Microbes: Mini Iron Factories

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Abstract Microbes have flourished in extreme habitats since beginning of the Earth and have played an important role in geological processes like weathering, mineralization, diagenesis, mineral formation and destruction. Biotic mineralization is one of the most fascinating examples of how microbes have been influencing geological processes. Iron oxidizing and reducing bacteria are capable of precipitating wide varieties of iron oxides (magnetite), carbonates (siderite) and sulphides (greigite) via controlled or induced mineralization processes. Microbes have also been considered to play an important role in the history of evolution of sedimentary rocks on Earth from the formation of banded iron formations during the Archean to modern biotic bog iron and ochre deposits. Here, we discuss the role that microbes have been playing in precipitation of iron and the role and importance of interdisciplinary studies in the field of geology and biology in solving some of the major geological mysteries.

Keywords Microbes · Biomineralization · Banded iron formation · Geomicrobiology

Earth has been a habitat for microbes almost since the beginning of its history and these microorganisms have flourished in extreme habitats such as Antarctica, acid mine drainage, glacier ice, geothermal springs, and deep-sea vents [1–7]. Although not emphasized much but microbes play an important role in a number of geologic processes including weathering, diagenesis, biomobilization, biomineralization, biogeochemical cycle, mineral formations,

transformations and biodegradation [8–13]. Fossilised microbial remains have also been reported from Early Archean rocks [14, 15] suggesting their presence in the early stages of Earth's evolution, thereby making this interdisciplinary field of geomicrobiology extremely important. One of the most intriguing and fascinating examples of importance of microbes in geology is the role they play in ore deposition and mineralization which is referred to as biomineralization. Recently, there has been increasing interest in processes leading to the biomineralization of Iron oxides [16, 17] because it is believed that microbes had a significant role in the deposition of BIFs.

Biominerals are considered to be composite minerals (carbonates, phosphates, silicates, sulfates, sulfides, oxides or hydroxides) composed of both organic and inorganic components [18–20]. They are important in the geologic record and provide information on the evolution of early life on Earth [21, 22]. Traditionally, the process of biomineralization has been grouped into: biologically induced mineralization (BIM) and biologically controlled mineralization (BCM). Variable terminologies such as, passive and active-biomineralization or organic-matrix mediated mineralization have also been used in literature [23].

Biominerals that are formed by BIM process generally nucleate and grow extracellularly and are a consequence of uncontrolled and unintended bacterial metabolic activity. The composition and properties of the resulting biomineral is influenced by environmental conditions making the biominerals formed by this process indistinguishable from inorganic counterparts [24]. *Geobacter metallireducens* and *Shewanella putrefaciens* are the most extensively studied bacterial species that produce crystals of magnetite [25]. Bacteria living in anaerobic habitats are particularly important in BIM processes and biogenic iron and manganese are the most common products of BIM [24]. In contrast,

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microbes exert direct control over all aspects of the nucleation and mineral growth in case of BCM, thereby giving biominerals well-ordered crystals and consistent morphologies [26]. Magnetotactic bacteria are the most widely studied microbes exhibiting controlled mineralization [26]. Studies indicate that group of magnetotactic bacteria accumulate considerable amount of dissolved iron [27, 28] for intracellular synthesis of magnetite or greigite crystals depending on the availability of oxygen or sulphur [29, 30]. Concentration of oxygen and presence or absence of nitrogen oxides influence BCM process for example, *Magnetospirillum magnetotacticum* requires microaerobic conditions, and nitrate growing medium for magnetite production [31].

Iron, one of the most abundant metals in the earth's crust, is ubiquitous in many biogeochemical processes and is an essential nutrient for all organisms [32, 33]. Microbes have played an important role in the history of evolution of sedimentary rocks on Earth in the form of BIFs [33]. Here we discuss the role of microbes in precipitation of iron.

Iron oxidizing bacteria are known to be responsible for the precipitation of a wide diversity of Fe^{+3} minerals at acidic and neutral pH, and under anaerobic and aerobic conditions [32, 34–35]. Iron oxidation in aerobic conditions generally involves the transformation of Fe^{2+} to Fe^{3+} [32]. *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans* are the best characterized acidophilic bacteria. At neutral pH, microaerophilic bacteria such as *Gallionella ferruginea* play an important role in Fe^{+2} oxidation while in anaerobic conditions, phototrophic bacteria (*Rhodobacter* spp) and some nitrate-respiring bacteria (*Dechlorosoma* spp) are known to oxidize Fe^{2+} to Fe^{3+} oxyhydroxides [36, 37]. The biomineralization reactions in case of reducing bacteria are considered to be limited to neutral pH [38] conditions for example, *G. metallireducens* and *M. magnetotacticum* are known to induce the precipitation of magnetite, siderite, and vivianite [39].

Studies also indicate that the presence of iron oxidizing and reducing bacteria might have played an important role in Precambrian biogeochemical cycle of Iron and formation of BIFs [32, 40]. Because of economic interests and their restricted formational time, the genesis of BIF has puzzled scientists all through the years and the know-how of the exact mechanism of BIF formation is still an enigma [41]. Konhauser [32] in their study concluded that microbial activity can be a viable mechanism for BIF formation which is also supported by stable isotope studies [42]. Involvement of cyanobacterial microbial mats for iron deposition as in the case of some hot springs in Yellowstone National Park also supports biogenic origin of BIF [43]. Modern biotic iron oxide deposits include ochre and bog iron deposits. Biogenic ochre deposits involving *G. ferruginea* from Greek island and *Geobacter sulfurreducens* and *Shewanella denitrificans* from north east England have been reported [44, 45]. On the

other hand, several bacteria viz. *A. ferrooxidans*, *Leptothrix ochracea* and iron oxidizing Metallogenium have helped in bog iron deposits in New Jersey [39 and references therein].

Regardless of which of the two processes (BCM or BIM) exerts maximum control on biomineralization, it is for sure that such processes are and have been important in the modern and ancient mineralizations, and have had a major impact on the fields of biology and geology. In addition to the advantages in the field of mineral formation, geological microbiology or geomicrobiology can allow a number of problems of practical importance to be solved. In spite of the emerging awareness amongst international researchers of the vital role that microbes play as geologic agents, geomicrobiology has not become an important interdisciplinary subject in India. Although, the information given above does not cover the aspects of biomineralization completely but the aim of this article is to bolster wakefulness among geoscientists, of some of the important roles that microbes have played and are playing as important geologic agents.

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