Direct and indirect biomineralization of iron in the ferruginous Lake Pavin

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Iron-reducing, iron-oxidizing and sulfate-reducing bacteria are involved in the formation and alteration of Fe-bearing minerals through both direct and indirect biomineralization pathways. The anoxic, iron-rich bottom waters of Lake Pavin are characterized by their unique Fe mineralogy (water-column precipitation of Fe-phosphates) and constitute a perfect habitat for such bacteria potentially involved in Fe cycling. We aimed to investigate the microbial transformations of Fe(III)-phosphate, a key iron phase at the Lake Pavin oxycline, in enrichment cultures with lactate as the electron donor in the presence or absence of added sulfate. Despite low endogenous sulfate concentrations (< 20 µM), sulfate-reducers were the most competitive microorganisms in our enrichments both with and without added sulfate and transformed ferric iron into a diversity of ferrous minerals: vivianite, mackinawite, greigite, and pyrite. As vivianite and pyrite are important mineral phases found *in situ*, we suggest that sulfate and sulfur-reducing bacteria along with iron-reducing bacteria strongly influence iron mineralogy in the water column and sediments of Lake Pavin. Finally, we propose a mechanism for the formation of vivianite ($Fe^{II}_3(PO_4)_2 . 8H_2O$) and Fe-sulfides in the water column, whereby amorphous Fe(III)-phosphate is transformed via reductive dissolution or solid-phase rearrangement due to microbial activity.