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Metal-Reducing Bacteria in Subsurface Environments: Who's Out There and What They Are Doing?

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Microbial metal reduction plays an important role in the cycling of metals such as iron(III), manganese(VI), and organic matter in natural environments. Many metal-reducing bacteria can also reduce a variety of metals and radionuclides including U(VI), Tc(VII), Co(III), Cr(VI), As(V), and Se(VI) as well as degrade petroleum hydrocarbons [1, 2]. Metal-reducing bacteria participate in a variety of geochemical processes such as weathering and formation of minerals, formation of ore deposits, and cycling of organic matter [1, 3]. Metal-reducing bacteria can precipitate or transform amorphous or crystalline Fe(III) oxides into crystalline iron phases such as magnetite (Fe_3O_4), siderite ($FeCO_3$), vivianite [$Fe_3(PO_4)\cdot 2H_2O$], maghemite (Fe_2O_3), and green rust [4, 5].

Metal-reducing microorganisms that grow under diverse environmental conditions, prefer environments that are very hot (thermophiles), room temperature (mesophiles), very cold (psychrophiles), increased salt concentrations (halophiles), very acidic (acidophiles), or high in alkalinity (alkaliphiles) [6-9]. Their habitat may be cold polar seas, deep-sea sediments, deep subsurface sedimentary rocks, highly saline lakes, tidal flat sediments, carbonate springs, or soda lakes. Metal-reducing microorganisms from diverse environments are of great interest to researchers trying to develop improved synthesis of useful materials, immobilize radionuclides and heavy metals at contaminated field sites, or produce hydrogen and electrons for energy. The objective of this presentation summarizes recent research results on metal reduction and biomineralization by psychrophilic, mesophilic, thermophilic, and alkaliphilic metal-reducing bacteria isolated or enriched from diverse subsurface environments as well as the utilization of microbial processes for nanoparticle synthesis, bioremediation, and carbon sequestration.

Thermophilic, mesophilic, psychrophilic, and alkaliphilic metal-reducing bacteria were isolated or enriched from a variety of cold, hot, and alkaline environments such as deep marine sediments, sea water near hydrothermal vent, deep subsurface environments, tidal flat sediments, groundwater, and a leachate-pond containing high levels of salt and boric acid. Thermophilic metal-reducing bacteria were isolated from deep sedimentary rocks in the Taylorsville basin, Virginia, and Piceance basin, Colorado. Phylogenetic analysis indicates that the thermophilic metal-reducing bacteria were closely related to *Thermoanerobacter ethanolicus* [8, 10]. Mesophilic metal-reducing bacteria were isolated or enriched from tidal flats in southwest coast of South Korea. Phylogenetic analysis indicated that the mesophilic metal-reducing bacteria were closely related to the members of *Shewanella* genus such as *Shewanella oneidensis* and *Shewanella saccharophilus* [11, 12]. Psychrotolerant metal-reducing bacteria were isolated from deep marine sediments in the Pacific Ocean, off the coast of Washington state, and sea water near hydrothermal vents off the coast of Hawaii. Phylogenetic analysis indicated that the psychrotolerant Fe(III)-reducing bacteria were closely related to the members of *Shewanella* genus, *Shewanella loihi* and *Shewanella pealeana* [12, 13]. Alkaliphilic metal-reducing bacteria were isolated from and a leachate-pond containing high levels of salt and boric acid from a boron mine. Phylogenetic analysis indicates that the alkaliphilic metal-reducing bacteria were closely related to *Alkaliphilus transvaalensis*, an alkaliphilic bacterium isolated from a deep South African gold mine [14].

Metal-reducing microorganisms isolated or enriched from diverse environments have the capacity to reduce various contaminant metals and radionuclides, which can lead to immobilization of these contaminants in subsurface environments. Thermophilic microorganisms isolated from Taylorsville and Piceance Basin were found to reduce Co(III), Cr(VI), Fe(III), Mn(IV), and U(VI) to reduced species such as Co(II), Cr(III), Fe(II), Mn(II), and UO_2 at temperatures up to 75°C [10, 15]. Mesophilic microorganisms isolated from tidal flats were found to reduce As(V), Cr(VI), Fe(III), Mn(IV), and Se(VI) to reduced species such as As(III), Cr(III), Fe(II), Mn(II), and Se(0) at room temperature [11]. Psychrotolerant and alkaliphilic metal-reducing bacteria were also able to reduce Co(III), Cr(VI), Fe(III), and Mn(IV) to reduced species such as Co(II), Cr(III), Fe(II), and Mn(II) [2, 5, 14]. In diverse subsurface environments, microbial oxidation of organic matter or hydrogen coupled to the reduction of Fe(III), Mn(IV), and other metals is an important process for the bioremediation and natural attenuation strategy for waters and sediments contaminated with heavy metals and radionuclides.

Metal reduction and mineral formation by metal-reducing bacteria isolated from diverse environments support the hypothesis that metal-reducing bacteria such as *Thermoanaerobacter* and *Shewanella* species are important components in the overall biogeochemical cycling of iron, manganese, and other elements in subsurface sediments. Microbial metal reduction influences not only the speciation of metals in anoxic subsurface environments, but also the carbon cycles and the fate of a variety of trace metals and nutrients. Given the abundance of metals including Fe and Mn in anaerobic subsurface systems, the capacity of metal-reducing bacteria to precipitate siderite ($FeCO_3$) and rhodochrosite ($MnCO_3$) using iron/manganese oxides and dissolved Fe/Mn ion species could have a significant impact on carbon sequestration. In addition to precipitation of iron carbonate mineral, the microbial utilization of organic matter and hydrogen may also contribute to direct or indirect precipitation of redox sensitive metals in subsurface environments.

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