Iron sulfides from magnetotactic bacteria: Structure, composition, and phase transitions

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ABSTRACT

Using transmission electron microscopy, we studied the structures and compositions of Fe sulfides within cells of magnetotactic bacteria that were collected from natural habitats. Ferrimagnetic greigite (Fe₃S₄) occurred in all types of sulfide-producing magnetotactic bacteria examined. Mackinawite (tetragonal FeS) and, tentatively, sphalerite-type cubic FeS were also identified. In contrast to earlier reports, we did not find pyrite (FeS₂) or pyrrhotite (Fe₁₋₂S). Mackinawite converted to greigite over time within the bacteria that were deposited on electron microscopy grids and stored in air. Orientation relationships between the two minerals indicate that the cubic-close-packed S substructure remains unchanged during the transformation; only the Fe atoms rearrange. Neither mackinawite nor cubic FeS are magnetic, and yet they are aligned in chains such that when converted to magnetic greigite, the probable easy axis of magnetization, [100], is parallel to the chain direction. The resulting chains of greigite are ultimately responsible for the magnetic dipole moment of the cell. Both greigite and mackinawite magnetosomes can contain Cu, depending on the sampling locality. Because bacterial mackinawite and cubic FeS are unstable over time, only greigite crystals are potentially useful as geological biomarkers.

INTRODUCTION

Magnetotactic bacteria synthesize membrane-bounded, intracellular, ferrimagnetic crystals called magnetosomes that cause the bacteria to orient along geomagnetic field lines (Blakemore 1975). Depending on the species, the bacteria contain either magnetite, Fe₃O₄ (Frankel et al. 1979), greigite, Fe₃S₄, (Mann et al. 1990; Heywood et al. 1990), or both (Bazylinski et al. 1993a). The bacteria appear to exercise a high degree of control over the sizes, morphologies, and crystallographic orientations of these minerals. Individual magnetosomes are usually arranged in chains, with the easy magnetization axis of the crystals aligned parallel to the chain, providing for the largest possible magnetic dipole moment of the cell (Frankel and Blakemore 1989). A review of magnetotactic bacteria and the magnetic properties of biogenic minerals is given by Bazylinski and Moskowitz (1997).

There is some uncertainty as to which Fe sulfides occur inside the magnetotactic bacteria. Intracellular Fe sulfides are known to be produced by a many-celled, magnetotactic prokaryote (MMP) and several morphological types of single-celled, rod-shaped bacteria (Bazylinski et al. 1994). Only greigite was observed in the rod-shaped species (Heywood et al. 1991), whereas in MMP Mann et al. (1990) found greigite and pyrite (FeS₂), and Farina et al. (1990) identified monoclinic pyrrhotite (Fe₁₋₂S). There are no subsequent reports of pyrrhotite, and the presence and role of pyrite in magnetotactic bacteria remains unclear (Bazylinski and Moskowitz 1997). Although information exists about magnetite formation (Frankel et al. 1983; Gorby et al. 1988), nothing has been reported about the mode of formation of greigite in bacteria. In a brief study, we reported that greigite forms by solid-state transformation from mackinawite (tetragonal FeS) (Pósfai et al. 1998); here we discuss our findings in more detail.

The discovery of nanometer-scale magnetite and Fe sulfides in the Martian meteorite ALH84001 and their suggested biogenic origin (McKay et al. 1996) raises the question of whether inorganically formed minerals can be distinguished from those produced by magnetotactic bacteria. Our goals were to identify the Fe sulfide magnetosomes and study their defects and compositions to understand their mechanism of formation and to determine whether the crystals are any different from nonbiogenically formed Fe sulfides. In this study, we present new findings concerning intracellular, bacterially produced Fe sulfides. We discuss microstructural features of magnetite magnetosomes in a companion paper (Devouard et al. 1998).

EXPERIMENTAL METHODS

Magnetotactic bacteria that produce Fe sulfides only have been described from anaerobic, brackish-to-marine aquatic habitats containing H₂S and have not yet been isolated and cultivated in axenic cultures. We therefore...