Transmission electron microscopy study of magnetites in a freshwater population of magnetotactic bacteria

A. ISAMBERT,¹ N. MENGUY,²* E. LARQUET,² F. GUYOT,² AND J.-P. VALET¹

¹Laboratoire de Géomagnétisme et Paléomagnétisme, UMR 7577, Institut de Physique du Globe de Paris, Paris, France
²Département de Minéralogie, Institut de Minéralogie et Physique des Milieux Condensés, UMR CNRS 7590, Université Denis Diderot, Université Pierre et Marie Curie, et Institut de Physique du Globe, Paris, France

ABSTRACT

A freshwater population of magnetotactic bacteria has been extracted from the Seine River (France) and studied using transmission electron microscopy. Seventeen different morphotypes were recognized using morphological criteria, which rely on the number of magnetite crystals and their organization within cells, the size and shape of the cells and their statistical distribution. This study revealed new features in some magnetotactic bacteria that have not been described in the literature. In addition X-ray energy dispersive spectroscopy and electron diffraction analyses revealed cells containing Ba-rich and CaO inclusions. Two major modes of magnetite crystals growth were derived from the distributions of the crystal shapes in this population. Numerous cases of crystals elongations along axes different from the [111] axis are related to one singular process of crystal growth. Thus, this population of magnetites collected from cells extracted from the Seine River does not meet some of the criteria for biogenicity, which have been used so far for biomagnetites, particularly those concerning the [111] elongation axis.

Keywords: Magnetotactic bacteria, biogenic magnetite, crystal growth, transmission electron microscopy, biomineralization, crystal morphology, magnetosomes, morphotype census, morphology of biomagnetite, CSD

INTRODUCTION

Magnetotactic bacteria mineralize magnetosomes, which are nanometer-sized magnetite (Fe₃O₄) (Frankel et al. 1979) or greigite (Fe₃S₄) crystals (Heywood et al. 1990, 1991; Mann et al. 1990) in intracellular vesicles. The sizes, morphologies, crystallographic characteristics, and chemical compositions of the biogenic crystals of magnetite are controlled by the bacteria and are thus used as potential signatures of their biologic origin. Magnetosomes are generally arranged in chains with the easy magnetization axis of each crystal (corresponding to the [111] crystallographic axis of magnetite) aligned parallel to the chain. The chains, parallel to the motility axis of the cells, act as compass needles so that the bacteria tend to align passively along the Earth’s magnetic field lines (Blakemore 1975). This phenomenon called magnetotaxis, coupled with flagellar motility and aerotaxis, allows the cells to locate and maintain an optimal position in vertical chemical gradients within aquatic environments.

These motile Gram-negative prokaryotes, ubiquitous in aquatic environments (Flies et al. 2005a), are cosmopolitan in distribution and are most frequently found in the oxic-anoxic transition zone (OATZ) (Flies et al. 2005b). They include coccoïd, rod-shaped, vibrioid, and spirilloid (helical) forms. The habits of magnetite crystals appear to be consistent within a given strain (Meldrum et al. 1993a, 1993b), although some variations in shape and size can occur within single magnetosomes chains (Bazylinski et al. 1994). Bacterial magnetites display restricted width to length ratios (w/l) corresponding to the stable single-magnetic-domain (SD) size range (Moskowitz 1995). In addition to the cuboctahedral habits synthesized by spirilla, the most common morphologies are prismatic, tooth, and bullet-shaped (Bazylinski et al. 1993; Mann et al. 1987a, 1987b). Small and rounded crystals are common at the end of the chains and interpreted as immature crystals. They indicate that growth of the chain is produced by precipitation of new magnetosomes from the extremities.

In this paper, we studied magnetite crystals from a freshwater population of magnetotactic bacteria, extracted from a natural environment in the Seine River (France) using high-resolution transmission electron microscopy. Measurements of the width to length ratio of the magnetite crystals within individual cells led us to identify different growth processes. We observed also structural and morphological anomalies in some biomagnetite crystals that could question some of the biogenicity criteria used to determine the origin of nanometer-sized magnetite in sediments.

EXPERIMENTAL METHODS

The freshwater magnetotactic bacteria were collected from a calm and sandy riverside of the Seine River (Bray sur Seine, Seine et Marne, France), from November 2003 to June 2004 to cover a large range of temperatures. The pH was about 7.1 and water temperatures varied between 10 and 25 °C. Sampling was done at the water-sediment interface by filling 500 mL jars with approximately 40% sediment,