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Ooid diversity and Ooimmuration in the Neoproterozoic Kunihar Formation, Lesser Himalaya, India

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Neoproterozoic Kunihar Formation is a mixed siliciclastic-carbonate succession where the carbonate units exhibit diverse types of microbial ooids and stromatolites. The ooids were classified based on: (i) ooid size (normal sized ooids and giant ooids), (ii) cortical microfabric (tangential and micritic ooids), (iii) ooid morphology (broken ooids, regenerated ooids, composite ooids, asymmetric and eccentric ooids) and (iv) ratio of cortex to nuclei (normal ooids and superficial ooids). In the Kunihar Formation, ooimmuration of stromatolitic and ooid clasts (regenerated and composite ooids) served as a mode for preservation of microbial imprints. SEM and petrographic analysis of the ooids indicate their primary generation from microbial activities. Ooimmuration of the studied ooids can be classed under bioimmuration by virtue of the biotic origin. Due to the absence of skeletal fossils, the dominant fossil imprints of the Precambrian constitute microbial stromatolites, ooids, oncoids, MISS, etc. Since ooids are widespread in the Proterozoic, ooimmuration can be considered as a potential mode of fossil preservation which will enhance our understanding of evolution of life, palaeoenviroment and sedimentary mechanisms.

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INTRODUCTION

The Precambrian biosphere was a realm of microbes (Awramik, 1971; Brasier and Lindsay, 1998; Soudry, 2000; Stal, 2000; Mukherjee, *et al*. 2018; Jeong-Hyun, 2019; Popall, *et al*., 2020; Noffke, 2021). In the absence of grazing and burrowing animals, microbial communities formed biofilms that enveloped the ocean floor. Microbial activities produced ooids, stromatolites and microbially induced sedimentary structures (MISS). Though recognised as sedimentary structures, ooids, stromatolites and MISS are vestiges of microbial matter, i.e., organosedimentary structures that carries record of biologic activities but are not fossilised entities. These microbialites are trace fossils because they are the evidences of interaction between organisms and the environment (Seilacher, 1967, 2007; Schopf, 2004; Shapiro, 2006; Hasiotis and Brake, 2019; Jeong-Hyun, 2019). During the Precambrian, even the minutest remains of organic matter become crucial evidence of life (Seilacher, 2007).

In palaeontological parlance, the term "immuration" is implied to preservation of organic remains by "walling in" or entombment. Two types of immuration are recognised: (i) lithoimmuration: Preservation of organic remains by abiotic overgrowths of minerals and (ii) bioimmuration: Preservation of organic remains by frameworks of other organisms (Vialov, 1961). Bioimmuration is further classified into: (i) substratum bioimmuration: the immurer overgrows an organic substratum. (ii) epibiont bioimmuration: the immurer together with immuree encases the organic substratum. (iii) bioclaustration: mutual intergrowth of immurer and immuree. Here, the immuree is a living entity and causes the overgrowth over the immured organism (Taylor, 1990). (iv) bryoimmuration: In this case, a bryozoan is the bioimmuring entity (Wilson *et al*., 2019).

An additional kind of immuration called ooimmuration was recognised by Wilson *et al*. (2021), whereby immuration occurs in response to accretion of ooidal cortexes around an organic remain. Encrustation of organic matter by ooids is frequently encountered in the rock record (Flügel, 2004). Ooimuration is a vital taphonomic mechanism as it preserves fossils which under normal circumstances would be obliterated by weathering, erosion, or dissolution. Ooimmuration may arise through lithoimmuration or bioimmuration depending on whether the ooids are precipitated biotically or abiotically.

Ooids are spherical, sub-spherical or elongated carbonate grains constituting a nucleus encrusted by laminated cortexes. The nuclei of the ooid usually comprise peloids, lithoclasts, bioclasts, siliciclastics, etc. Normally, most ooids possess a diameter of less than 2mm. However, some ooids may reach diameters of over 2mm and are known as giant ooids (Flügel, 2004). Giant ooids have been documented in the rock record from an array of sedimentary environments such as carbonate platforms, shallow marine, hypersaline and groundwater domains (Swett and Knoll, 1989; Sumner and Grotzinger, 1993; Lehrmann *et al*., 2012; Tang *et al*., 2015; Thorie *et al*., 2018; Lu *et al*., 2020). Generation of giant ooids occur in response to factors such as saturation of sea water, high accretion rate of cortex, low rates of abrasion, limited supply of nuclei, high energy conditions, etc. (Knoll and Swett, 1990; Sumner and Grotzinger, 1993; Trower and Grotzinger, 2010, Trower *et al*, 2017; Thorie *et al*., 2018; Trower, 2020). Another major control on ooid growth rate is the circulation of organic matter and microbial activity (Flugel, 2004; Thorie *et al*., 2018).

In the geological rock record, Neoproterozoic Era and Triassic Period are commonly known for the widespread growth of giant ooids, which may have been attributed to abundance of microbialites and with insignificant or total lack of metazoan activity (Trower and Grotzinger, 2010; Lehrmann *et al*., 2012; Tang *et al*., 2015; Thorie *et al*., 2018). In the Neoproterozoic, giant ooids were associated with warmer phases before, between or after glaciations (Thorie *et al*., 2018).

Ooimmuration as a mode of fossil preservation in Precambrian rocks is not widely studied. This study presents ooimmuration in the ooids of Neoproterozoic Kunihar Formation in response to biologic and physical conditions that prevailed in the carbonate shelf. This will improve our understanding of microbial and physical interactions which helped in the preservation of biotic imprints through ooimmuration.

GEOLOGICAL SETTING

Simla Group comprises about 4400m thick sedimentary succession within a broad open synform. It is surrounded by the Shali antiform in the north and east and Giri Thrust in the south. Tertiary rocks are thrusted directly over the Simla Group along the Bakhalag and Nunnhatti Thrust (Geological Survey of India, 1976). Simla Group is sub-divided into Basantpur, Kunihar, Chhaosa and Sanjauli Formations (Fig. 1.1-1.2). Basantpur Formation encompasses stromatolitic limestones, Kunihar Formation consists of stromatolitic limestones and siliciclastics, while Chhaosa and Sanjauli Formations comprises siliciclastics. The Simla Group exhibits a gradational and unconformable contact with the overlying rocks of Baliana Group (Kumar & Brookfield, 1987; Geological Survey of India, 1976; Geological Survey of India, 2012) (Table-1). Detrital zircon studies and 40Ar/39Ar dating of detrital micas from Simla Group have yielded an age range of 770-850 Ma and 860 Ma respectively (Frank, et al., 2001; McKenzie, et al., 2011).

The parentage of the Simla Group of rocks is considered to be from the Aravalli ranges (Kumar & Brookfield, 1987). The inception of Simla basin began with the unconformable deposition of the Basantpur Formation over the Shali Group and Darla volcanics. Thereafter, the 450m thick mixed silicicastic-carbonates of Kunihar Formation was deposited (Srikantia & Sarma, 1971). Giant ooids were recorded in the Neoproterozoic Kunihar Formation by Thorie *et al*. (2018). The Kunihar Formation also hosts an array of microbial build-

Table 1- Stratigraphy of Simla Group of rocks

Krol Group	
Baliana Group	Infra Krol Formation
	Blaini Formation
	Unconformity
	Sanjauli Formation
	Chhaossa Formation
Simla Group	Kunihar Formation
	Basantpur Formation
	Unconformity
Darla Volcanics	
Shali Group	

ups in the form of MISS and stromatolites (Mukhopadhyay & Thorie, 2016; Thorie, et al., 2018; Thorie, et al., 2020). This was followed by the deposition of the deltaic Chhaosa Formation (Kumar & Brookfield, 1987). Sedimentation of the fluvial Sanjauli Formation over the Chhaosa Formation marks the cessation of Simla Group (Mukhopadhyay, et al., 2016). The Simla Group is succeeded by the deposition of Marinoan Blaini diamictites or Blaini Group (Tewari, 2010). Several stromatolites of Collenia sp. (Valdiya, 1969; Srikantia & Sharma, 1976), Jurusania sp. (Sinha, 1977) and Osagia sp. (Bhargava & Ahluwalia, 1980) were identified in the Simla Group.

MATERIALS AND METHODS

For the purpose of analysing the giant ooids of Kunihar Formation, ooid bearing horizons around Sherpur, Bahawan, Haridal, Kakkarhatti, Arki and Kunihar were studied to understand the lithofacies and sedimentary structures (Fig. 1.1). Oolitic rock samples were collected during field study for the purpose of preparation of thin sections for petrographic analysis. Scanning electron microscope (SEM) studies of polished rock chips were carried out with JEM-2100 High Resolution Transmission Electron Microscope to analyse the mineralogical and biological properties.

OOID DIVERSITY IN KUNIHAR FORMATION

Kunihar Formation was deposited in a proximal peritidal and distal reef rimmed shelf setting. Five facies associations comprising peritidal (FA1), lagoonal (FA2), ooidal shoals (FA3), reefal complex (FA4) and fore reef (FA5) facies associations were previously identified from the mixed siliciclastic-carbonate Kunihar Formation (Thorie *et al*., 2020). Peritidal facies associations consisted of sandstones, laminated siltstones, mudstones, wavy-domal stromatolites and giant ooid bearing rudstone. Lagoonal facies associations constituted shales, columnar stromatolites and dolomudstones. Ooidal grainstones were associated with the ooidal shoal facies associations (FA3). Reefal complex

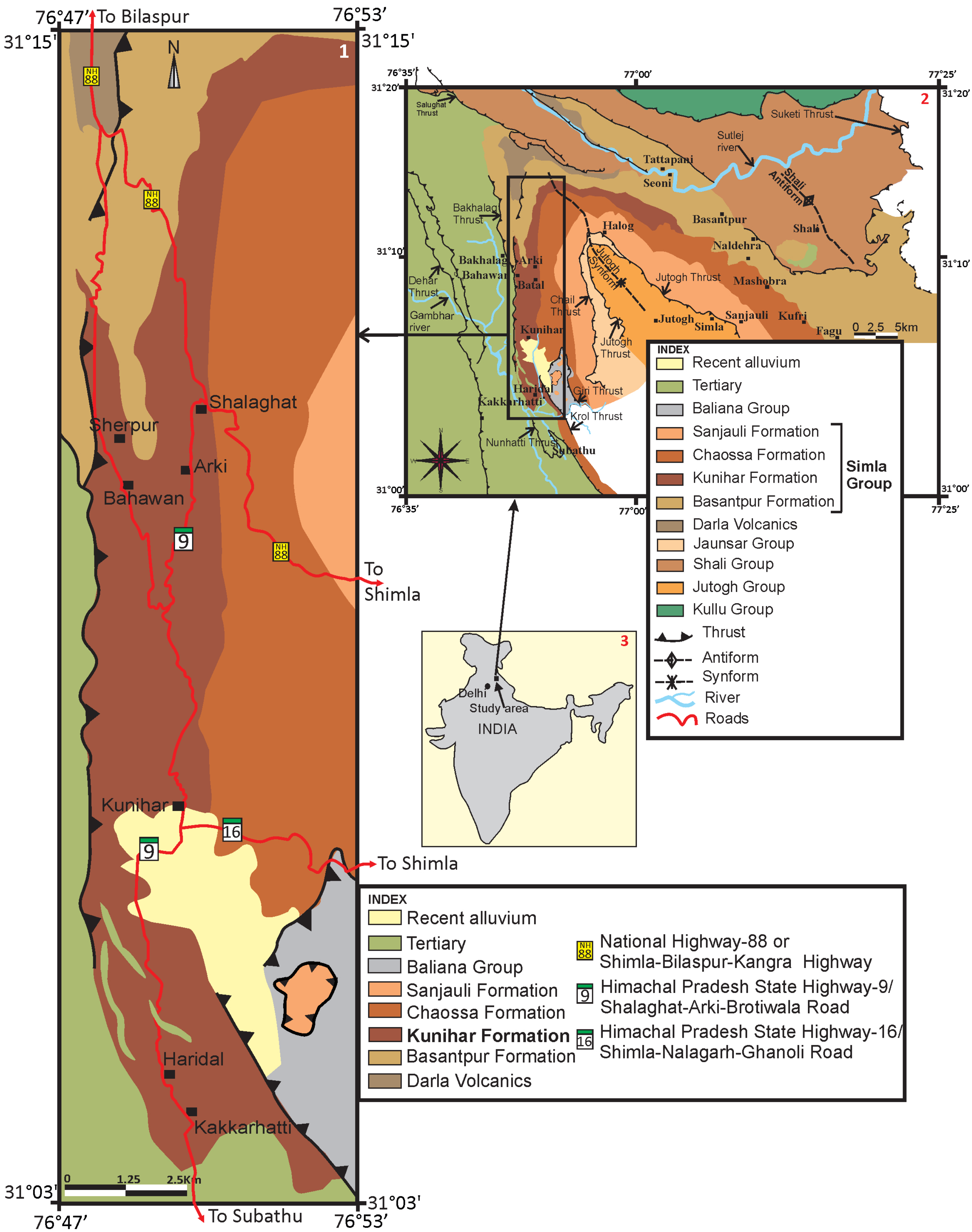

Fig. 1.1 Enlarged view of the geological map of Simla Group. Fig. 1.2 Geological map displaying the distribution of the Simla Group of rocks around Simla (modified after GSI, 1976). Fig. 1.3 Schematic map of India specifying the location of the study area.

(FA4) comprised domal stromatolites. Fore-reef facies associations were composed of intraclastic grainstones, conical stromatolites and carbonate breccia. Ooids were documented from the peritidal zones and ooidal shoals of the Kunihar carbonate shelf (Thorie *et al*., 2018, 2020).

The studied ooids were associated with peloids, intraclasts, oncoids, etc. The diversity of ooids belonging to the Kunihar Formation are discussed in detail in the segments below.

(i) Based on the ooid size, ooids in the studied sections can be classified into: (a) Normal sized ooids: These ooids exhibit diameters lesser than 2mm (Fig. 2.1-2.2). (b) Giant ooids: These ooids have diameters of more than 2mm (Fig. 2.3-2.4). They are identifiable with the naked

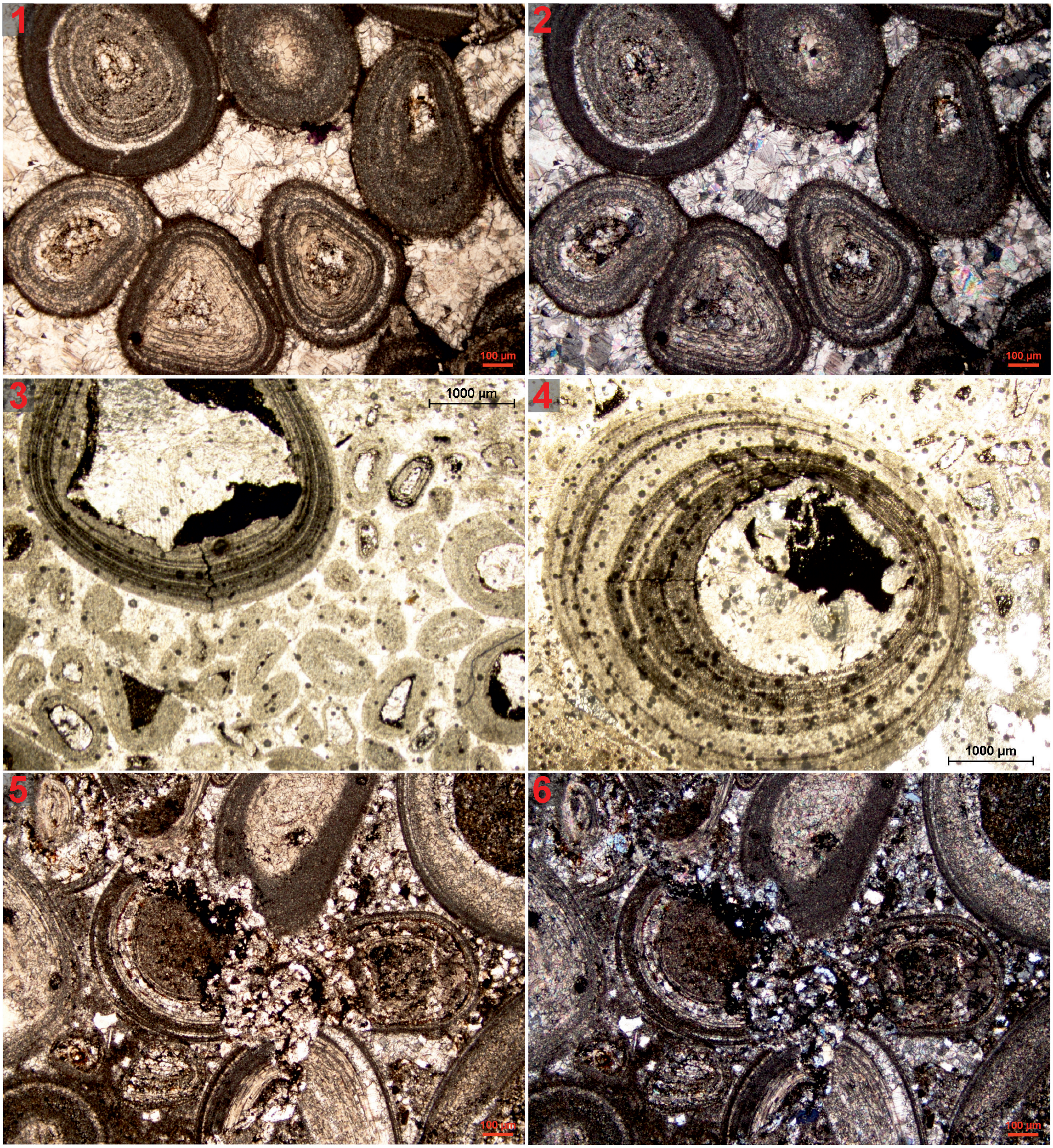

Fig. 2.1 Photomicrograph showing normal sized ooids of the Kunihar Formation. The ooids exhibit tangential and concentric cortexes under PPL. Fig. 2.2 Photomicrograph exhibiting normal sized ooids under crossed nicols. Tangential and concentric cortexes are common here. Fig. 2.3 Photomicrograph of a giant ooid (>2mm) from the Kunihar Formation. The giant ooid is surrounded by normal sized ooids under PPL. Fig. 2.4 Photomicrograph showing giant ooid under PPL. Fig. 2.5 Photomicrograph showing broken ooid under PPL. Fig. 2.6 Photomicrograph showing broken ooid under crossed nicols.

eye. But microscopic study is also required for detailed examination. The recorded dimension of giant ooids from the Kunihar Formation is the largest of all giant ooids recorded in the geologic history (Thorie *et al*., 2018). Ooimmuration is observed in some of the giant ooids.

(ii) Based on the cortical microfabric, Kunihar ooids comprise tangential sparry calcitic and micritic ooids. Tangential sparry calcitic ooids exhibit tangentially aligned sparry calcite cortexes enclosing the nuclei. The cortexes are concentric. Micritic ooids have nuclei surrounded by micritic cortexes. Micritic cortexes appear dark, microcrystalline and featureless. Both tangential and micritic cortexes occur together in most ooids (Fig. 2.1-2.2). Most of the ooids exhibit micritic composition. However, micritic cortexes are more common than tangential cortexes.

(iii) Based on the ooid morphology, ooids from Kunihar formation are of the following types: (a) Broken ooids: They consist of broken clasts of ooids (Fig. 2.5-2.6). (b) Regenerated ooids: Here, broken fragments of ooids constitute the nucleus, which is encrusted by new cortexes forming a new ooid (Fig. 3.1-3.2). (c) Composite ooids: Multiple ooids bounded together by ooid cortexes form composite ooids. In the studied slides, it was observed that composite ooids constituted two to over six smaller ooids enclosed within the ooid cortex (Fig. 3.3-3.4). Micrite and sparite fills the spaces between the ooids which for the core of the composite ooid. Quartz grains are sometimes encountered in these spaces. (d) asymmetric and eccentric ooids: These ooids have asymmetric layers of cortex around the nucleus (Fig. 3.5-3.6, 5.1). At times, superficial ooids serve as an eccentric nucleus for the new ooid cortexes that accrete preferentially upwards.

(iv) Based on the ratio of cortex to nuclei, Kunihar ooids display two varieties of ooids: (a) normal ooids: In normal ooids, the thickness of the ooid cortex is equal or more than half of ooid diameter (Fig. 4.1). (b) superficial ooids: The thickness of ooid cortex is lesser than half of ooid diameter in superficial ooids (Fig. 4.2). In normal sized superficial ooids (<2mm), only one or two layers of cortex is observed. However, within giant superficial ooids (>2mm), more than 2 layers of cortexes occur.

Association of the ooids with peloids reflect their microbial origin. Siliciclastic inclusion in the ooids indicate transportation of the siliciclastic grains from the hinterland and subsequent deposition in the carbonate shelf. Giant ooids are formed when normal sized ooids are driven from ooidal shoals into shallow subtidal zones. The dimensions of ooids also increase under the influence of increasing energy conditions. Ooids with tangential sparry calcitic cortexes are generally deposited under agitative and saturated conditions. Ooids with tangential sparry calcitic cortexes form in tidal zones and domains stabilised by algae. Algal imprints are important indicators of environmental conditions. Micritic ooids develop from precipitation by biofilms (Thorie *et al*., 2018, 2020). Porosity of micritic ooids (upto 50%) is comparatively higher than those with other compositions (Ferronatto *et al*., 2021). The dominance of micritic ooids in the Kunihar Formation suggests a high degree of porosity of the host carbonate sediment.

Broken and regenerated ooids indicate deposition in energy settings which is agitated enough to fracture and fragment the ooids (Thorie e al., 2020). Also, regrowth of cortexes around broken ooids reflect syn-sedimentary reworking and resurgence of ooid formation (Flügel, 2004). Regenerated ooids of Kunihar Formation is thus, associated with disintegration, redeposition and subsequent revival of ooid accretion.

Composite ooids suggest occurrence of calm periods when the smaller ooids were adhered together by microbial precipitation. Presence of micrite within the interstitial spaces of the ooids in the nucleus suggest microbial activity which may have fused the ooids. Sparite cement in the ooid core indicates agitative conditions (or neomorphism) (Flügel, 2004). Following this, strong agitative conditions of storm or tides would have suspended and/or rolled the conjoined ooids over which the formation of cortexes around the ooids took place (Thorie *et al*., 2018).

Asymmetric and eccentric ooids originate in subtidal environments where highly mobile ooids are transported into low energy zones (Woods, 2013). Micritic cortexes in these ooids develop from microbial influence during tranquil periods (Flügel, 2004). The eccentric habit of the ooids form when agitation is inadequate for rolling the grains on the sea floor (Scholle and Ulmer-Scholle, 2003). The eccentric cortex is also regulated by transitions in transportation processes. For instance, shift from suspension to saltation and/or traction mechanisms on the sea bottom (Flügel, 2004). The aforesaid mechanisms are indicated by the occurrence of asymmetric and eccentric ooids in Kunihar Formation.

The thickness of cortex is linked to environmental and energy conditions. Ooids with small nuclei usually have thicker cortexes than those with larger nuclei. Smaller grains are more mobile. On the contrary, larger grains are not easily set into motion and can only be transported periodically by strong surges in energy caused by storms and tidal currents, giving rise to superficial ooids (Flügel, 2004). A similar scenario can be postulated for the superficial ooids documented in the Kunihar Formation.

The remarkable diversity of ooids and size of giant ooids in Kunihar Formation is attributed to the emplacement of the tholeiitic Darla volcanics in the Simla basin. The weathering of these basalts enriched the Proterozoic oceans with nutrients which boosted microbial growth in the sediments (Thorie *et al*., 2018, 2020).

OOIMMURATION IN GIANT OOIDS OF KUNIHAR FORMATION

The giant ooid bearing rudstones and ooidal grainstones of Kunihar Formation display different varieties of ooid types. The giant ooids are mostly visible even with the naked eye (Fig. 5). Further, microscopic examination of the ooids reveal remarkable nuclei with different compositions. The nuclei are composed of broken ooids, stromatolitic clasts, quartz, etc. and are frequently coated by iron oxides.

In the Kunihar Formation, ooimmuration occured as a result of the encrustation of microbial ooid cortex over

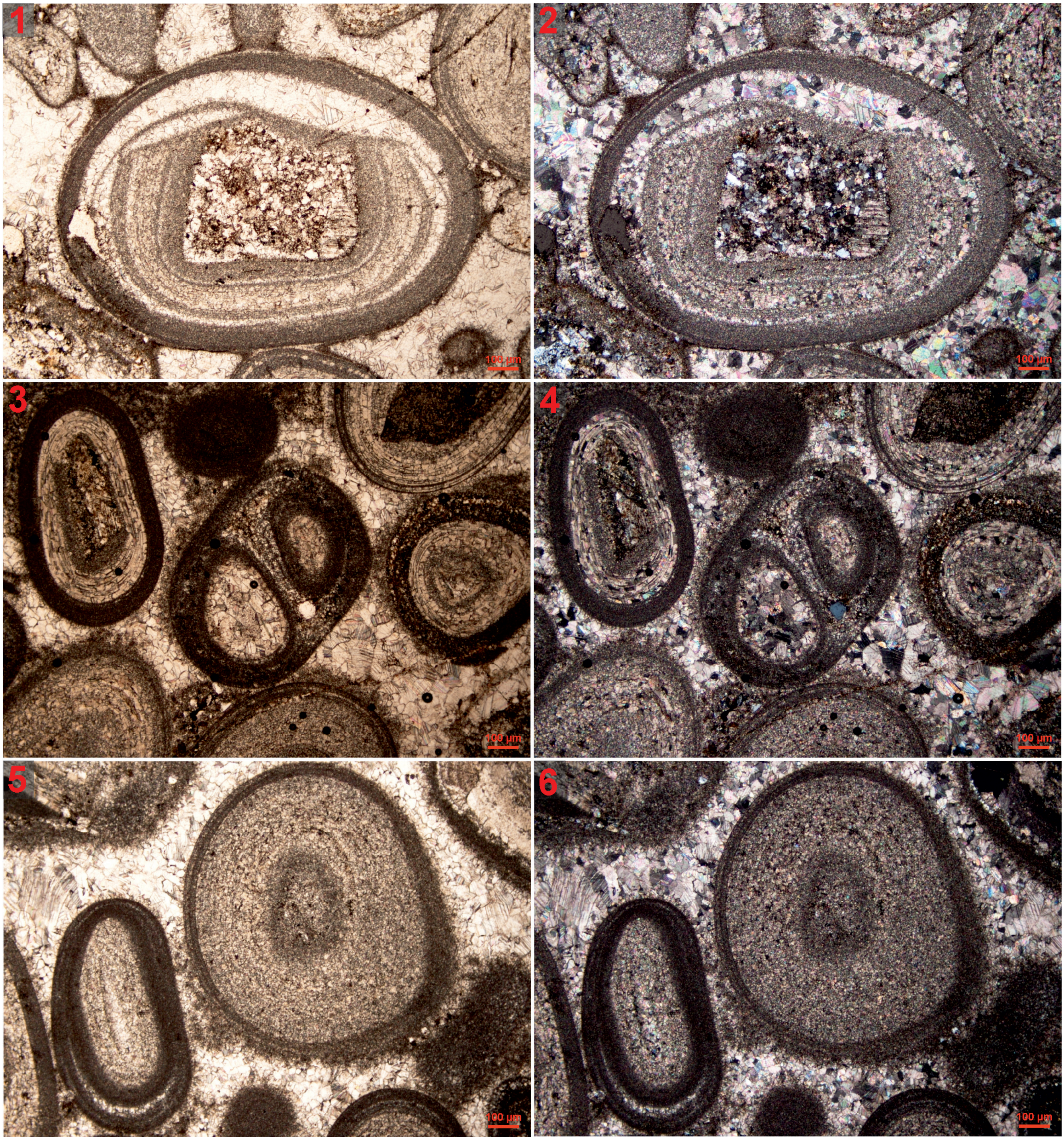

Fig. 3.1 Photomicrograph exhibiting a regenerated ooid from the Kunihar Formation under PPL. Fig.3.2 Photomicrograph exhibiting a regenerated ooid from the Kunihar Formation under crossed nicols. Fig. 3.3 Photomicrograph showing a composite ooid surrounded by normal ooids under PPL. Fig.3.4 Photomicrograph showing a composite ooid surrounded by normal ooids under crossed nicols. Fig. 3.5 Photomicrograph showing an eccentric ooid and normal ooid under PPL. Fig. 3.6 Photomicrograph showing an eccentric ooid and normal ooid under crossed nicols.

microbial ooids, broken ooids and stromatolitic clasts. In the studied sections, stromatolitic clasts were identified in the nuclei of normal sized ooids and giant ooids (Fig. 4.1, 4.2, 6.1). These clasts are mostly sub-rounded in shape. The length of the clasts ranges from a few microns to over 5000 microns (5 cm). In most of the stromatolitic clasts, laminated accretions are observed. Also, domal morphology of the stromatolite is preserved in some clasts. The stromatolitic clasts are enclosed within concentric rims of micritic cortex. Some of the giant ooids associated with ooimmuration are superficial ooids. However, the smaller stromatolitic nuclei to cortex ratio of the normal sized ooids indicates the fragmentation of the stromatolitic clasts into smaller grains, followed by higher accretion rate of the cortex, which

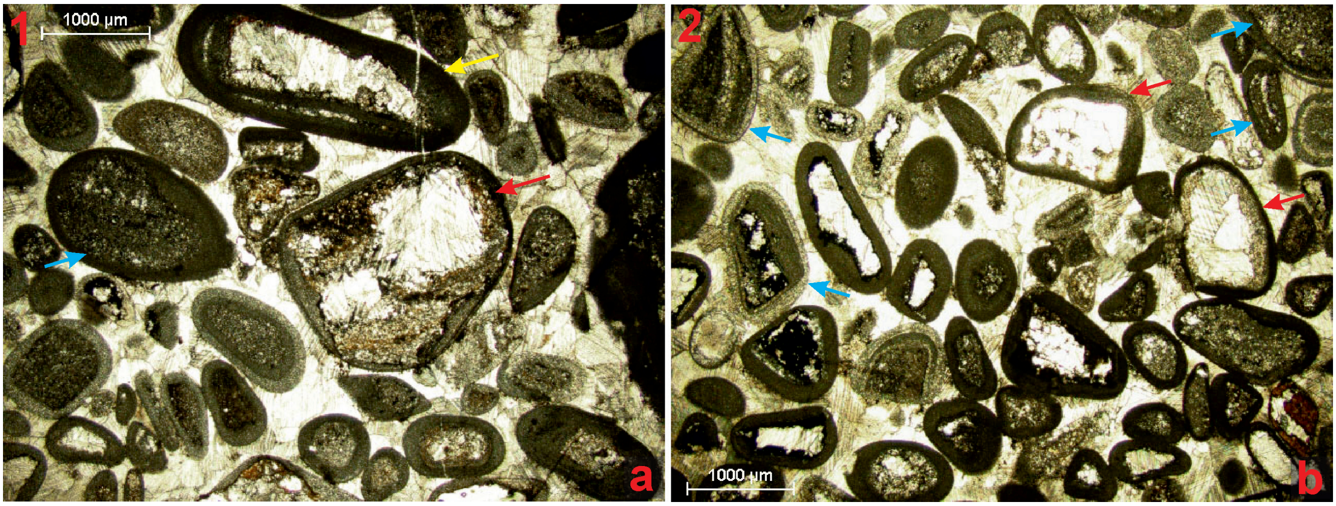

Fig. 4.1-4.2 Photomicrograph of ooids in the Kunihar Formation. Yellow arrow indicates eccentric ooids. Blue arrows indicate stromatolitic clasts encrusted by ooid cortexes. Red arrows indicate superficial ooids.

Fig. 5 Photograph of Kunihar normal sized ooids and giant ooids from an exposure near Haridal. The nuclei of the giant ooids is identifiable with the naked eye. Scale: Length of 1 unit- 1cm.

is attributed to the easy mobility of smaller grains (Flügel, 2004).The stromatolitic materials within the nuclei of the ooids were derived from the microbial stromatolitic reefs in the carbonate shelf system (Thorie *et al*., 2018, 2020). SEM studies of the stromatolitic clasts in the nucleus and the ooid laminations reveal the presence of filamentous material which confirms the microbial origin of the intraclasts (Fig. 6.2 and 6.3). The stromatolitic clasts were ooimmured before the clasts were further disintegrated.

The Kunihar Formation also exhibits a number of regenerated ooids (Fig. 6.4). Microbially generated ooids were fragmented by agitative processes, following which these broken ooids were coated by microbial ooid cortexes. Regenerated ooids also indicate the abundance of microbiota that amplified the propagation of the cortexes and the continuity of agitative conditions in the basin (Thorie *et al*., 2018). Composite ooids documented in the Kunihar Formation also encompass the preservation of previously formed microbial ooids by new cortexes that envelope and bind them together (Fig. 3.3-3.4 and 6.5). The ooids forming the core of the composite ooids are protected by the microbial cortex from further erosion or disintegration. SEM analysis of the ooids from Kunihar Formation indicate their generation primarily from microbial activities (Thorie *et al*., 2018, 2020). Since the immurer of the stromatolitic and ooid clasts in the studied ooids is microbial in origin, ooimmuration in this case can be considered as a subcategory of bioimmuration.

TAPHONOMIC SIGNIFICANCE OF MICROBIAL OOIMMURATION

Microbial activity in stromatolites was the only biologic record during the Precambrian (Grotzinger and Knoll, 1999; Schopf, 2006; Altermann, 2008; Homann, 2019; Wang *et al*., 2021). Neoproterozoic reefs are known to be microbial in origin (Chen *et al*., 2019; Thorie *et al*., 2020). It was not until the late Neoproterozoic, i.e., Ediacaran that metazoans dominantly evolved in the fossil record (Xiao and Laflamme, 2009; Evans *et al*., 2020). Thus, preservation of the organic stromatolitic clasts by ooimmuration retains evidences of deep-time biosedimentary record as they were the only imprints of life during Precambrian.

In the case of Neoproterozoic Kunihar Formation that is considered in this study, stromatolitic clasts were derived from microbial stromatolite reefs. These stromatolitic clasts and microbial ooids were fragmented and eroded by waves, tides and ocean currents (Thorie *et al*., 2018, 2020). The fundamental influence of ooimmuration on the intraclasts is significant as it preserved microbial impressions that could have been destroyed by the elements of nature like abrasion, dissolution and micritisation. Further, regeneration of ooid cortex over microbial broken ooids indicate intermittent resurgence of normal environmental conditions for microbial ooid accretion.

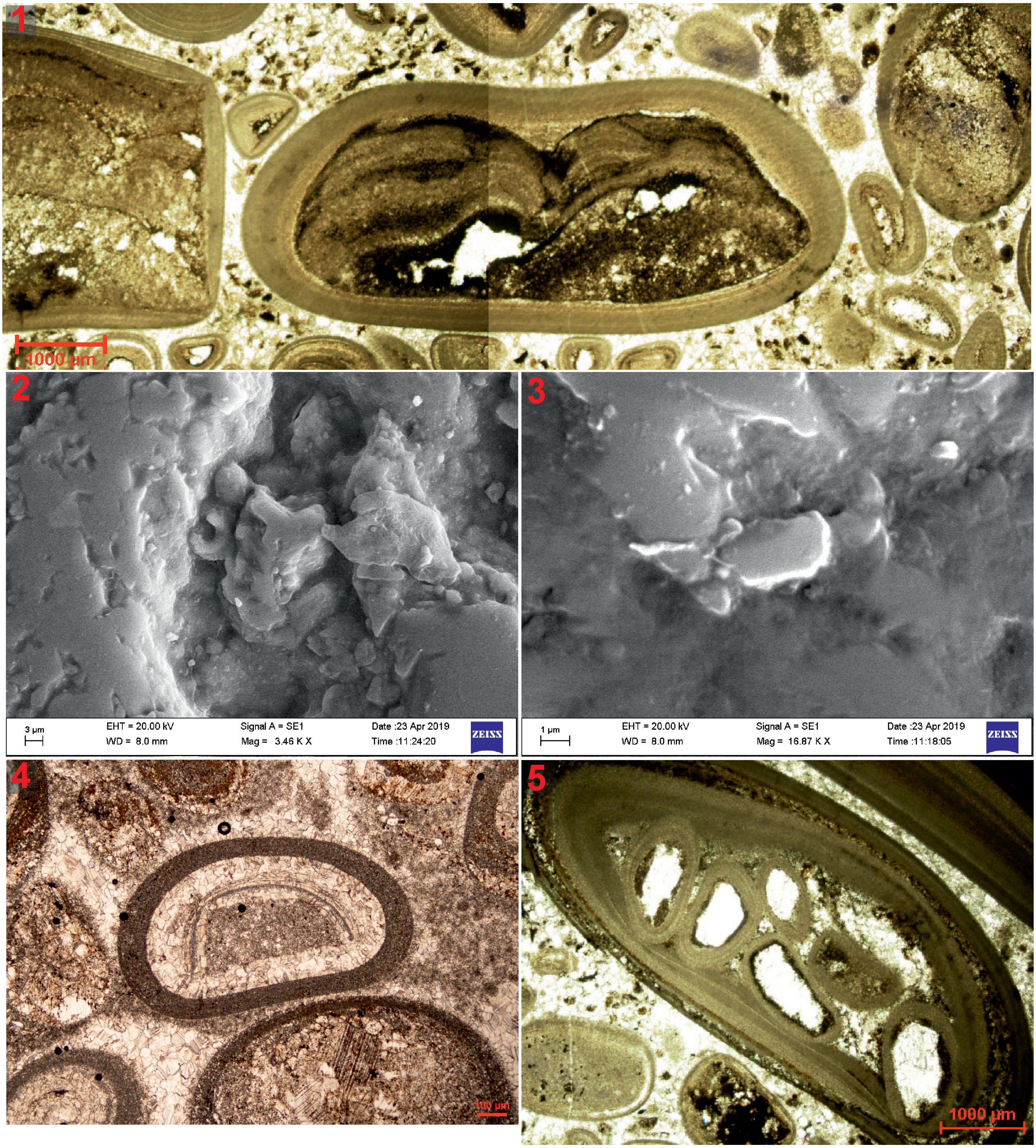

Fig. 6.1 Photomicrograph of a microbially ooimmured stromatolitic clast from the Kunihar Formation. The ooimmured stromatolitic clast is a superficial giant ooid surrounded by normal sized ooids. Fig. 6.2 Scanning electron microscope (SEM) photograph of the nucleus (stromatolitic clast) of the giant ooid. Sheath like matter (indicated by arrow) encrusting the calcitic material is observed which indicates the microbial origin of the stromatolitic clast. Fig. 6.3 Scanning electron microscope (SEM) photograph of the cortex of the giant ooid. Filamentous matter (indicated by arrow) is observed which reflects the microbial origin of the ooidal cortex. Fig. 6.4 Photomicrograph of a regenerated ooid. Fig. 6.5 Photomicrograph of a composite ooid. Six normal sized ooids are encrusted by the new ooid cortexes developing into a giant ooid.

Ooids are normally known to be reliable palaeoenvironmental indicators but are yet to be widely considered as mechanisms of fossil preservation. Though the Phanerozoic reveals abundant fossil record, the Precambrian lacks skeletal fossil record. As such, microbial imprints in the form of stromatolites, ooids, oncoids, MISS, etc. are the only fossil record, wherein ooimmuration can help in preservation of organic signatures. Ooids, specifically giant ooids are widely recorded in Proterozoic carbonates (Singh, 1987; Sumner and Grotzinger, 1993; Trower and Grotzinger, 2010; Tang *et al*., 2015; Trower *et al*., 2017; Thorie *et al*., 2018; Trower, 2020). As such, these ooids can be considered as potential depositories which preserve pre-metazoan fossils by mechanism of ooimmuration.

In this study, we highlight the role of ooids or ooimmuration as a mode of fossil preservation in carbonates. At this point, the understanding of ooimmuration in Precambrian rocks is not understood enough. Thus, consideration of ooimmuration in the Precambrian record will further help in shedding light on early life processes.

CONCLUSION

The Kunihar Formation records several evidences of microbial activity in the form of MISS, stromatolites, ooids, etc. Various types of ooids were identified. In the Kunihar Formation, ooimmuration of stromatolitic and ooid clasts served as a mode for preservation of microbial imprints. Ooimmurer of the microbial intraclasts is biotic in origin. Thus, ooimmuration in the studied ooids is recognised as a subcategory of bioimmuration.

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