrics and mineralogy. In low energy ooids, there is no strong isolation of nuclei from the intimate cortex and c-axis of aragonite crystals is radially positioned. In the Cambrian ooids, nuclei are frequently derived from adjoining microbial community, especially the cyanobacteria[4,5,8]. Alternations between discrete cortices are not more distinctive and characterized by gradations of dark/light laminae. Active role of biofilm is due to access of organic matter[26]. Difference in the thicknesses of organic laminae obviously specifies that the biofilm and time span is of crucial important in their development by primary colonizing microbes. Their external and internal cortices are uneven. However, high energy ooids reveal typically different characteristic from calm energy ooids. These ooids have often irregular surfaces, indicate diameter of 0.25 to 2.0 mm and morphology of the grains is spherical to ellipsoidal. Nucleus consists of foreign material, enclosed through one or more precipitated concentric coverings with concentric and/or radial arrangement of constituent crystals[37]. They are usually composed of aragonite or Mg-calcite composition.

The extensive oolitic grain bank from Cambrian strata in the NCP is well preserved, and provides excellent example for the study of the early Paleozoic shallow-marine environment. The architecture of carbonate platform ooids in Miaolingian strata depict the rounded, elliptical, pseudo-ooids, geopetal, neomorphosed, composite, and superficial ooids. Ooids are easily observed in outcrop due to their particular sandy appearance and are very common in shallow water carbonates. Their size range is identical to the sand *i.e*. 0.2 – 1.2 mm in diameter and are usually spherical to oval in geometry. Grainstones and packstone facies contains abundant ooids, however, micrite intraclasts sometimes comprise of ooids floating in the matrix[27]. The development of oolitic-grain banks in the Miaolingian strata corresponds to Schlager model of falling-stage system tract[20], but deviates from the standard model (STM) of carbonate facies development, where major deposition prevails during sea-level rise and still-stands, followed by a continuous erosional unconformity during the sea-level fall[22].

The study of ooids and their various features is an important tool to comprehend certain geological processes. Ooids are thought to be good reservoirs for oil and gas leading to their detail investigation by researchers in the field of hydrocarbons[43]. Moreover, they are used as an important tool for paleo-environmental research[2,31]. However, the effect of biological and non-biological factors on oolitic beds is a considerable factor and may lead to some pronounced geochemical changes, due to which ooids as such, are not appropriate in paleoclimatology[3].

Summarizing up, a variety of depositional fabrics were recognized for ooids, including radial, radial-concentric, micritic, superficial, composite, neomorphosed and geopetal, which attribute to a range of depositional settings. Overall, the oolitic grain bank facies in the Miaolingian at the Xiaweidian section are mostly limited to high-energy shallow ramp depositional settings.

Acknowledgments

This research is funded from the National Natural Science Foundation of China (Project No. 41472090, 40472065). We are grateful to Professor Mei Mingxiang (CUGB) for providing field and outcrop data, and Dr. Xiao Enzhao (CUGB) and Dr. Long Wang (CUGB) for their valuable suggestions in drafting this manuscript. Part of this research was presented orally at the Earth sciences Pakistan-2018 in Baragali, Pakistan, and participants are acknowledged for their fruitful discussion.

Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

All authors have either contributed directly to the research reviewed and/or assisted in the analysis, writing, editing, and/in searching for and referencing the works cited.

References

1 Opdyke B N & Wilkinson B H, Paleolatitude distribution of Phanerozoic marine ooids and cements, *Palaeogeogr Palaeoclimat Palaeoecol*, 78 (1-2) (1990) 135-148.

2 Flügel E, *Microfacies of carbonate rocks*, (Springer-Verlag Berlin Heidelberg), 2010, pp. 976.

3 Diaz M R & Eberli P E, Decoding the mechanism of formation in marine ooids: A review, *Earth-Sci Rev*, 190 (2019) 536-556.

4 Riaz M, Xiao E, Latif K & Zafar T, Sequence-stratigraphic position of oolitic bank of Cambrian in North China Platform: Example from the Kelan section of Shanxi Province, *Arab J Sci & Eng*, 44 (1) (2019a) 391-407.

5 Riaz M, Zafar T, Latif K, Ghazi S & Xiao E Z, Cambrian ooids, their genesis and relationship to sea-level rise and fall: A case study of the Qingshuihe section, Inner Mongolia, China, *Stratigraphy*, 18 (2) (2021a) 139-151.

6 Tucker M E & Wright V P, *Carbonate sedimentology* (Oxford: Blackwell Science), 1990, pp. 496.

7 Davies P J, Bubela B & Ferguson J, The formation of ooids, *Sedimentology*, 25 (5) (1978) 703-730.

8 Xiao E, Riaz M, Zafar T & Latif K, Cambrian marine radial cerebroid ooids: Participatory products of microbial processes, *Geol J*, 56 (9) (2021) 4627-4644.

9 Riaz M, Bhat G M, Latif K, Zafar T & Ghazi S, Sequence stratigraphy, depositional and diagenetic environments of the Late Cambrian glauconite bearing oolitic limestones in the Kelan Section, Shanxi, China, *J Earth Syst Sci*, (2021b). https://doi.org/10.1007/s12040-021-01743-7

10 Simone L, Ooids: A review, *Earth-Sci Rev*, 16 (1980) 319-355.

11 Qi Y A, Yang X W, Dai M Y, Li D, Wang M, *et al.*, Evolution of ooids and oolitic limestones and their significance from the Cambrian Series 3 in Dengfeng area, western Henan Province, *J Palaeogeogr*, 16 (1) (2014) 55–64.

12 Riaz M, Zafar T, Latif K, Ghazi S & Xiao E, Petrographic and rare earth elemental characteristics of Cambrian Girvanella oncoids exposed in the North China Platform: Constraints on forming mechanism, REE sources, and paleoenvironments, *Arab J Geosci*, 13 (17) (2020). https://doi.org/10.1007/s12517-020-05750-8

13 Riaz M, Latif K, Zafar T, Xiao E Z & Ghazi S, Morphology and Genesis of the Cambrian oncoids in Wuhai Section, Inner Mongolia, China, *Carbonate Evaporite*, 37 (4) (2021c). https://doi.org/10.1007/s13146-021-00750-5

14 Wang C S, Fan K Q & Yin Z G, Features of ooids in the middle cambrian Zhangxia formation in the Western Hills, Beijing, and their environmental significance, *Bull of Chinese Acad Geologic Sci*, 22 (1990) 39-55 (*In Chinese*).

15 Xing Y L & Feng L Q, A study on ooids in limestones of the Cambrian Xuzhuang formation at Xiaweidian outcrop in Western Hill of Beijing, *J Paleogeogr*, 4 (2015) p. 8 (*In Chinese with English abstract*).

16 Ma Y S, Mei M X, Zhou R X & Yang W, Forming patterns for the oolitic bank within the sequence-stratigraphic framework: an example from the Cambrian series 3 at the Xiaweidian section in the Western Suburb of Beijing, *Act Petrol Sin*, 33 (4) (2017) 1021-1036 (*In Chinese with English abstract*).

17 Meng X H, Ge M & Tucker M E, Sequence stratigraphy, sea-level changes and depositional systems in the Cambro-Ordovician of the North China carbonate platform, *Sediment Geol*, 114 (1-4) (1997) 189-222.

18 Mei M X, Ma Y S, Mei S L & Hu J Z, Sequence-stratigraphic framework and carbonate-platform evolution for the Cambrian of the North-China Platform, *Geosciences*, 11 (3) (1997) 275-282 (*In Chinese with English abstract*).

19 Schlager W, Type 3 Sequence Boundaries, In: *Advances in Carbonate Sequence Stratig.: Application to Reservoirs, Outcrop, and Models*, edited by P M Harris, A H Saller & J A Simo, (SEPM Special Publication), 1999, pp. 35-46.

20 Mei M X & Yang X D, Forced regression and forced regressive wedge system tract: revision on traditional Exxon model of sequence stratigraphy, *Geologic Sci Techn Info*, 19 (2) (2000) 17-21 (*In Chinese with English abstract*).

21 Mei M X, Depositional trends and sequence-stratigraphic successions under the Cambrian second-order transgressive setting in the North China Platform: A case study of the Xiaweidian section in the western suburb of Beijing, *Geol in China*, 38 (2) (2011) 317-337 (*In Chinese with English abstract*).

22 Catuneanu O, Galloway W E, Kendall C G S C, Mail A D, Posamentier H W, *et al*., Sequence stratigraphy: methodology and nomenclature, *Newsl Stratigr*, 44 (3) (2011) 173-245.

23 Riaz M, Latif K, Zafar T, Xiao E, Ghazi S, *et al*., Assessment of Cambrian sequence stratigraphic style of the North China Platform exposed in Wuhai division, Inner Mongolia, *Him Geol*, 40 (1) (2019b) 92-102.

24 Latif K, Xiao E, Riaz M, Wang L, Khan M Y, *et al*., Sequence stratigraphy, sea-level changes and depositional systems in the Cambrian of the North China Platform: A case study of Kouquan section, Shanxi Province, China, *J Himalayan Earth Sci*, 51 (1) (2018) 1-16.

25 Robin N, Bernard S, Miot J, Blanc-Valleron M M, Charbonnier S, *et al*., Calcification and diagenesis of bacterial colonies, *Minerals*, 5 (3) (2015) 488-506.

26 Brehm U, Krumbein W E & Palinska K A, Biomicrospheres generate ooids in the laboratory, *Geomicrobiol J*, 23 (7) (2006) 545-550.

27 Siahi M, Hofmann A, Master S, Mueller C W & Gerdes A, Carbonate ooids of the Mesoarchaean Pongola Super group, South Africa, *Geobiology*, 15 (6) (2017) 750-766.

28 Rankey E C, Riegl B & Steffen K, Form, function and feedbacks in a tidally dominated ooid shoal, Bahamas, *Sedimentology*, 53 (6) (2006) 1191-1210.

29 Halley R, Ooid fabric and fracture in the Great Salt Lake and the geologic record, *J Sediment Res*, 47 (3) (1977) 1099-1120.

30 Heller P L, Komar P D & Pevear D R, Transport processes in ooid genesis, *J Sediment Res*, 59 (3) (1980) 943-951.

31 Amao A O & Al-Ramadan K, Discussions on Arabian Gulf ooids, *Carbonates Evaporite*, 33 (4) (2018) 683-695.

32 Pacton M, Ariztegui D, Wacey D, Kilburn M R, Rollion Bard C, *et al*., Going nano: A new step toward understanding the processes governing freshwater ooid formation, *Geology*, 40 (6) (2012) 547-550.

33 Newell N D, Purdy E G & Imbrie J, Bahamian oolitic sand, *J Geol*, 68 (5) (1960) 481-497.

34 Medwedeff D A & Wilkinson B H, Cortical fabrics in calcite and aragonite ooids, In: *Coated grains*, edited by T M Peryt, (Springer, Berlin), 1983, pp. 109-115.

35 Loreau J P & Purser B H, Distribution and ultrastructure of Holocene ooids in the Persian Gulf, In: *The Persian Gulf*, edited by B H Purser, (Springer, Berlin), 1973, pp. 279-328.

36 Husinec A & Read J F, Transgressive oversized radial ooid facies in the Late Jurassic Adriatic Platform interior: Low-energy precipitates from highly supersaturated hypersaline waters, *Geol Soci America Bull*, 118 (5-6) (2006) 550-556.

37 Major R P, Halley R B & Lukas K J, Cathodoluminescent bimineralic ooids from the Pleistocene of the Florida continental shelf, *Sedimentology*, 35 (50) (1988) 843-855.

38 Mariotti G, Pruss S B, Summons R E, Newman S A & Bosak T, Contribution of benthic processes to the growth of ooids on a low-energy shore in Cat Island, The Bahamas, *Minerals*, 8 (6) (2018) p. 252.

39 Dupraz C & Visscher P T, Microbial lithification in marine stromatolites and hypersaline mats, *Trends Microbiol*, 13 (9) (2005) 429-438.

40 Purser B H & Loreau J P, Aragonitic, Supratidal Encrustations on the Trucial Coast, Persian Gulf, In: *The Persian Gulf*, edited by B H Purser, (Springer, Berlin, Heidelberg, New York), 1973, pp. 343-376.

41 Teng H H, Dove P M, Orme C A & Yoreo J J, Thermodynamics of calcite growth: baseline for understanding biomineral formation, *Science*, 282 (5389) (1998) 724-727.

42 Stanley S M, Influence of seawater chemistry on biomineralization throughout Phanerozoic time: paleontological and experimental evidence, *Palaeogeogr Palaeoclimat Palaeoecol*, 232 (2-4) (2006) 214-236.

43 Keith B D & Zuppann C W, Mississippian Oolites and petroleum reservoirs in the United States - an overview: Chapter 1, In: *Mississippian Oolites and modern analogs*, AAPG Studies in Geology (American Association of Petroleum Geologists), 1993, pp. 1-12. https://doi.org/10.1306/St35571C1