Cambrian ooids, their genesis and relationship to sea-level rise and fall: A case study of the Qingshuihe section, Inner Mongolia, China

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ABSTRACT: The Cambrian strata at the northwestern margin of the North China Platform in Inner Mongolia hold thick oolitic-grain bank deposits. Generally, the strata are dominated by calcareous mudstone of shelf facies in the lower part, micritic limestone consisting of deep to middle ramp facies in the middle part, and oolitic limestone encompassing shallow ramp to grain bank facies in the upper part of each formation. The shelf and deep ramp facies are the result of relative sea-level rise, while oolitic limestones developed in response to relative sea-level fall. Microscopically, the studied ooids are represented by radial crystal structures and concentric laminations with or without cores, single crystal or neomorphosed ooids, and highly bored ooids. The size and morphology of the ooids indicate a two-fold mechanical influence of microbes; constructive in the Miaolingian and destructive in the Furongian ooids. Based on these observations, it can be inferred that microbes (predominantly composed of filamentous fossils of cyanobacteria) excreted extracellular polymeric substances (EPS) to develop multiple bacterial biofilms microbial mats. The subsequent decay of the EPS through sulfate reducing bacteria most likely caused precipitation around these ooids. The depositional style of ooids occupying the upper parts of the formations, and their possible genesis from microbes provide clue for regional correlation, as well as affirm biological control in the formation of ooids.

Keywords: Ooids; Origin; Filamentous cyanobacteria; Cambrian; North China Platform

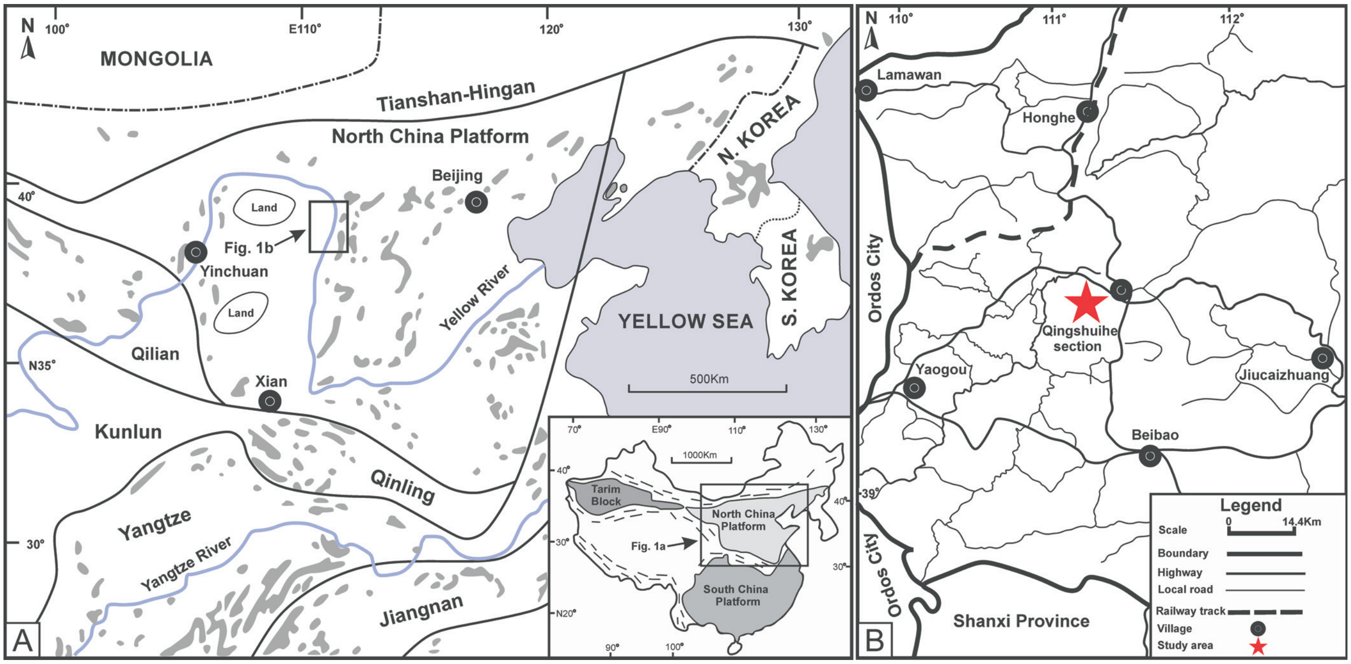
INTRODUCTION

Ooids are spherical to ellipsoidal sand-sized concretionary particles (diameter 0.25 to 2 mm) with tangentially or radially arranged laminae of aragonite or calcite crystals (Davies et al. 1978; Folk and Lynch 2001; Diaz et al. 2015; O'Reilly et al. 2017; Sipos et al. 2018; Riaz et al. 2019a). These grains form either through chemical (Davies et al. 1978; Duguid et al. 2010) or biological processes (Brehm et al. 2003, 2006), or by combination of the two (Riege et al. 1991; Diaz et al. 2017; Riaz 2019). The varieties of ooids mostly flourish in both high- and low- energy settings, and make various geomorphic structures such as shoals and bars that can extend over 100 km long and 30 km wide areas (Ball 1967; Harris 2010; Diaz et al. 2015; Riaz 2019). They are present throughout the rock record in geological history but seem to be mostly abundant and exquisitely preserved in the Precambrian and Cambrian carbonates (O'Reilly et al. 2017; Riaz et al. 2019a).

The representative sedimentary features and unique cyclicity in the sediments of the Cambrian strata of the North China Platform is of great interest for stratigraphers. Willis et al. (1907) initially separated the Cambrian strata of the Jinan and Laiwu areas into numerous lithostratigraphic units, including the Mantou Shale, the Changhia Limestone, the Kushan Shale, and the Chaumitien Limestone (see Chough et al. 2010). Based on biostratigraphic subdivision, the lithostratigraphic scheme has been revised into seven formations, namely the Mantou, Maozhuang, Xuzhuang, Zhangxia, Gushan, Changshan, and Fengshan (Xiang et al. 1999). Recently, a new scheme of lithostratigraphic units was introduced based on broad chronostratigraphic division (Peng 2009; Peng et al. 2012; Peng and Zhao 2018). Several researchers followed this chronostratigraphic division and studied the widely exposed Cambrian ooids of the North China Platform (Wang et al. 1990; Sha 1999; Chen et al. 2012; Liu and Zhang 2012, 2015; Dai et al. 2014; Qi et al. 2014; Xing and Feng 2015; Ma et al. 2017; Riaz et al. 2019a, b). The present study also follows this latest scheme and describes oolitic-grain banks are mainly restricted to the upper part of the Cambrian strata. Furthermore, for the first time, the current study highlights the dual nature of microbes in the formation and evolution of Cambrian ooids (constructive in Miaolingian and destructive in Furongian) which are most likely associated with calcification of extracellular polymeric substances (EPS) in microbial mats.

GEOLOGICAL SETTING

The North China Platform consists of a Cambrian–Ordovician mixed siliciclastic-carbonate succession that developed on a stable craton of the Sino-Korean Block (Meng et al. 1997). Several studies have reported that the thick Cambrian–Ordovician plat-



TEXT-FIGURE 1
A–Simplified geological map of the North China Platform and associated blocks (modified after Myrow et al. 2015; Riaz et al. 2019a, b). Gray areas show Cambrian-Ordovician outcrop exposures. The text "Land" in two circles indicates a Late Cambrian exposed landmass on the western side of the North China Platform. Rectangle shows the study area; B–Red star indicates the location of the study area "Qingshuihe section".

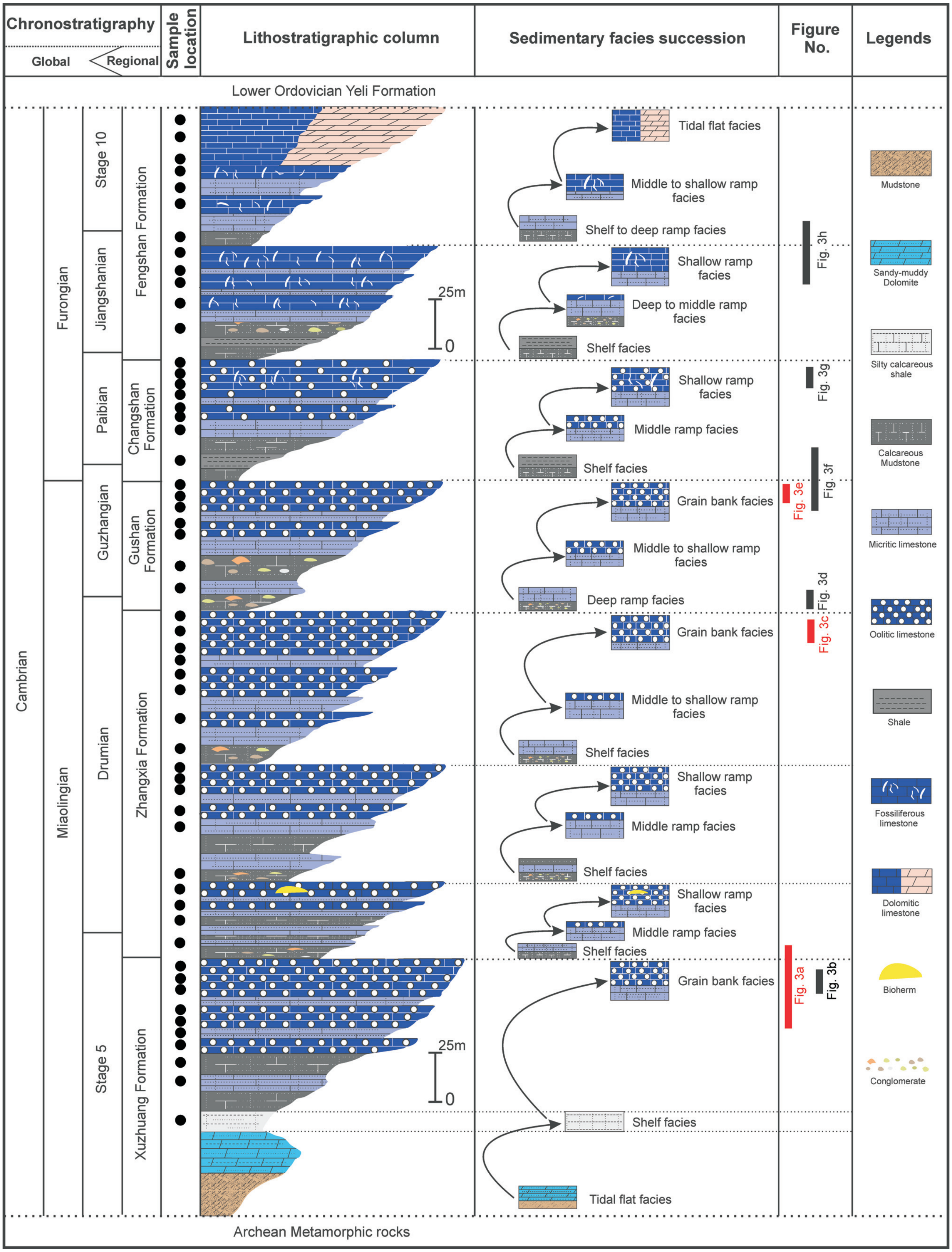
form, platform-margin and deep-basinal sequence is preserved on the western margin of the block, where the Ordos Basin developed throughout the extensive area (ca. 250,000 km^2) across Shaanxi, Shanxi, Gansu, Ningxia, and Inner Mongolia, northwestern China (e.g. Yang et al. 2008) (text-fig. 1A). Based on lithology and chronostratigraphic division, the Cambrian strata can be categorized into three types in ascending order (Meng et al. 1997; Feng et al. 2004; Mei 2011; Ma et al. 2017; Xiao et al. 2017a, b, 2020a, 2021; Latif et al. 2018; Riaz et al. 2019a, b, 2020): 1) A mixed clastic-carbonate succession dominated by red beds of coastal sabkha deposited between late Series 2 and early Miaolingian; 2) a carbonate succession predominated by oolitic grainstones formed during Miaolingian; 3) and a succession of carbonate mud developed in the Furongian. The strata of Cambrian Series 2 are absent in most parts of the North China Platform due to sediment influx (Xiao et al. 2017a, b; Latif et al. 2018; Riaz et al. 2019a, b, 2020). The Qingshuihe section is located 3 km to the east of Qingshuihe at the western boundary of the North China Platform (text-fig. 1B).

MATERIALS AND METHODS

Extensive geological fieldwork was carried out at the Qingshuihe section, Inner Mongolia region of North China, where the Cambrian formations (Xuzhuang, 119 m; Zhangxia, 106 m; Gushan, 32 m; Changshan, 35 m; and Fengshan, 103 m) were well-exposed. The Fengshan Formation is located beside the G109 road to Ordos city. The Cambrian Series 2 is missing in the studied section. The Cambrian strata have a conformable upper contact with the Lower Ordovician Yeli Formation and an unconformable lower contact with Archean metamorphic rocks. Sedimentary fabrics, particularly ooids, were examined in the upper part of the Cambrian strata whereas conglomerates within calcareous mudstone were observed in the lower part of some formations. For comprehensive study, 55 samples were collected systematically from bottom to top of the entire Cambrian strata. Special emphasis was given to the ooid bearing strata in the upper part of the formations that developed during relative sea-level fall. A detailed lithologic column was produced that documents the field observations (text-fig. 2). Thin sections were prepared and studied under a Zeiss Axio Scope A1 microscope at the China University of Geosciences, Beijing in order to understand the microscopic characteristics of ooids such as structure, morphology, size, and the influence of microbes. Photomicrographs were taken in plane polarized light (PPL) and cross polarized light (XPL) that document the characteristics of Cambrian ooids at various resolutions.

SEDIMENATRY FACIES SUCCESSION

The strata and rock units of the Cambrian Miaolingian (Xuzhuang Formation, Zhangxia Formation, and Gushan Formation) and Furongian (Changshan Formation, and Fengshan Formation) are predominantly associated with calcareous mudstone, micritic limestone, and oolitic limestone formed in response to relative sea-level rise and fall (text-figs. 2-3). The Xuzhuang Formation is the oldest Miaolingian formation and its sedimentary facies changes from red bedded, massive mudstone and sandy muddy dolomite of the tidal flat facies to silty calcareous shale of the shelf facies, and upward to the oolitic limestone of a grain bank facies (text-figs. 2, 3A-B). The oolitic limestone was developed in the upper part of the Xuzhuang Formation during relative sea-level fall (text-fig. 3B). The shelf facies that forms the condensed section of the Xuzhuang



TEXT-FIGURE 2
The diagram shows the global and regional chronostratigraphic division, lithology, and sedimentary facies succession of the exposed Cambrian strata at the Qingshuihe section, Inner Mongolia, North China Platform.

Formation can be deemed to mark the border between immature- and mature- deposits (see Mei et al. 1997; Riaz 2019). The Zhangxia Formation at the studied section can be categorized into three fourth order units on the basis of cyclicity in lithology (text-fig. 2). Each unit comprises calcareous mudstone of the shelf facies in the middle, suggestive of relative sea-level rise. The banded mudstone interbedded with thin beds of oolitic limestone signifies subtidal meter-scale cycles and together with the massive oolitic limestone in the top part denotes relative sea-level fall (text-fig. 3C). The Gushan Formation is the last formation of the Miaolingian (text-fig. 2). It has a basal deep ramp facies associated with calcareous mudstone and conglomerate lenses (text-figs. 2, 3D) overlain by a middle and shallow ramp facies represented by calcareous mudstone interbedded with thick micritic limestone (text-fig. 2). Grain shoal facies associated with thin micritic limestone and thick oolitic limestone were deposited during relative sea-level fall (text-fig. 3E). The oolitic limestone of the grain shoal facies is overlain by calcareous mudstone and shale of the shelf facies of the Changshan Formation (text-fig. 3F) and possibly represents the typical sequence boundary of a drowned unconformity made by rapid sea-level rise as proposed by Gómez and Fernández-López (1994) and Schlager (1989, 1999). In comparison, the Changshan Formation lies in the Furongian Series (text-fig. 2) in which the lower part consists of calcareous mudstone and shale of shelf facies, overlain by calcareous mudstone and massive micritic limestone of deep ramp facies (text-fig. 3F). The middle ramp facies of the formation is associated with a succession of micritic and oolitic limestone, while the shallow ramp facies is a massive fossiliferous limestone containing an abundance of ooids (text-fig. 3G). These facies of the Changshan Formation were mainly developed during relative sea-level fall (text-figs. 2, 3G). The Fengshan Formation of the Furongian Series exhibits two third order units that show various sedimentary facies (text-figs. 2, 3H). The sedimentary facies of the first unit of the Fengshan Formation and the Changshan Formation have a similar trend (text-fig. 2). The second unit of the Fengshan Formation has a facies change from calcareous mudstone to dolomitic limestone of the tidal flat facies (text-figs. 2, 3H). The dolomitic limestone in the top portion of the formation continues up to the Lower Ordovician where it makes conformable contact with the Yeli Formation.

PETROGRAPHY

The upper part of the Cambrian strata that is dominated by oolitic limestone at Qingshuihe section of the North China Platform was examined in detail. These grains developed during relative sea-level fall and show typical characteristics under microscope. The detailed description of each formation is given below:

Xuzhuang Formation

The oolitic limestones of the Xuzhuang Formation are associated with rounded to elliptical ooids, with an obvious dominance of the rounded ooids (text-fig. 4A). These ooids display a concentric fabric with radially arrayed crystals, and concentric laminations composed of calcite or high magnesium calcite (text-fig. 4A). The radial crystals of calcite form the cortices of ooids during their growth. However, the presence of dark micrite (microbes) in the core and cortex of ooids needs explanation (text-fig. 4A). These most likely developed during or after the development of ooids, i.e., they show either syndepositional or digenetic features (text-fig. 4B). If microbial activity was involved during the formation of an ooid then its nucleus was most likely associated with bacterial biofilms, which are amalgamations of cyanobacteria and sulfate reducing bacteria (i.e., Brehm et al. 2003, 2006). The rounded to slightly elliptical ooids without cores exhibit the radially arranged structure of microbes in their cortices (text-fig. 4C). Some of the rounded ooids also display radial crystals of calcite, along with concentric laminations of microbes (text-fig. 4D).

TEXT-FIGURE 3

A Field photograph shows the oolitic limestone in the upper part of the Cambrian Xuzhuang Formation. It has a conformable upper contact with the overlying Zhangxia Formation;

B Oolitic limestone in the Xuzhuang Formation that formed during relative sea-level fall;

C Oolitic limestone in the upper part of the Zhangxia Formation;

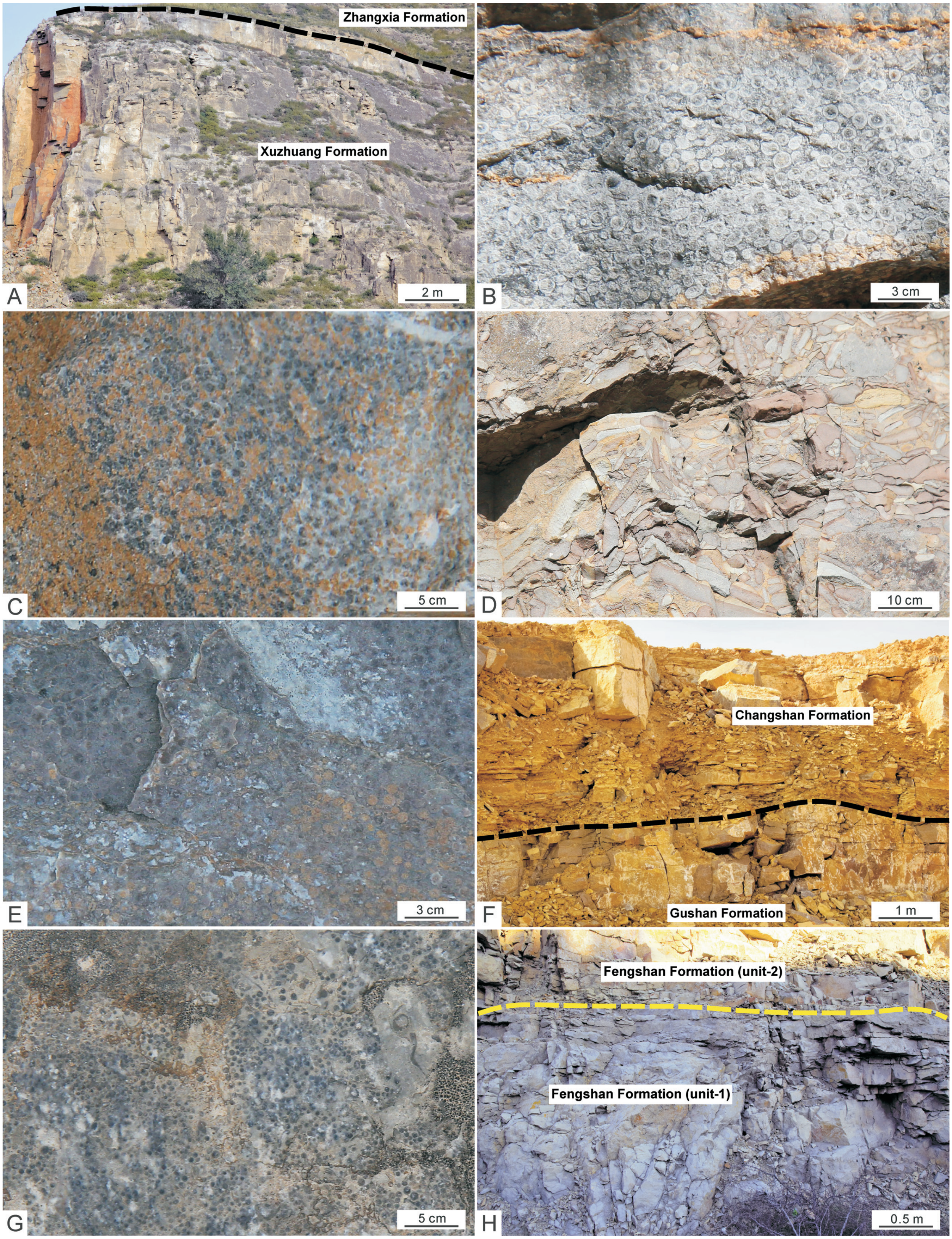
D Conglomerate lenses in the lower part of the Gushan Formation;

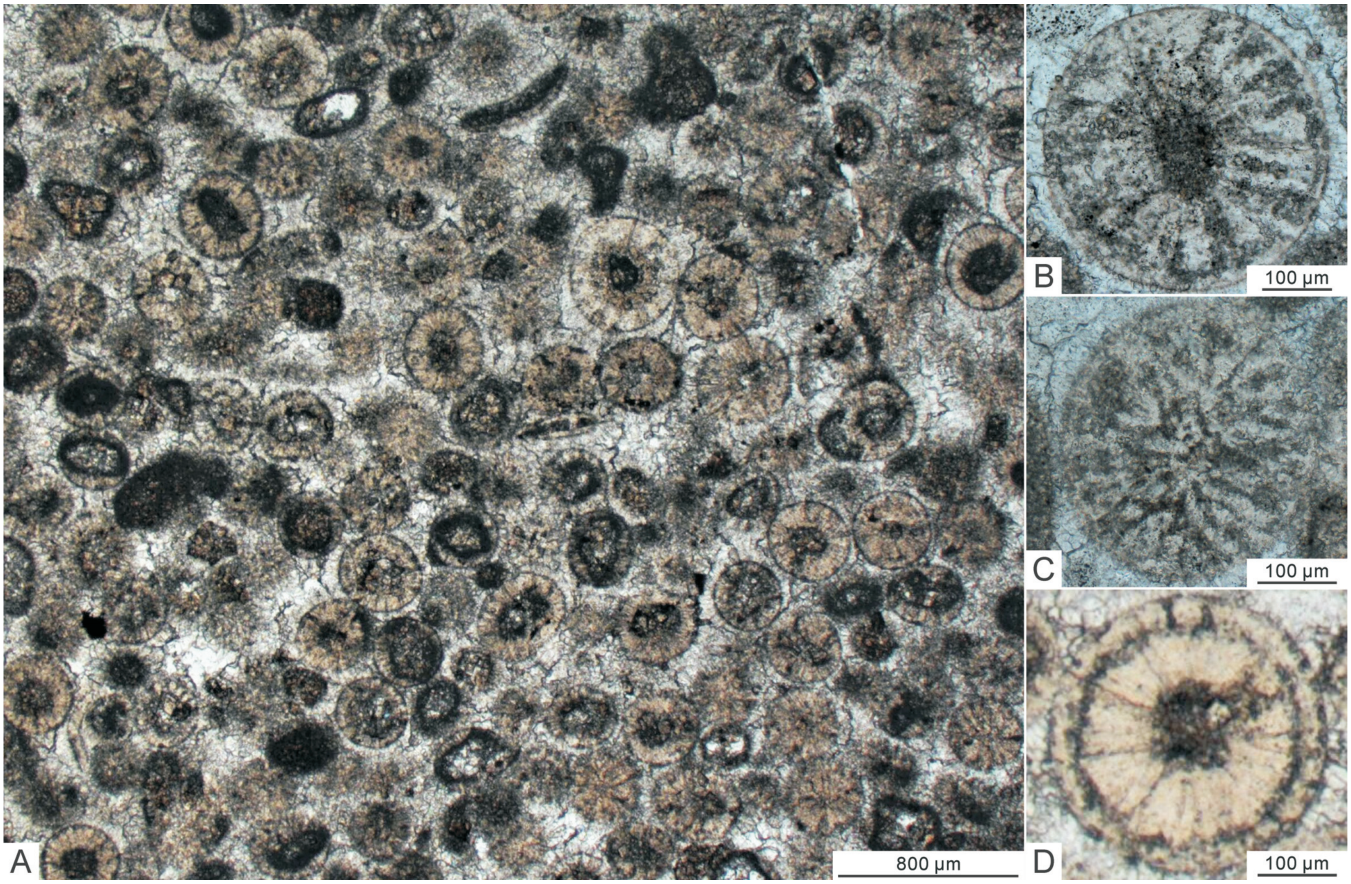
E Oolitic limestone in the upper part of the Gushan Formation;

F The conformable contact between the Miaolingian Gushan Formation and the Furongian Changshan Formation;

G Oolitic limestone in the upper part of the Changshan Formation;

H Yellow dashed line differentiates the sedimentary facies of the Fengshan Formation beside the G109 road to Ordos city.


Zhangxia Formation
Xuzhuang Formation
2 m
A
3 cm
B
5 cm
C
10 cm
D
3 cm
E
Changshan Formation
Gushan Formation
1 m
F
5 cm
G
Fengshan Formation (unit-2)
Fengshan Formation (unit-1)
0.5 m
H



TEXT-FIGURE 4
Photomicrographs depict ooids from the oolitic-grain bank of the Xuzhuang Formation at Qingshuihe section, Inner Mongolia. Photomicrographs taken under PPL.

A The oolitic-grain bank is dominated by dark micrite surrounded by sparite, forming the upper part of the Miaolingian Xuzhuang Formation;

B Dark microte form the core and the radial structure of the rounded ooids;

C Rounded to slightly elliptical ooids without a core display the radial structure of dark micrite in the cortex;

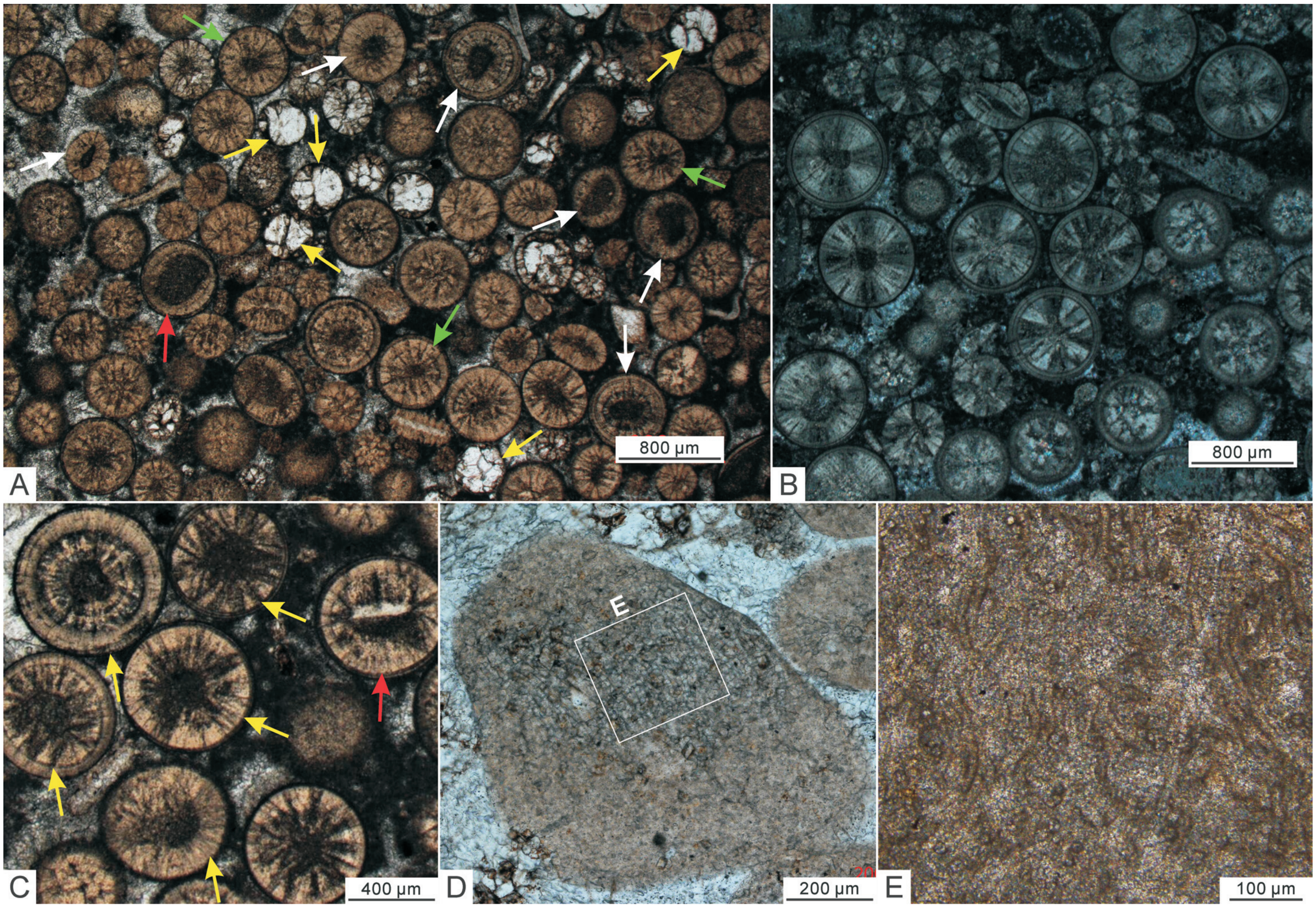
D Rounded ooids show that the radial crystals of calcite cut-cross the concentric laminations.

Zhangxia Formation

The oolitic limestones of the Zhangxia Formation are composed of radial ooids, *Girvanella* (cyanobacterium) ooids, neomorphosed ooids, and superficial ooids (text-figs. 5A-E). The high density of preserved microbes is obvious in these ooids, and it is apparent that the microbes were involved in their formation (text-figs. 5C-E), in a similar fashion as defined by Brehm et al. (2006), Liu and Zhang (2012), Edgcomb et al. (2013), and Diaz and Eberli (2019). These well-developed ooids indicate a relatively low energy setting as compared to the ooids of the Xuzhuang Formation (text-figs. 4A-D). Radial ooids are rounded, and their radial concentric laminae are distinguished based on alternating dark and light bands (text-figs. 5A-C). Oval to spherical *Girvanella* core ooids were also observed in these samples, which are comparable to superficial ooids having a thin cortex and thick core (text-figs. 5D-E).

Gushan Formation

The ooids in the Gushan Formation occuras neomorphosed ooids, rounded ooids and bioclasts (text-figs. 6A-C). Neomorphosed ooids comprise a random mosaic of sub-equant anhedral spar crystals that were most likely originally aragonitic in composition (e.g., Tucker and Wright 1990; Riaz et al. 2019a) (text-fig. 6A), and later experienced dissolution of aragonite and replacement with calcite. Moreover, broken pieces of brachiopods are also observed (text-fig. 6A). These brachiopods have a low-angle fibrous wall structure. A trilobite fragment with complex curvature of the shell and a homogeneous prismatic shell structure was also identified (text-fig. 6A). A large semi-circle echinoderm fragment is present in some thin sections (text-fig. 6B), where the small pores in the outermost portion of the grains are filled with micrite. The rounded ooids (text-fig. 6C) are composed of calcite crystals with radial-con-



TEXT-FIGURE 5
Photomicrographs of ooids from the oolitic-grain bank of the Zhangxia Formation at Qingshuihe section, Inner Mongolia.

A Rounded radial ooids (green arrows), *Girvanella* ooids (white arrows), superficial ooids (red arrows), and neomorphosed ooids (yellow arrows) forming the upper part of the Miaolingian Zhangxia Formation (PPL);

B Radial structure of ooids (XPL);

C Ooids with with cluster *Girvanella* (yellow arrows) and trilobite or brachiopod fragments (red arrow) in their core with a radial microbial structure in the cortex (PPL);

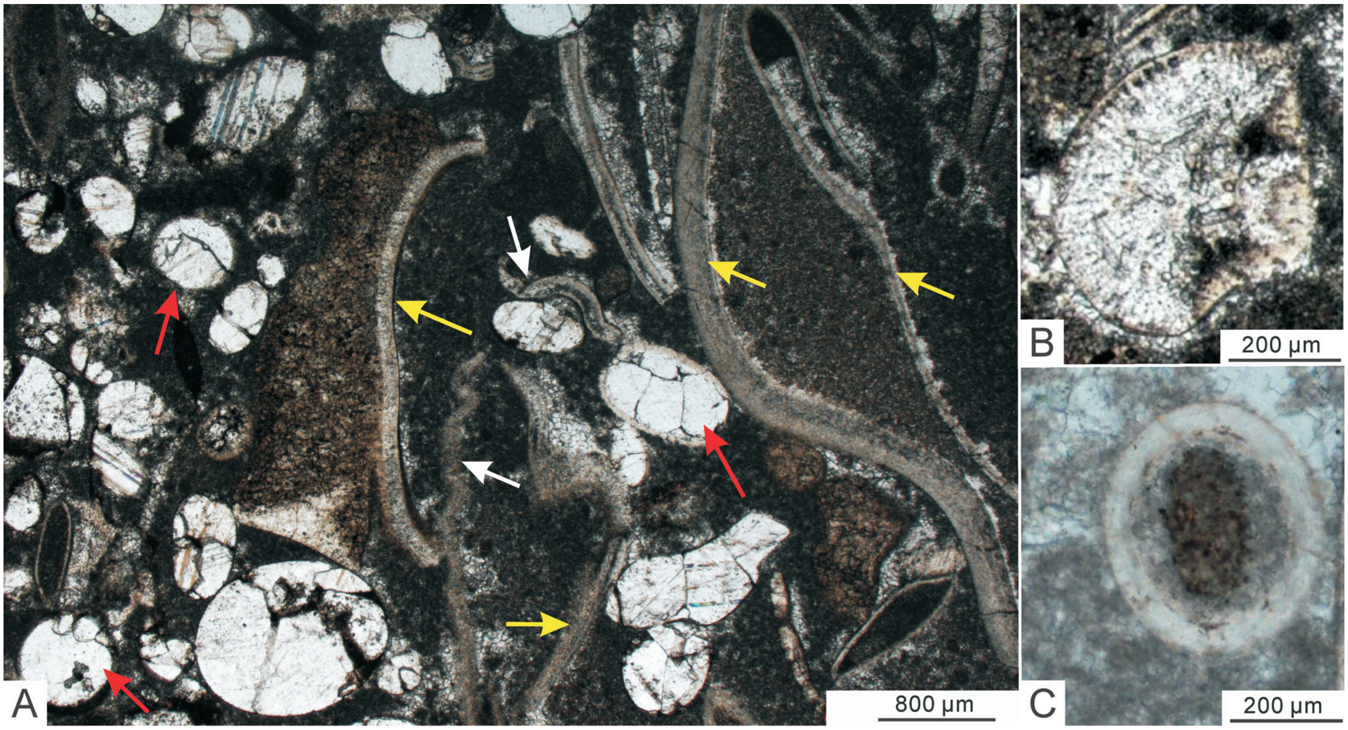
D *Girvanella* in the core of ooids indicating the influence on the shape of ooids (PPL). Square shows a close view of *Girvanella* in text-fig. E;

E Typical filamentous fossils of the cyanobacteria (*Girvanella*) representing involvement in the formation of ooids (PPL).

centric structures. These ooids exhibit an abundance of dark micrite in their structures. The nuclei of these ooids (text-fig. 6C) possibly formed through microbial activity by cyanobacteria and sulfate reducing bacteria as proposed by Brehm et al. (2006) in the modern Bahamian ooids.

Changshan Formation

The upper part of the Changshan Formation is characterized by rounded to elliptical, highly bored ooids with or without a nucleus, and bioclasts (text-figs. 7A-D). Most of them are identified as superficial ooids covered by *Girvanella* (text-fig. 7E); some are associated with pellet nuclei (text-fig. 7D). Rounded ooids with pellet cores and radial crystals of calcite cross-cutting the concentric laminae, display highly micritized cores and cortices (text-fig. 7D). The superficial ooids with *Girvanella* cores provide two important inferences (text-figs. 7E-F), (1) the core is occupied by *Girvanella* that might have developed after the formation of the ooid, and (2) microboring in a thin cortex is interpreted as evidence that boring activity by organisms occurred during genesis of the ooids. The morphology of bioclasts demonstrates the destructive micritization in which cyanobacteria produce tube-like microboring on the surface of bioclasts, which is then filled with calcite after death of the microorganisms (e.g., Bathurst 1966; Margolis and Rex 1971; Flügel 2010) (text-figs.



TEXT-FIGURE 6
Photomicrographs show the sedimentary fabric in the upper part of the Miaolingian Gushan Formation at Qingshuihe section, Inner Mongolia. Photomicrographs taken under PPL.

A Neomorphosed ooids (red arrows) along with brachiopods (yellow arrows) and trilobites (white arrows) are enclosed by micrite, depicting the relatively deeper energy setting of the upper part of the Gushan Formation;

B A large semi-circle echinoderm fragment from the upper part of the Gushan Formation;

C A rounded ooid with a smooth cortex is surrounded by sparite and micrite, suggesting deposition in a slightly shallower and higher energy setting than A or B.

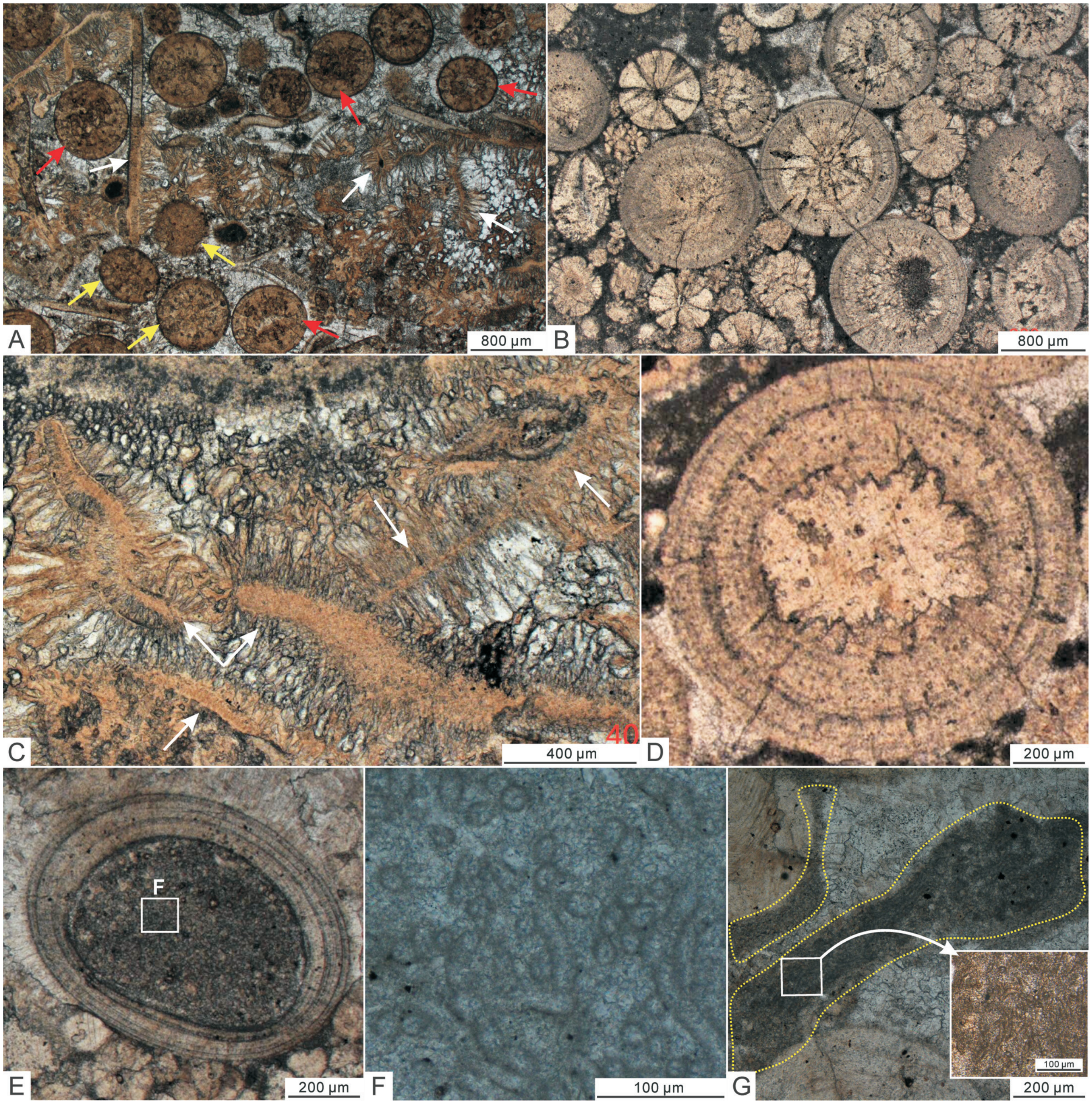
7A, C). It is worth mentioning that microborings provide credible evidence of the destructive role of cyanobacteria during or after the development of ooids (text-fig. 7A-G).

Fengshan Formation

Middle and shallow ramp facies of the first unit of the Fengshan Formation are comprised of fossiliferous limestone (text-figs. 2, 3H). Microscopic study reveals a variety of the intraclasts (text-fig. 8A). The dark clots within the intraclasts are predominantly composed of filamentous fossils of *Girvanella* (text-fig. 8B) (see Xiao et al. 2018; Latif et al. 2019; Mei et al. 2020a, b). The surrounding matrix of these intraclasts is associated with micrite and suggests a relatively deeper depositional setting (text-fig. 8A). An oolitic-grain bank did not develop in the upper part of both units of the Fengshan Formation, where lithology changes from shelfal calcareous mudstone to dolomitic limestone of tidal flat setting (text-fig. 3H).

DISCUSSION

The studied Cambrian strata at the Qingshuihe section, Inner Mongolia suggest that the deposition occurred in an epicontinental sea, with sea-level fluctuations that resulted in several episodes of platform drowning. The Cambrian Miaolingian at Qingshuihe section developed as a sandy muddy dolomite and tidal flat mudstone in the lower part of the Xuzhuang Formation during the immature phase (Mei et al. 1997; Meng et al. 1997; Riaz et al. 2019a) of the North China Platform. Grain bank deposits in the overlying strata represent the mature stage of carbonate platform formation in the Miaolingian (text-figs. 3B-C, E, G). During the mature stage of platform development, the deposition of grain banks suggests that deposition occurred during relative sea-level fall in a similar manner as proposed by Hunt and Tucker (1992), Mei and Yang (2000), Schlager and Warrlichw (2009), and Samanta et al. (2016). The Furongian Changshan Formation is similar to the Miaolingian strata and is dominated by oolitic limestones whereas the Furongian Fengshan Formation is predominantly associated with fossiliferous limestone instead of an oolitic



TEXT-FIGURE 7
Photomicrographs exhibit the sedimentary fabric of the upper part of the Furongian Changshan Formation at Qingshuihe section, Inner Mongolia. Photomicrographs taken under PPL.

A Destructive role of endolithic cyanobacteria in the bioclasts (white arrows), and ooids (red arrows) and without (yellow arrows) nucleus;

B Microboring in the core as well as in the cortex of rounded radial structure ooids;

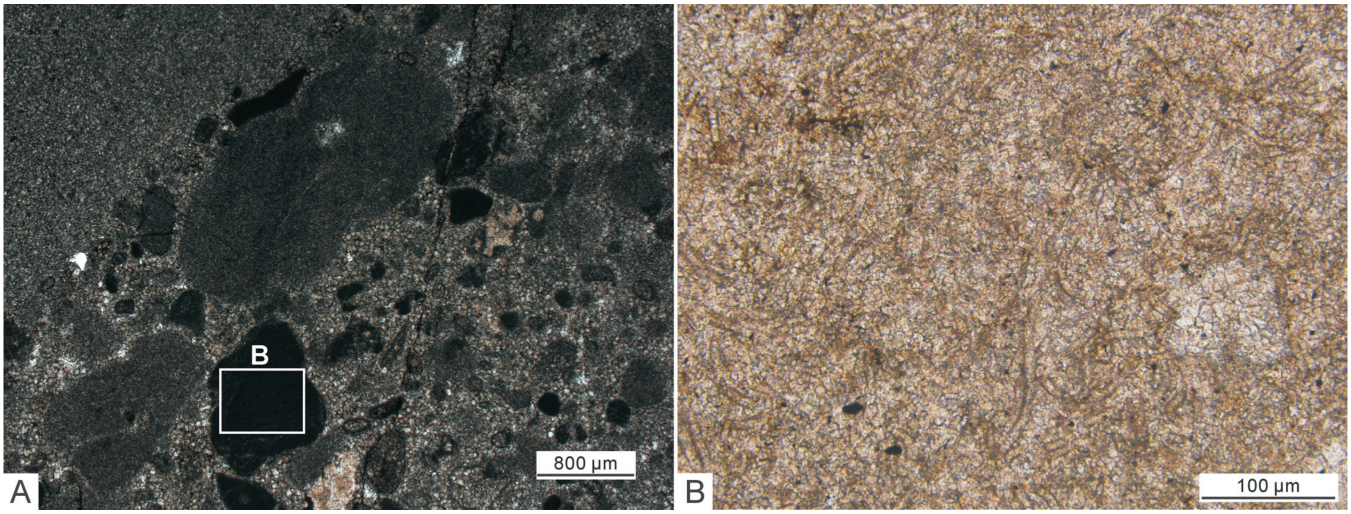
C Destructive micritization phenomena in the bioclasts (white arrows);

D Rounded ooids associated with pellet core and radial crystals of calcite cross-cut the concentric laminae, displaying the highly micritized core and cortex;

E Superficial ooids have a core covered by *Girvanella* after the formation of the ooid and boring in the thin cortex during the formation of ooids;

F Cross-section of the *Girvanella* cluster in the core of ooids;

G Destructive *Girvanella* in the core of ooids. Expanded view shows the presence of *Girvanella*.



TEXT-FIGURE 8
Photomicrographs show the sedimentary fabric of the upper part of the first unit of the Furongian Fengshan Formation beside the G109 road to the Ordos city, Inner Mongolia. Photomicrographs taken under PPL.

A Variety of intraclasts and irregular clots surrounded by micrite. The box on the clot is shown in greater detail in text-fig. B;

B Clots associated with intraclasts show the abundance of filamentous fossils of cyanobacteria.

grain bank. The oolitic-grain bank, which first appears in the Xuzhuang Formation and continues through the Miaolingian and Furongian series (Paibian), could not develop in the Furongian Fengshan Formation (Jiangshanian and Stage 10; text-fig. 2), which is the terminal sequence of the Cambrian in the Qingshuihe section.

The oolitic-grain banks represent a high-density preservation of microbes in the Qingshuihe section (text-figs. 4-7). The Miaolingian Series is characterized by rounded to elliptical ooids composed of radially arrayed crystals and concentric laminae in the Xuzhuang Formation (text-fig. 4), by radial ooids, *Girvanella* ooids, neomorphosed ooids, and superficial ooids in the Zhangxia Formation (text-fig. 5), and by neomorphosed and rounded ooids in the Gushan Formation (text-fig. 6). The Furongian Changshan Formation is characterized by highly bored rounded to elliptical ooids (text-fig. 7), delineating formation in a high-energy shallow water environment. The calcification of biological membranes, especially in the Miaolingian ooids, not only suggests bacterial biofilm development but also shows that the calcification process associated with complex microbial metabolism activities in the Cambrian is similar to processes documented in today's Bahamian ooids (O'Reilly et al. 2017; Diaz and Eberli 2019).

The size of the studied ooids usually ranges from 0.2-0.4 mm, which is smaller than those from the Kelan section, Shanxi Province, North China Platform where sizes reach up to 0.8 mm (Riaz et al. 2019a), but is similar or slightly larger than those from the Xiaweidian section, Beijing (0.1-0.3 mm, Ma et al. 2017). Morphologically, ooids are well-rounded, similar to the Xiaweidian section, but different from the Kelan section. The small size and radial structure of the studied ooids indicate that they could not avail sufficient time to develop cortices as compared to the concentric ooids of the Kelan area. The rounded shape, however, indicates suitable turbulent conditions.

The ooids in the studied section were highly affected by microbes. Microorganisms play a dual role in the formation of Cambrian ooids: (1) *Girvanella* aided in the development of the ooidal cortex of the Cambrian Miaolingian Series. These are found in the core and radially arranged in the cortex. The outermost cortex of the ooids is similar to those described by Trichet (1968) and Liu and Zhang (2012); (2) the cyanobacteria destroyed the ooids by producing tube-like microborings through biochemical dissolution on the surface of Furongian ooids. These tube-like structures were later filled with micritic aragonite or high-Mg calcite cement after the death of the microorganism, which altered the chemistry of the ooid (Bathurst 1966; Margolis and Rex 1971; Duguid et al. 2010). Microboring and change of cortex structure can be observed in the ooids of the Furongian Changshan Formation (text-fig. 7), but not in the ooids of the Miaolingian strata (text-figs. 4-6). The presence of neomorphosed and rounded ooids surrounded by micrite in the Gushan Formation (Guzhangian) indicates a relatively deeper energy setting when compared to the ooids of the Xuzhuang and Zhangxia formations of the studied section. These ooids, along with brachiopod, trilobite and echinoderm fragments, provide evidence of a relatively deeper environment of deposition for the upper part of the Gushan Formation. This differs from other outcrops of the Gushan Formation in the North China Platform, which developed in relatively high energy settings (Ma et al. 2017; Riaz et al. 2019a).

Microbes influenced ooid formation in the Changshan Formation as well, but the nature of the microbes was different, as they destroyed the cortex rather than developing it. The Changshan Formation most likely formed under high energy conditions where ooids had a suitable environment for development, similar to the ooids of the Changshan Formation in the Kelan section, Shanxi Province of the North China Platform. However, storm events that formed the fossiliferous limestone of the Fengshan Formation in the Qingshuihe section were different than those that formed the Kelan and Xiaweidian sections. During stormy periods, the Kelan area remained relatively elevated during the ooids deposition. By comparison, the Xiaweidian and Qingshuihe sections were paleogeographically similar and developed in relatively deeper water, therefore, the conditions were not that favorable for ooid development.

The Cambrian ooids in the studied section provide sound evidence for the formation of ooids via microbial activity. The presence of microbes in these ooids reflects the complicated calcification of EPSs that form biofilms in a microbial mat (Latif et al. 2019; Xiao et al. 2020b, c; Mei et al. 2020a, b; 2021). This complex process may have resulted in shaping ooids that were produced by rolling over microbial mats. The observations and interpretations of the present study provide insight about how ooids form, and the role that sophisticated calcification of EPSs forming photosynthetic biofilms plays inside microbial mats.

CONCLUSIONS

Cambrian ooids in the Qingshuihe section, Inner Mongolia, on the northwestern margin of the North China Platform developed in the upper part of the Cambrian strata during relative sea-level fall. Standard carbonate microfacies analysis documents the size and shape of ooids, as well as the influence of microbes, particularly the cyanobacteria *(Girvanella)*, in their formation. Ooids from the Miaolingian Xuzhuang and Zhangxia formations developed in a shallow and high energy setting, whereas those from the Miaolingian Gushan Formation and the Furongian Changshan Formation formed in a relatively deeper water setting. Microbes in the Miaolingian strata played a constructive role by generating multiple biofilms inside the microbial mat, whereas, they played a destructive role by destroying the ooidial cortex through microborings in the Furongian strata. The absence of ooids in the Furongian Fengshan Formation suggests severe stormy events that prevailed through the region. This case study provides reference data for future comparative studies of the North China platform on a larger scale.

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