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ORIGINAL ARTICLE

Morphology and genesis of the Cambrian oncoids in Wuhai Section, Inner Mongolia, China

Muhammad Riaz[1,2,3] · Khalid Latif[4] · Tehseen Zafar[5] · Enzhao Xiao[6] · Shahid Ghazi[7]

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Abstract

Cambrian oncoids were deposited in the upper part of the Miaolingian Xuzhuang Formation at the Wuhai Section, Inner Mongolia, China in the late highstand systems tract of the third-order depositional sequence. Microscopic studies show an abundance of dark micrite in the dolomitic, bioclastic and micritic oncoids that possibly indicate the presence of microbes such as filamentous cyanobacteria and sulfate reducing bacteria either in the cortices and/or nuclei of these oncoids. These rounded to elliptical oncoids, forming packstone-to-grainstone facies in the Xuzhuang Formation, existed in a high energy setting with an abundance of filamentous fossils of cyanobacteria. These observations demonstrate a complicated mechanism of oncoid formation associated with calcification of extracellular polymeric substances in the cyanobacteria dominated microbial mats. The present work provides evidences about the active mediation of cyanobacteria in the formation of the Cambrian oncoids in the Xuzhuang Formation. It offers a reference example for the development of microbial carbonates in the North China Platform during the Cambrian period.

Keywords Filamentous cyanobacteria · Microbial mat · Oncoids · Depositional setting · Cambrian (Miaolingian) Xuzhuang Formation · North China Platform

Introduction

Among the coated grains, oncoids have irregular calcareous cortices of microbial origin overlapping each other (Tucker and Wright 1990; Wilmeth et al. 2015; Mei et al. 2019a, b; Xiao et al. 2020a, b). Oncoids generally comprise nuclei of several grain types, while their cortices are composed of calcified microbes, algae or metazoans (Peryt 1981; Riding 1991; Flügel 2004; Liu and Zhang 2012; Riaz et al. 2020). Oncoids are distinct from ooids; the latter are having a diameter commonly less than 2 mm and a regular shape with an uncertain origin (Davies et al. 1978; Brehm et al. 2006; Duguid et al. 2010; Diaz and Eberli 2019).

Majority of the Cambrian oncoids are believed to have formed by the action of calcified cyanobacteria under high energy shallow water conditions, having sufficient nutrient supply (Pratt 2001; Liu and Zhang 2012; Han et al. 2015; Zhang et al. 2015a). It is reported that the calcification and agglutination of cyanobacteria can develop microbial carbonates, such as microbialites including varieties of laminated stromatolite, clotted thrombolite, dendrolitic dendrolite, and aphanitic leiolite, as well as microbial mud and grains (Braga et al. 1995; Riding 2000; Shapiro 2000; Dupraz et al. 2009; Latif et al. 2019; Mei et al. 2019c, 2020a, 2021a, b; Xiao et al. 2020c). It is also documented that reworking of these microbial carbonates through various physical, chemical and biological processes can also produce carbonate grains including intraclasts and microbial lumps

✉ Muhammad Riaz
riazjass@yahoo.com

1 State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China

2 College of Energy Resources, Chengdu University of Technology, Chengdu 610059, China

3 Centre for Geographical Information System, University of the Punjab, Lahore 54590, Pakistan

4 National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Pakistan

5 Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China

6 Key Laboratory for Polar Science, MNR, Polar Research Institute of China, Shanghai 200136, China

7 Institute of Geology, University of the Punjab, Lahore 54590, Pakistan

(Adachi et al. 2013; Yang et al. 2013; Han et al. 2015). Moreover, oncoids are usually confused with other coated grains due to their comparable size, shape and composition (Yang et al. 2011; Xiao et al. 2020b).

Worldwide, oncoids exists abundantly in the Cambrian shallow marine carbonates. Most of these shallow marine oncoids occur in diverse regions, such as North America, Europe, Middle East, Australia, Antarctica, and China (Flügel 2010; Qvarnström 2012; Riaz et al. 2020; Villafañe et al. 2021). These oncoids are mainly formed by recognizable *Girvanella* (a genus of fossil cyanobacteria) (Elliott 1975; Peryt 1981; Riding 1991; Hicks and Rowland 2009; De los Ríos et al. 2015). The oncoids reported in Antarctica are predominantly comprised of *Girvanella* and *Epiphyton*, as visible in their cortices (Rees et al. 1989). Likewise, the spongiostromate oncoids reported from the Cambrian of Spain are believed to have possibly generated by micritization of porostromate oncoids (Monty 1981). However, the oncoid cortices noticed in the carbonates of Sweden are reported as phosphatic (Sturesson 1988). A comprehensive study on Las Quionoas oncoids from the Salar de Antofella area (Argentina) was performed by Villafañe et al. (2021), who highlighted the morphologies (internal and external) and the main biological signatures of the oncoids. They interpreted the ancient ecosystem of Las Quionoas oncoids in comparison to other parts of the Europe and America. Similar features are observed in the oncoids from the North China epeiric platform, especially in the Henan Province (Zhang et al. 2015b), Shandong Province, and southeastern parts of the North China Platform (Zhang et al. 2014a, b; Han et al. 2015). Recently, Xiao et al. (2020a, b; 2021) described the fundamental relationship between the morphological disparities of Cambrian oncoids and associated paleoenvironmental factors; however, a few morphological disparities and geomicrobiological processes in the formation of the Cambrian oncoids were not discussed. To highlight these aspects of the Cambrian oncoids, a detailed investigation was carried out on a 0.3 m thick bed of oncoid-bearing oolitic limestone that developed in the upper part of the Cambrian Xuzhuang Formation in the Wuhai Section of Inner Mongolia, North China Platform. Such strata are remarkable sedimentary deposits that have a particular influence of microbes in their genesis via extracellular polymeric substances (EPSs; Flemming et al. 2016; Decho and Gutierrez 2017) that organize as photosynthetic biofilms and microbial mats (Gerdes 2010). Based on petrographic observations, the present study describes the influence of microbial activity in the formation of oncoids. It also elaborates the depositional settings of the Cambrian oncoids in the Xuzhuang Formation at the study section.

Geological background

The Wuhai Section of Inner Mongolia is located 10 km to the south of Wuhai City, beside the Yellow river under the gigantic Statue of Gen Gi Khan erected on the mountain top (Fig. 1a, b). This area comprises a part of the North China Platform, which developed on a stable craton of the Sino-Korean Block, restricted by major suture zones to the north (Hinggan Fold Belt), east (Tanlu Fault) and south (Qinling Dabieshan Belt) (Meng et al. 1997; Myrow et al. 2015) (Fig. 1a). In the North China Platform, marine sedimentation took place after the extinction of archaeocyaths at the end of the Cambrian Series 2. Previous studies reported that carbonate buildups lack metazoan reefs during the Middle

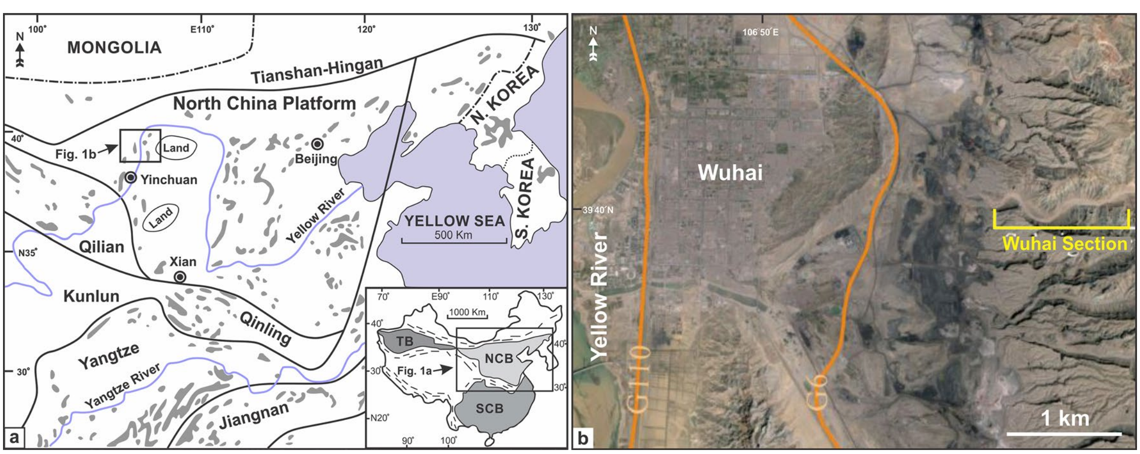


Fig. 1 **a** Map showing North China Platform, associated blocks and location of the study area in the Inner Mongolia region. Gray areas depict the exposed strata of Cambrian–Ordovician interval. The text "Land" in two circles indicates late Cambrian unsubmerged landmass in the western side of the North China Platform. Inset image shows three main blocks of China: *NCB* North China Block, *SCB* South China Block, *TB* Tarim Block (modified after Myrow et al. 2015; Riaz et al. 2019a, b); **b** Google earth based image of the study area (modified after Riaz et al. 2019b).

Cambrian to earliest Ordovician interval (Wood 1999; Riding 2002; Kiessling 2009). By that time, the marine depositional environment was no longer ultimate source of carbonate supply for the skeletons of metazoans. Contemporaneously, flat-pebble limestone, also called edgewise conglomerate, and ooids became well developed in most of the strata across the world, which could be regarded as the product of tempestites (Pratt and Bordonar 2007; Pruss et al. 2010). Moreover, the abundance of microbial carbonates increased with variations in metazoan diversity during this period, which was inherited from the past and continued onwards. Hence, this period can be considered as the recovery stage of microbial carbonates (Riding and Liang 2005; Riding 2006a). During the Late Ordovician to Early Carboniferous, the whole platform was subaerially exposed, and experienced erosion.

Materials and methods

The Xuzhuang Formation in the Wuhai Section is 59 m thick, with a conformable upper contact with the Cambrian Zhangxia Formation and an unconformable lower contact with the massive dolomite of the Mesoproterozoic Wangquankou Group. The field and petrographic investigations of the top part of the Xuzhuang Formation were carried out in great detail. Macroscopic features, particularly of oncoids, are observed in a 0.3 m thick bed in the upper part of the Xuzhuang Formation. Subsequently, petrographic analysis of 28 carbonate samples from bottom to top of the formation was carried out. Detailed microfacies analysis was conducted to appraise the microscopic composition and fabric of the oncolitic bed, the structure of the oncoids, variety of associated microbes and other related grains.

Thin sections were observed under a high magnification petrographic microscope at the China University of Geosciences, Beijing. High-resolution photomicrographs of oncoids were captured with a camera attached to the petrographic microscope. Subsequently, scanning electron microscopy (SEM) analysis was performed on suitable sections of the oncoids for detailed observations of filamentous fossils of cyanobacteria at the micron scale. CorelDraw graphic software was used to construct different figures for the current study.

Stratigraphy of the Xuzhuang Formation

The Xuzhuang Formation marks the base of the Cambrian Miaolingian Series in the study area, and is composed of one third-order depositional sequence (DS_1) in the depositional style of trangressive system tract (TST) + condensed section (CS) + highstand system tract (HST) (Fig. 2a–c). The sedimentary facies analysis of the Xuzhuang Formation shows a shift from the silty calcareous shale of an evaporative tidal flat facies in the lower part, to a mixed oncolitic– and oolitic–grain bank facies in the top part of the formation (Fig. 2a–c). The lower part of the Xuzhuang Formation (8 m thickness) comprises a muddy silty sand layer developed during the early transgression (TST). The overlying strata consist of gray–green silty calcareous mudstone and shale in the middle part of the formation (2 m thickness), which represent the shelf facies, and constitute the condensed section (CS) of the third-order sequence DS_1 (Fig. 2c). The condensed section can be reflected as a marking periphery at the end of immature sediments (*platform initiation stage*) and start of mature sediments (*platform foundation stage*), which ultimately laid the base of carbonate deposition and circulation on extensive area of the North China Platform (i.e., Meng et al. 1997; Xiao et al. 2017a, b; Latif et al. 2018; Riaz et al. 2019a, b, 2021). The interbedding of thin-to-medium-bedded calcareous mudstone and the medium-bedded oolitic and oncolitic limestones in the upper part of the formation forms a subtidal type meter-scale cycle, showing a shallow ramp deposit (15 m thickness) (Fig. 2b, c). The top part of the formation is comprised thin-bedded mud-intercalated micritic limestone and massive oolitic limestone of oolitic grain bank facies, forming subtidal type meter-scale cycle (36 m thickness).

Petrography

Petrography classified oncoids into dolomitic, bioclastic and micritic oncoids on the basis of variable structures and features of cortex and core. All these oncoids commonly comprise dark micrite (organic matter) that is either present in core or cortex or both. The detailed description of each oncoid type is given below:

Dolomitic oncoids

Petrographic observations show the predominant density of dolomitic oncoids in forming oncolitic grain bank of the Xuzhuang Formation (Fig. 3a). They are rounded to elliptical in shape with smooth cortices, ranging in size from 1.3 to 2 mm (Fig. 3a–c). These oncoids are composed of tiny crystals of dolomite that range in size from 50 to 100 µm (Fig. 3a–c). These crystals are possibly joined together by bacterial biofilms that are mainly associated with filamentous cyanobacteria. Further observations show the clear, thin and well developed laminae of dark micrite in these oncoids (Fig. 3a–c). Moreover, pyrite crystals are observed within the oncoids and the surrounding matrix (Fig. 3a–c). Furthermore, ooids also developed in noteworthy abundance in association with the dolomitic oncoids (Fig. 3a–c). Radial–concentric ooids (Fig. 3a; green arrow) and neomorphosed ooids (Fig. 3a–c; pink arrow) are the most

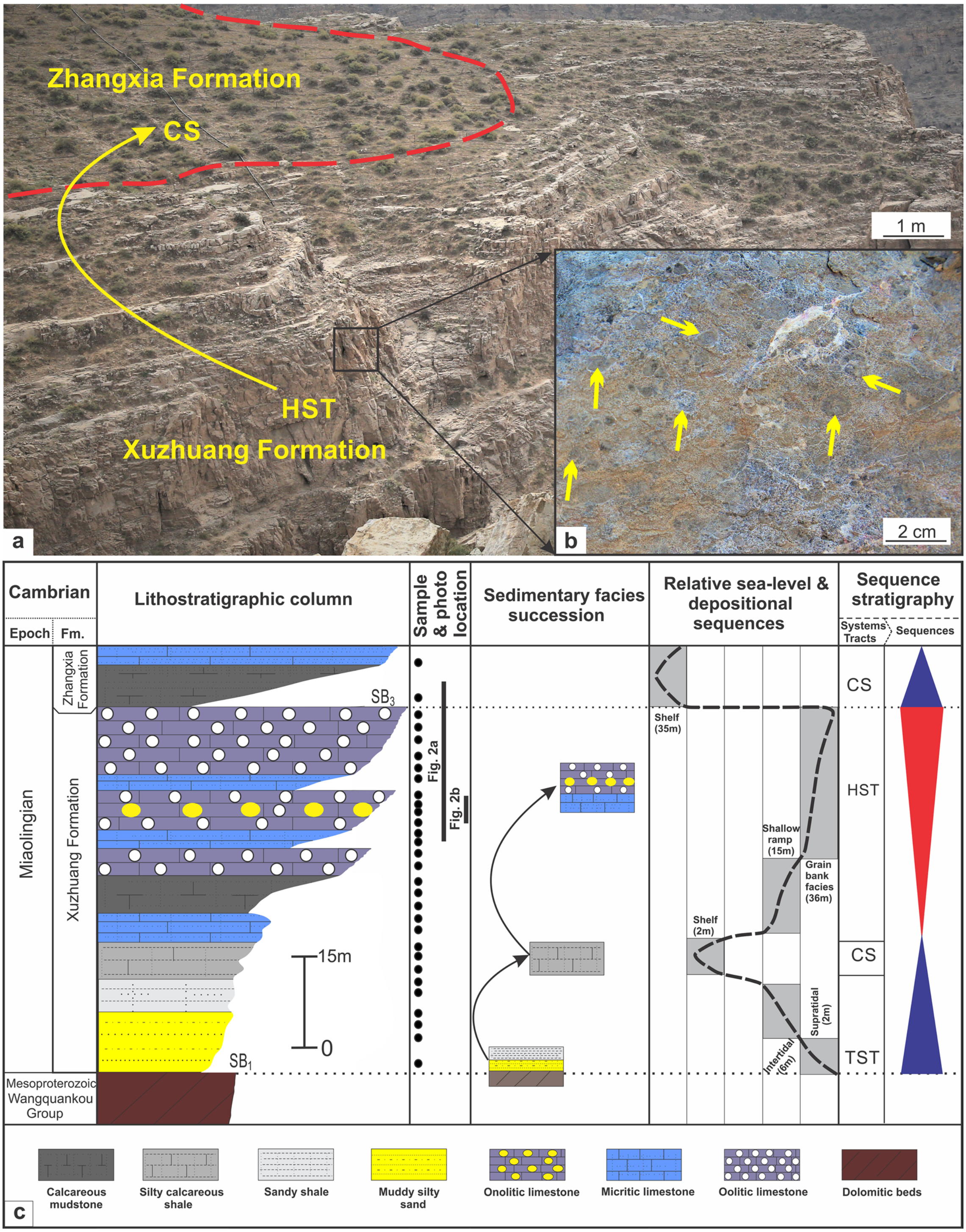


Fig. 2 Field photographs presenting **a** the upper part of the Xuzhuang Formation associated with massive oolitic limestone developed during late highstand systems tract (LHST), which makes conformable upper contact with the Zhangxia Formation; **b** Oncoids (yellow arrows) forming oncolitic limestone in the upper part of the Xuzhuang Formation; **c** Sequence stratigraphy of the Cambrian Miaolingian Xuzhuang Formation at the Wuhai Section, Inner Mongolia, showing shallowing upwards style of sedimentary facies. *TST* transgressive systems tract, *CS* Condensed Section, *HST* highstand systems tract, *Fm* Formation

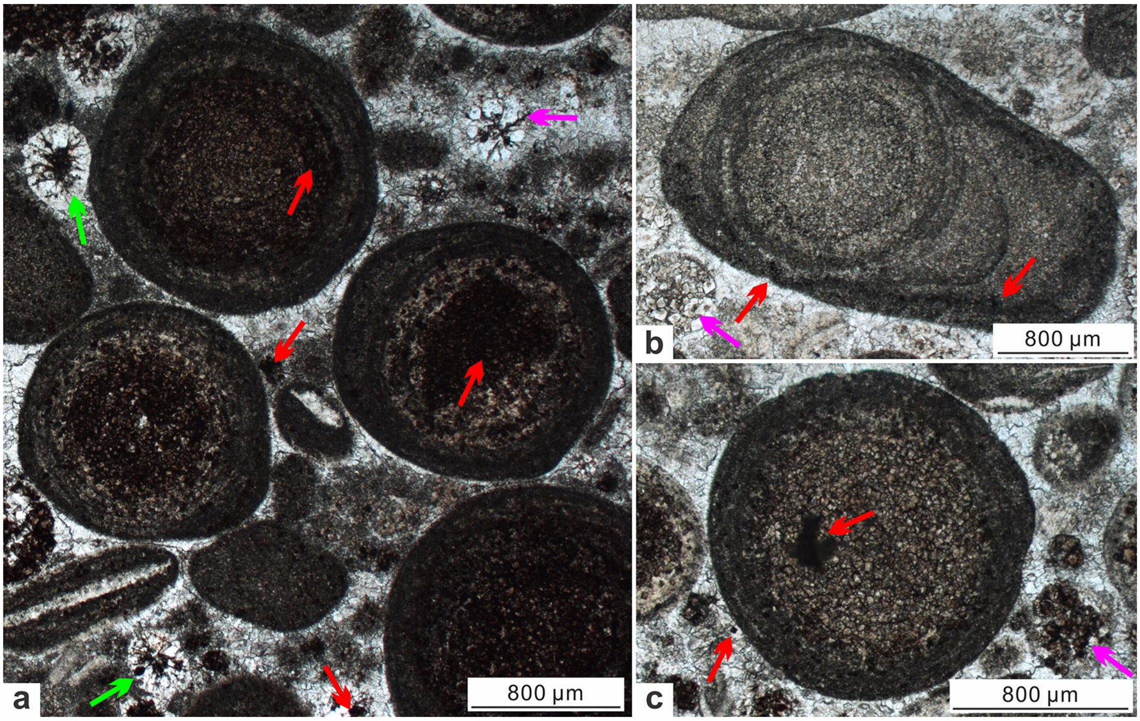


Fig. 3 Photomicrographs portraying dolomitic oncoids at the Wuhai Section, Inner Mongolia, North China Platform. **a** Rounded dolomitic oncoids forming the oncolitic grainstone of the Xuzhuang Formation; **b** elliptical oncoids have thin laminae of dark micrite and cemented by sparite; **c** rounded oncoids have dark laminae of micrite and crystals of dolomite that form by the combination of tiny crystals of dolomite through bacterial biofilm; **a–c** pyrite crystals are represented by red arrows. Radial–concentric and neomorphosed ooids are denoted by green and pink arrows, respectively

common types (<0.2 mm diameter). All these coated grains are cemented by sparite cement (i.e., meniscus cement) (Fig. 3a–c).

Bioclastic oncoids

These oncoids are rounded to elliptical, and surrounded by micrite cement (Fig. 4a, b). The morphology of these oncoids is strongly controlled by the shape of the nuclei (e.g., Liu and Zhang 2012). These oncoids have regular and smooth cortices. Typically, they are larger than 1.5 mm in diameter (Fig. 4a–c). The nuclei of these oncoids are with the bioclasts of trilobite or brachiopods fossils, whereas their cortices comprise clear laminae of dark micrite (Fig. 4a, b). Furthermore, a few oncoids are having the cores of ooid grains and thin concentric laminae of dark micrite (Fig. 4c). These oncoids are cemented by sparite (Fig. 4c). Further observations show pyrite crystals within the oncoids and the surrounding matrix (Fig. 4a–c).

Micritic oncoids

Micritic oncoids have rounded to elliptical shapes and a diameter ranging from 1.5 to 2 mm in size (Fig. 5a–d). These oncoids have the same composition of dark micrite (organic matter) from the center to the outermost cortices. Microscopic observations show irregular cortices and clear mixed laminae of dark micrite (Fig. 5a). Further observations show the discontinuous crude laminae of dark micrite that are thickening outward (Fig. 5b, d). Moreover, elliptical micritic oncoids show obvious dark micrite associated with clustering filamentous cyanobacteria and crystals of pyrite (Fig. 5c). The dark micrite in these oncoids (Fig. 5a–d) is possibly associated with significant preservation of calcified sheaths of filamentous cyanobacteria. Moreover, pyrite crystals (framboidal pyrite) are also observed in these oncoids (Fig. 5a–d). These oncoids are surrounded by micrite (Fig. 5a) and sparite cement (Fig. 5b–d), similar to the bioclastic oncoids (Fig. 4a–c).

Discussion

A variety of oncoids is deposited in the upper part of the Cambrian Xuzhuang Formation at the Wuhai Section in a high energy depositional environment. These grains were formed during the late highstand systems tract of the third-order depositional sequence that represents a typical example

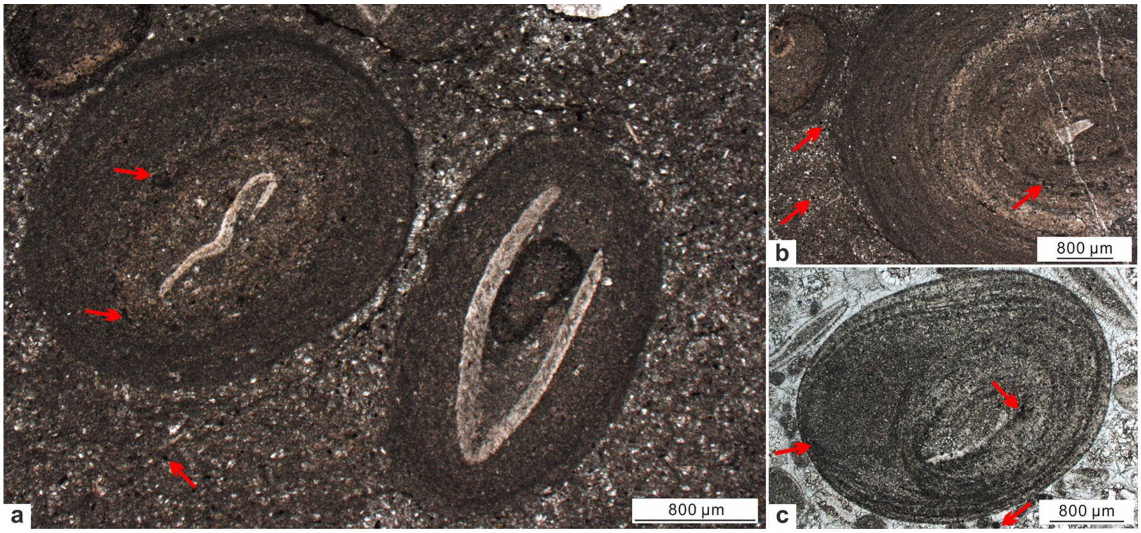


Fig. 4 Photomicrographs depicting bioclastic oncoids at the Wuhai Section, Inner Mongolia, North China Platform. **a** Bioclastic oncoids are cemented by micrite, forming packstone facies; **b** clear thin laminae made up of dark micrite and core of bioclast; **c** elliptical, clear, smooth cortices with concentric laminae and core of ooid. The cementing material is sparite; **a–c** pyrite crystals are shown by red arrows

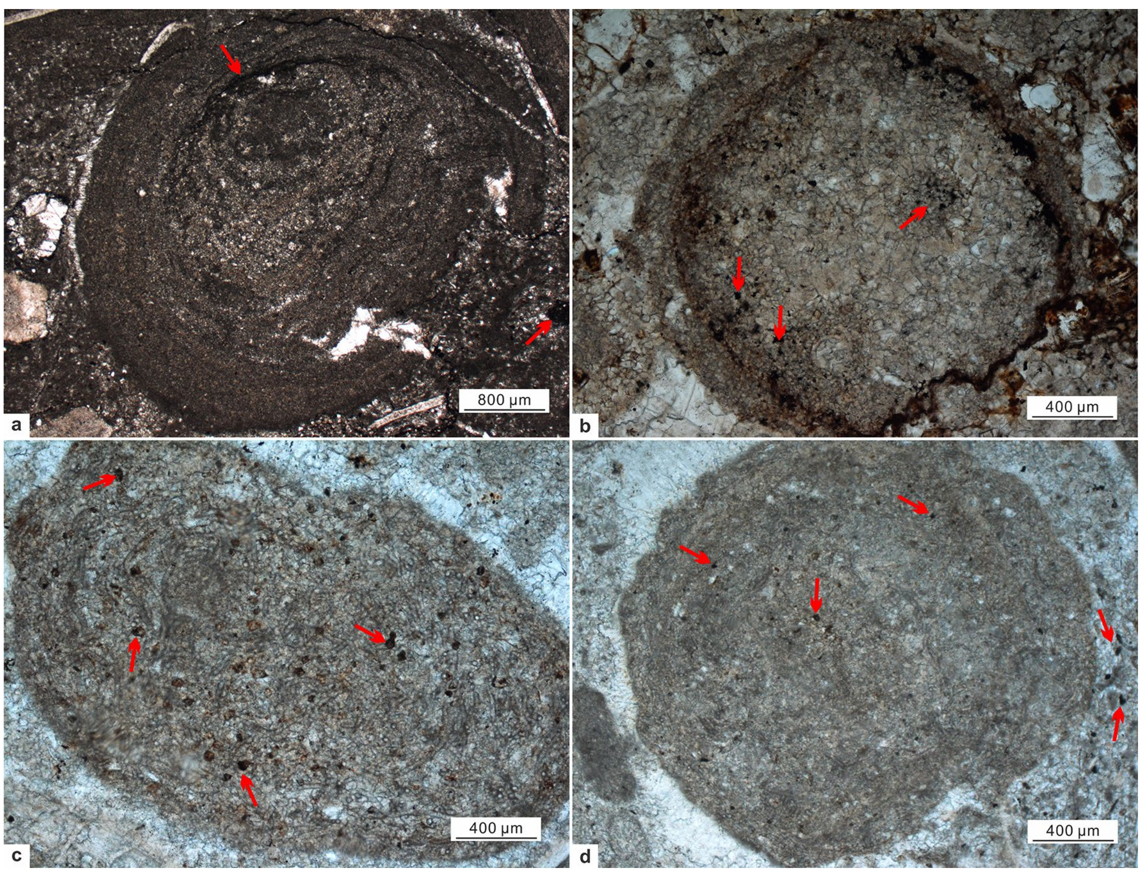
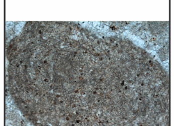


Fig. 5 Photomicrographs showing micritic oncoids, which form oncolitic packstone in the Xuzhuang Formation at the Wuhai Section, Inner Mongolia, North China Platform. **a** Rounded oncoid with rough and irregular cortex and mixed laminae of dark micrite; **b** rounded oncoid with a crudely laminated cortex having thick to thin laminae out- and inward, respectively; **c** elliptical micritic oncoids with abundantly preserved fossils of calcified sheath of filamentous cyanobacteria; **d** rounded oncoids with abundantly preserved filamentous fossils of cyanobacteria and cemented by sparite; **a**–**d** red arrows show the pyrite crystals

of a drowning unconformity (Schlager 1999). The microscopic observations of the studied Cambrian oncoids show that they are mostly rounded to elliptical in shape (Figs. 3, 4, 5). The dolomitic oncoids are associated with crystals of dolomite that were combined by an extracellular polymeric substance (EPS) mainly excreted by the filamentous cyanobacteria (Dupraz et al. 2009, 2011; Decho 2010; Decho and Gutierrez 2017). These oncoids have thin laminae of dark micrite that are generally thought to be developed through microbially mediated processes, particularly photosynthesis, which occurs mainly in cyanobacteria. Such activity results in building the microenvironment(s) suitable for the development and calcification of microbes during the genesis of oncoids (Logan et al. 1964; Arp et al. 2001; Flügel 2004). In the current oncoids, the rounded to elliptical shapes, thin concentric laminae of micrite, and their association to radial–concentric ooids (Fig. 3a–c), all indicate a high energy setting for the development of dolomitic oncoids. Furthermore, the sparite cement also indicates a high energy setting for the development of these oncoids (Flügel 2010). The shape of bioclastic oncoids is controlled by the shapes of cores and concentric laminae (Fig. 4a–c). These oncoids are having the nuclei of trilobite or brachiopod fossils and cortices of thin laminae of dark micrite (Fig. 4a, b) that are possibly formed by microbial activities. On the other hand, the presence of micrite cement in the bioclastic oncoids indicate a relatively low energy setting compared to the dolomitic oncoids (Fig. 3a–c) that flourished in high energy setting. Furthermore, the bioclastic oncoids with nuclei of ooid grains and cemented by sparite cement (Fig. 4c) also indicate high energy setting similar to the dolomitic oncoids (Fig. 3a–c). In addition, the micritic oncoids from their cores to cortices have the same composition (Fig. 5a–d) and they indicate varying energy conditions similar to the bioclastic oncoids, i.e., relatively low- (Figs. 4a, b, 5a) to high-energy settings (Figs. 4c, 5b–d). The petrographic characteristics of these oncoids can be summarized in Table 1.

The Cambrian oncoids of the Xuzhuang Formation at the Wuhai Section indicate dark micrite, as possible residue of organic matter (i.e., cyanobacteria and sulfate reducing bacteria) either in core or cortex (Figs. 4, 5). The oncoids that have nuclei composed of dark micrite (Fig. 5) show similar characteristics to the modern Bahamian coated grains as described by Brehm et al. (2003, 2006), where the nuclei are associated with cyanobacteria, sulfate reducing bacteria and diatoms. Whereas the oncoids with cortices composed of dark micrite (Figs. 4, 5) support the view of Liu and Zhang (2012), and Riaz et al. (2020) who reported dark micrite (filamentous cyanobacteria) in the cortices of ancient coated grains. The dark micrite (organic matter) in these oncoids comprises of flexuous, unsegmented and unbranched tubular filamentous cyanobacteria (Figs. 5a–d, 6a) (e.g., Xiao et al. 2018; Latif et al. 2019). Each individual form indicates a constant diameter and is enclosed by a well-preserved micritic wall (Fig. 5c, d), similar to the filamentous fossils of cyanobacteria described by several researchers (Mei et al. 2019a, b, 2020a; b; Riaz et al. 2020; Xiao et al. 2021). The external diameter of the filament ranges from 20 to 30 μm and the wall thickness varies between 2 and 3 μm (Xiao et al. 2018, 2020c). The presence of continuous walls, their identical thickness and homogeneous composition indicate an impregnation process instead of the aggregation of grains in the filamentous tubes (Fig. 5c, d) (e.g., Riding 2006b), and the centrifugal filament growth corresponds to frame-building microorganisms rather than endolithic ones (Latif et al. 2019). These filaments exhibit a dense and dark network,

Table 1 Comparison of dolomitic, bioclastic and micritic oncoids from the Cambrian Xuzhuang Formation at Wuhai Section, Inner Mongolia, North China Platform.

Age	Formation	Type	Morphology	Size (diameter)	Shape	Laminae	Nucleus	Rock type	Environment
Cambrian (Miaolingian)	Xuzhuang Formation	Dolomictic oncoids		1.3–2 mm	Rounded	Dolomite with concentric laminae of dark micrite	—	Grainstone	High energy setting
		Bioclastic oncoids		2 mm	Elliptical	Thin concentric laminae of dark micrite	Trilobite or brachiopode	Packstone	Relatively low energy setting
		Micritic oncoids		1.5–2 mm	Elliptical	Dark micrite (cyanobacteria) in the core and cortex	Calcified bacterial biofilm	Packstone	Relatively low energy setting

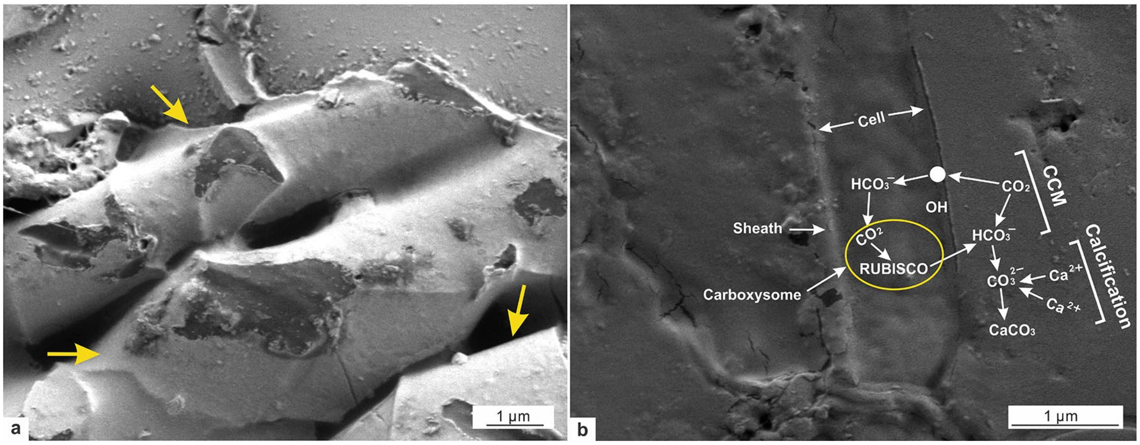


Fig. 6 SEM photomicrographs showing **a** the unsegmented and unbranched features of filamentous cyanobacteria; **b** Ultrastructural features of filamentous cyanobacteria indicate the CO_2 concentration mechanism (CCM) and calcification in the continuous sheath of cyanobacteria. (Modified after Xiao et al. 2018)

and appear as shadowy, poorly discrete structures (Fig. 5a–d) that result from cyanobacterial calcification (Riding 2006b). This type of calcification depends on the environment of the microbial mat, the carbonate saturation, and the CO_2 concentration mechanism (CCM) (Riding 2006b). Among these, the carbon compensation mechanism (Merz 1992; Riding 2006b) is the major driving force for the whole process that takes place in following steps: (1) the intake of carbon is increased by CO_2 acceptance and passage of HCO_3^- into the cell; (2) CO_2 is converted into HCO_3 by carbonic anhydrase (CA) enzymes; (3) diffusion of HCO_3^- into carboxysome occurs; (4) HCO_3^- is converted into CO_2 by CA enzymes; (5) OH^- ions are released from the cell by conversion of HCO_3^- into CO_2; (6) increase in pH in the sheath happens because of both CO_2 uptake and release of OH^-; and (7) HCO_3^- converts into CO_3^{2-} at the raised pH, giving rise to a state of saturation with respect to $CaCO_3$ minerals, which nucleates within the sheath (Fig. 6a, b). The calcification inside the filamentous fossils of cyanobacteria in the Cambrian oncoids from the Xuzhuang Formation reveals that surface sheath of these calcified fossils formed within living cyanobacteria, referred to as in vivo calcification.

The abundance of dark micrite, possibly associated with filamentous cyanobacteria, in the Cambrian oncoids of the Xuzhuang Formation provides certain clues for microbial precipitation on the microbial mat. The microbial activities inside the microbial mat produce EPS by secreting a diverse array of large molecules (De Philippis et al. 2001). This gel-like material known as EPS has the capability to prevent or stimulate calcium carbonate precipitation under particular conditions (Decho and Gutierrez 2017). It works as a "cation sponge" stopping carbonate precipitation by eliminating Ca^{2+} from solution due to negatively charged acidic assemblages in the EPS matrix (Sutherland 2001). Gradually, Ca^{2+} binding ability of EPS reduces significantly due to its heterogeneous nature. The molecules in the EPS are deprotonated by the increase in pH, resulting in an overall negative charge of the EPS under slightly acidic to alkaline conditions (Dupraz et al. 2009). The change in alkalinity initiates the precipitation that can be accomplished through biologically induced mineralization and biologically influenced mineralization. These processes alter the macro- and micro-environments, which lead to carbonate precipitation (Dupraz et al. 2009; Decho and Gutierrez 2017). It is inferred that the same process prevailed during the development of micritic oncoids and the cortex of bioclastic oncoids.

The dolomitic oncoids in the Xuzhuang Formation are formed because of the involvement of sulfate reducing bacteria (SRB) and the process of hydrolysis in the degradation of EPS. The SRB convert organic matter into raw materials for sulfate reduction. During hydrolysis, the EPS components are readily consumed by the mat community, particularly anaerobes. Meanwhile, the stimulation of anaerobic heterotrophic activity in mats is believed to be greater than that of aerobic heterotrophs. The combined action of fermentative organisms and SRB could be responsible for such a high consumption rate. Alongside, the oxygen levels are subject to rapid and extensive fluctuations when the light intensity changes (daytime–nighttime and/or cloud cover), and the O_2-consuming cell clusters in the EPS produce anoxic microenvironments. Therefore, the anaerobic pathway might be important in microbial EPS degradation that alters the crystal types from Ca^{2+} to Mg^{2+}. Consequently, it is asserted that the dolomitic oncoids and crystals of pyrite are formed in the Cambrian Xuzhuang Formation during degradation of EPS under anoxic condition.

The fluctuation of sea-level has a great influence on the nucleus, cortex structure and morphology of the oncoids

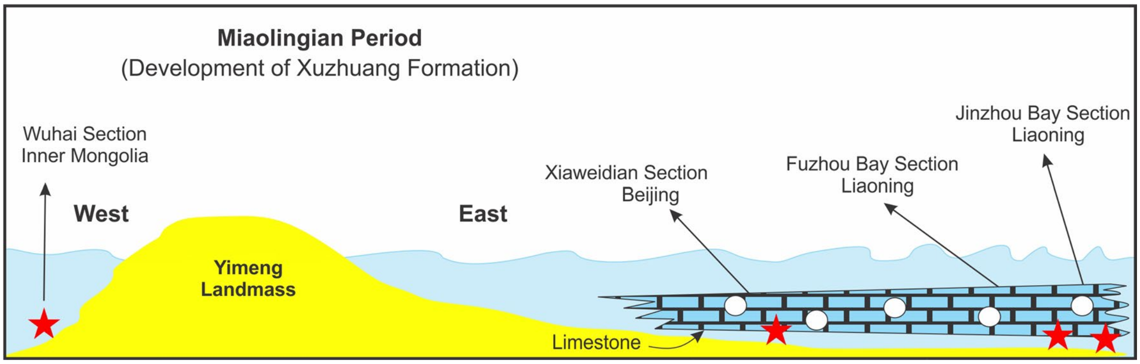


Fig. 7 Approximate positions of different sections of the North China Platform relative to the Yimeng landmass during Miaolingian Xuzhuang period (modified after Feng et al. 2004; Xiao et al. 2020b)

(Védrine et al. 2007, 2021; Xiao et al. 2020b). The current petrographic and stratigraphic studies show a 0.3 m thick oncoid-bearing oolitic limestone that is deposited in a nearshore environment, thinner than the oncoid-bearing oolitic limestone of the Xuzhuang Formation and the Zhangxia Formation at various sections formed in an offshore setting, i.e., Xiaweidian Section in Beijing (3.75 m thickness), and Fuzhou Bay (5.2 m thickness) and Jinzhou Bay sections (4.9 m thickness) of Liaoning Province of the North China Platform (Xiao et al. 2020a, b) (Fig. 7). The crossbeds and scouring surfaces provide a clue of sea-level change on a steeper slope that probably caused more rapid environmental changes over time (Xiao et al. 2020a, b), resulting in thin bedding of the oncoid-bearing oolitic limestone at the study section. In addition, the microscopic observations of the studied oncoids show concentric, rough-laminar, thin cortex and irregular oncoids, which are the characteristics of a nearshore setting developing thin laminae.

Summarizing, the Cambrian oncoids from the Xuzhuang Formation provide certain clues to their genesis through microbial activity (as indicated by presence of filamentous cyanobacteria, dolomite, and pyrite). The microbial components of the oncoids reflect the complicated calcification of extracellular polymeric substances (EPSs) that form biofilms in microbial mats dominated by cyanobacteria. Moreover, the current macroscopic and microscopic evidences of the Cambrian oncoids from the Xuzhuang Formation show their growth in a nearshore setting. However, there remain important questions about the complicated mechanism of formation and depositional setting of oncoids which need further research.

Conclusions

Cambrian oncoids in the Xuzhuang Formation of the North China Platform at the Wuhai Section, Inner Mongolia Province are categorized as dolomitic, bioclastic and micritic. The dolomitic oncoids indicate a high energy setting and form oncolitic grainstone, while the bioclastic and micritic oncoids depict both high and relatively low energy settings and form oncolitic packstone. These oncoids are related to extracellular polymeric substances (EPSs) that form biofilms in relatively thick microbial mats dominated by cyanobacteria, where they grew and rolled over it. Moreover, the pyrite grains and dolomite crystals associated with these oncoids signify microbial precipitation.

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Declarations

Conflict of interest There is no conflict of interest among the authors.

References

Adachi N, Liu J, Ezaki Y (2013) Early Ordovician reefs in South China (Chenjiahe section, Hubei Province): deciphering the early evolution of skeletal-dominated reefs. Facies 59:451–466

Arp G, Reimer A, Reitner J (2001) Photosynthesis-induced biofilm calcification and calcium concentrations in Phanerozoic oceans. Science 292:1701–1704

Braga JC, Martín JM, Riding R (1995) Controls on microbial dome fabric development along a carbonate-siliciclastic shelf-basin transect, Miocene, S.E. Spain. Palaios 10:347–361

Brehm U, Krumbein WE, Palinska KA (2003) Microbial spheres: a novel cyanobacterial-diatom symbiosis. Naturwiss 90:136–140
Brehm U, Krumbein WE, Palinska KA (2006) Biomicrospheres generate ooids in the Laboratory. Geomicrobiol J 23:545–550
Davies PJ, Bubela B, Ferguson J (1978) The formation of ooids. Sedimentology 25:703–730
De los Ríos A, Ascaso C, Wierzchos J, Vincent WF, Quesada A (2015) Microstructure and cyanobacterial composition of microbial mats from the High Arctic. Biodivers Conserv 24:841–863
De Philippis R, Sili C, Paperi R, Vincenzini M (2001) Exopolysaccharide-producing cyanobacteria and their possible exploitation: a review. J Appl Phycol 13:293–299
Decho AW (2010) Overview of biopolymer-induced mineralization: what goes on in biofilms? Ecol Eng 36:137–144
Decho AW, Gutierrez T (2017) Microbial extracellular polymeric substances (EPSs) in ocean systems. Front Microbiol 8:1–28
Diaz MR, Eberli GP (2019) Decoding the mechanism of formation in marine ooids: a review. Earth Sci Rev 190:536–556
Duguid SM, Kyser TK, James NP, Rankey EC (2010) Microbes and Ooids. J Sediment Res 80(3):236–251
Dupraz C, Reid RP, Braissant O, Decho AW, Norman RS, Visscher PT (2009) Processes of carbonate precipitation in modern microbial mats. Earth Sci Rev 96:141–162
Dupraz C, Reid RP, Visscher PT (2011) Microbialites, modern. In: Reitner J, Thiel V (eds) Encyclopedia of geobiology. Springer, Berlin, pp 617–635
Elliott GF (1975) Transported algae as indicators of different marine habitats in the English Middle Jurassic. Palaeontology 18:351–366
Feng ZZ, Peng YM, Jin ZK, Bao ZD (2004) Lithofacies palaeogeography of the Cambrian and Ordovician in China. Petroleum Industry Press, Beijing, pp 112–121 (**in Chinese**)
Flemming HC, Wingender J, Kjelleberg S, Steinberg P, Rice S, Szewzyk U (2016) Biofilms: an emergent form of microbial life. Nat Rev Microbiol 14(9):563–575
Flügel E (2004) Microfacies of carbonate rocks. Springer, Berlin, p 976
Flügel E (2010) Microfacies of carbonate rocks: analysis, interpretation and application. 2nd edn, Springer, Berlin
Gerdes G (2010) What are microbial mats? In: Seckbach J, Oren A (eds) Microbial mats: modern and ancient microorganisms in stratified systems. Cellular origin, life in extreme habitats and astrobiology, vol 14. Springer, Dordrecht, pp 5–25
Han Z, Zhnag X, Chi N, Han M, Woo J, Lee HS, Chen J (2015) Cambrian oncoids and other microbial-related grains on the North China Platform. Carbonate Evaporite 30(4):373–386
Hicks M, Rowland SM (2009) Early Cambrian microbial reefs, archaeocyathan inter-reef communities, and associated facies of the Yangtze Platform. Palaeogeogr Palaeoclimatol Palaeoecol 281:137–153
Kiessling W (2009) Geologic and biologic controls on the evolution of reefs. Annu Rev Ecol Evol Syst 40:173–192
Latif K, Xiao EZ, Riaz M, Wang L, Khan MY, Hussein AAH, Khan MU (2018) 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 Himal Earth Sci 51(1):1–16
Latif K, Xiao EZ, Riaz M, Hussein AAA (2019) Calcified cyanobacteria fossils from the leiolitic bioherm in the Furongian Changshan Formation, Datong (North China Platform). Carbonate Evaporite 34:825–843
Liu W, Zhang XL (2012) *Girvanella*-coated grains from Cambrian oolitic limestone. Facies 58(4):779–787
Logan BW, Rezak R, Ginsburg RN (1964) Classification and environmental significance of algal stromatolites. J Geol 72:66–83
Mei MX, Riaz M, Liu L, Meng QF (2019a) Oncoids built by photosynthetic biofilms: an example from the Series 2 of Cambrian at Fuzhouwan section in Liaodong Peninsula. J Palaeogeogr (chin Edn) 21(1):37–54 (**in Chinese with English Abstract**)
Mei MX, Riaz M, Meng QF, Liu L (2019b) Particular cap oncolitic grainstones of bank oolitic grainstones—an example from the Zhangxia Formation of the Cambrian Miaolingian at the Chafangzi Section in Fanshi County of Shanxi Province, North China. Geol Rev 65(4):839–856 (**in Chinese with English Abstract**)
Mei MX, Riaz M, Liu L, Meng QF (2019c) Leiolite bioherm dominated by cyanobacterial mats of the Furongian: an example from the Qijiayu section in Laiyuan County, Hebei Province. Geol Rev 65(5):1103–1122 (**in Chinese with English Abstract**)
Mei MX, Latif K, Mei CJ, Gao J, Meng QF (2020a) Thrombolitic clots dominated by filamentous cyanobacteria and crusts of radio-fibrous calcite in the Furongian Changshan Formation, North China. Sediment Geol. https://doi.org/10.1016/j.sedgeo.2019.105540
Mei MX, Riaz M, Zhang ZW, Meng QF, Hu Y (2021a) Diversified calcimicrobes in dendrolites of the Zhangxia Formation, Miaolingian Series (Middle Cambrian) of the North China craton. J Palaeogeogr. https://doi.org/10.1186/s42501-021-00087-z
Mei CJ, Riaz M, Wang L, Latif K, Zhang R (2020b) Development of Middle Cambrian leiolitic bioherms dominated by calcified microbes: a case study of the Xinji Section (North China Platform). Mar Micropaleontol. https://doi.org/10.1016/j.marmicro.2020.101858
Meng X, Ge M, Tucker ME (1997) Sequence stratigraphy, sea-level changes and depositional systems in the Cambro-Ordovician of the North China carbonate platform. Sediment Geol 114:189–222
Merz MUE (1992) The biology of carbonate precipitation by cyanobacteria. Facies 26(1):81–101
Monty CL (1981) Spongiostromate vs. porostromate stromatolites and oncolites. In: Monty C (ed) Phanerozoic stromatolites. Springer, Berlin. https://doi.org/10.1007/978-3-642-67913-1_1
Myrow PM, Chen J, Snyder Z, Leslie S, Fike D, Fanning M, Yuan J, Tang P (2015) Depositional history, tectonics, and provenance of the Cambrian-Ordovician succession in the western margin of the North China Block. Geol Soc Am Bull 127:1174–1193
Peryt TM (1981) Phanerozoic oncoids: an overview. Facies 4:197–214
Pratt BR (2001) Calcification of cyanobacterial filaments: *Girvanella* and the origin of lower Paleozoic lime mud. Geology 29:763–766
Pratt BR, Bordonar OL (2007) Tsunamis in a stormy sea: middle Cambrian inner-shelf limestones of western Argentina. J Sediment Res 77:256–262
Pruss SB, Finnegan S, Fischer WW, Knoll AH (2010) Carbonates in skeleton-poor seas: new insights from Cambrian and Ordovician strata of Laurentia. Palaios 25:73–84
Qvarnström M (2012) An interpretation of oncoid mass-occurrence during the Late Silurian Lau Event, Gotland, Sweden. Dissertations, Lund University, No. 326, p 18
Rees MN, Pratt BR, Rowell AJ (1989) Early Cambrian reefs, reef complexes, and associated lithofacies of the Shackleton Limestone, Transantarctic Mountains. Sedimentology 36:341–361
Riaz M, Xiao EZ, Latif K, Zafar T (2019a) 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):391–407
Riaz M, Latif K, Zafar T, Xiao EZ, Ghazi S, Wang L, Hussein AAA (2019b) Assessment of Cambrian sequence stratigraphic style of the North China Platform exposed in Wuhai division, Inner Mongolia. Him Geol 40(1):92–102
Riaz M, Zafar T, Latif K, Ghazi S, Xiao EZ (2020) Petrographic and rare earth elemental characteristics of Cambrian *Girvanella* oncoids exposed in the North China Platform: constraints on

forming mechanism, REEs sources and paleoenvironments. Arab J Geosci. https://doi.org/10.1007/s12517-020-05750-8
Riaz M, Zafar T, Latif K, Xiao EZ, Ghazi S (2021) 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):139–151
Riding R (1991) Calcified cyanobacteria. In: Riding R (ed) Calcareous algae and stromatolites. Springer, Berlin, pp 55–87
Riding R (2000) Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. Sedimentology 47:179–214
Riding R (2002) Structure and composition of organic reefs and carbonate mud mounds: concepts and categories. Earth Sci Rev 58:163–231
Riding R (2006a) Microbial carbonate abundance compared with fluctuations in metazoan diversity over geological time. Sediment Geol 185:229–238
Riding R (2006b) Cyanobacterial calcification, carbon dioxide concentrating mechanisms, and Proterozoic-Cambrian changes in atmospheric composition. Geobiology 4:299–316
Riding R, Liang L (2005) Geobiology of microbial carbonates: metazoan and seawater saturation state influences on secular trends during the Phanerozoic. Palaeogeogr Palaeoclimatol Palaeoecol 219:101–115
Schlager W (1999) Type 3 sequence boundaries. In: Harris P, Saller A, Simo A (eds) Carbonate sequence stratigraphy: application to reservoirs, outcrops and models, vol 63. SEPM Spec P, pp 35–46
Shapiro RS (2000) A comment on the systematic confusion of thrombolites. Palaios 15:166–169
Sturesson U (1988) Ooids and oncoids in a Middle Cambrian sandstone from Narke, Sweden. Geo Foren Stock for 110:143–156
Sutherland IW (2001) The biofilm matrix—an immobilized but dynamic microbial environment. Trends Microbiol 9:222–227
Tucker ME, Wright VP (1990) Carbonate sedimentology. Blackwell, Oxford, p 482
Vedrine S, Strasser A, Hug W (2007) Oncoid growth and distribution controlled by sea-level fluctuations and climate (Late Oxfordian, Swiss Jura Mountains). Facies 53:535–552
Villafañe PG, Lencina AI, Soria M, Saona LA, Gómez FJ, Alonso GE, Farias ME (2021) Las Quínoas oncoids: A new deposit of microbialites in the Salar de Antofalla (Catamarca, Argentina). Andean Geol. https://doi.org/10.5027/andgeoV48n2-3292
Wilmeth DT, Corsetti FA, Bisenic N, Dornbos SQ, Oji T, Gonchigdorj S (2015) Punctuated growth of microbial cones within early Cambrian oncoids, Bayan Gol Formation, western Mongolia. Palaios 30:836–845
Wood R (1999) Reef evolution. Oxford University Press, Oxford, p 414
Xiao EZ, Sui M, Qin Y, Latif K, Riaz M, Wang H (2017a) Cambrian sequence stratigraphic division for Qijiayu section in Hebei Laiyuan. Pet Geol Oilfield Dev Daqing 36(6):16–25 (**in Chinese with English abstract**)
Xiao EZ, Qin Y, Riaz M, Latif K, Yao L, Wang H (2017b) Sequence stratigraphy division of Cambrian in the northeast area of Luliang mountain: a case study of the Cangerhui section in Wenshui City. J Northeast Pet Univ 14(5):43–53 (**in Chinese with English abstract**)
Xiao EZ, Latif K, Riaz M, Qin YL, Wang H (2018) Calcified microorganisms bloom in Furongian of the North China Platform: evidence from microbialitic-bioherm in Qijiayu Section, Hebei. Open Geosci 10:250–260
Xiao EZ, Zafar T, Latif K, Riaz M, Lu Y (2020a) Geochemical and petrographic analyses of the Cambrian oncoids of the North China platform: implications for their paleogeography and paleoenvironment. Arab J Sci Eng 45(1):307–325
Xiao EZ, Mei MX, Jiang S, Zafar T (2020b) Morphology and features of Cambrian oncoids and responses to palaeogeography of the North China Platform. J Palaeogeogr. https://doi.org/10.1186/s42501-020-0055-1
Xiao EZ, Latif K, Riaz M (2020c) The genetic implications of microbial fossils for microbial carbonate: An example of Cambrian in North China Platform. Him Geol 41(2):183–194
Xiao EZ, Jiang S, Zafar T, Riaz M, Latif K, Setoyama E, Wang H, Xin H (2021) Sequence stratigraphic and petrological analyses of the Cambrian oncoids exposed in the Liaoning Province, North China Platform. Aust J Earth Sci. https://doi.org/10.1080/08120099.2021.1858156
Yang R, Fan A, Han Z, Chai N (2011) Status and prospect of studies on oncoid. Adv Earth Sci 26(5):465–474 (**in Chinese with English abstract**)
Yang R, Fan A, Han Z, Chi N, Han Y (2013) Characteristics and genesis of microbial lumps in the Maozhuang Stage (Cambrian Series 2), Shandong Province, China. Sci China Earth Sci 56(3):494–503
Zhang WH, Shi XY, Tang DJ, Jiang GQ (2014a) Oncolites from lower-middle Cambrian transition of the western north china platform: a study of their ultra-fabrics and biomineralization. Geoscience 28(1):1–15 (**in Chinese with English abstract**)
Zhang WH, Shi XY, Tang DJ, Wang X (2014b) Mass-occurrence of oncoids in the early-middle Cambrian transition at the western margin of north china platform: a response of microbial community to shallow marine anoxia. J Palaeogeogr (chin Edn) 16(3):305–318 (**in Chinese with English abstract**)
Zhang W, Shi X, Jiang G, Tang D, Wang X (2015a) Mass-occurrence of oncoids at the Cambrian Series 2–Series 3 transition: implications for microbial resurgence following an early Cambrian extinction. Gondwana Res 28(1):432–450
Zhang XY, Qi YA, Dai M, Chai S (2015b) Coupling variation of oncoids and trace fossils in the Zhangxia Formation (Cambrian Series 3), Dengfeng, western Henan province. Acta Micropalaeontol Sin 32(2):184–193 (**in Chinese with English abstract**)