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Crystallography of magnetite plaquettes and their significance as asymmetric catalysts for the synthesis of chiral organics in carbonaceous chondrites

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Abstract

We have previously observed the magnetite plaquettes in carbonaceous chondrites using scanning electron microscope (SEM) imaging, examined the crystal orientation of the polished surfaces of magnetite plaquettes in CI Orgueil using electron backscattered diffraction (EBSD) analysis, and concluded that these magnetite plaquettes are likely naturally asymmetric materials [1]. In this study, we expanded our EBSD observation to other magnetite plaquettes in Orgueil, and further examined the internal structure of these remarkable crystals with the use of X-ray computed microtomography.

1. Introduction

Magnetite (Fe_3O_4), a common mineral in some carbonaceous chondrites (CCs), has been shown to be an effective catalyst for the formation of amino acids that are commonly found in these meteorites [4]. Magnetite sometimes takes the form of plaquettes that consist of barrel-shaped stacks of magnetite disks that resemble a spiral [3] (Figure 1). However, a widely accepted description of the internal morphology of this particular magnetite form is still lacking, which is necessary in order to confirm or disprove the spiral configuration.

The spiral configuration of the magnetite plaquettes is worth attention due to their possible role in the synthesis of meteoritic amino acids with enantiomeric excesses (*ee*). *L-ee* is a crucial criterion for life, as extant life has developed a strict chiral homogeneity so that terrestrial proteins are made of exclusively *L*-amino acids. *L-ee* has also been observed for α -methyl amino acids (amino acids with limited terrestrial occurrence) in meteorites [2]. If magnetite plaquettes are naturally asymmetric materials, the asymmetric configuration can possibly be transferred to the prebiotic organic molecules that

can result in the chiral preferences we observe today for extant life.

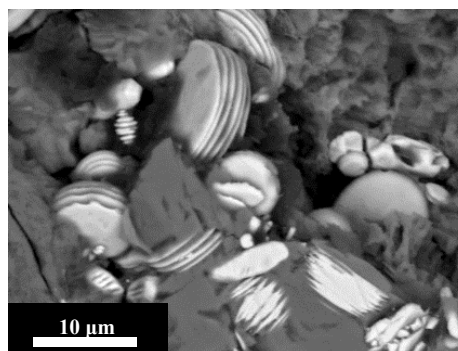


Figure 1: BSE image of the magnetite plaquettes observed in Orgueil.

In a previous study, we analyzed polished thin sections of fifteen CCs spanning different classes, and found that magnetite plaquettes are commonly associated with meteorites that have experienced aqueous alteration [1]. SEM imaging indicated that the surfaces of the terminating plates of protected plaquettes are smooth and clearly devoid of a spiral feature, which suggested that the plaquettes are stack of individual magnetite discs.

2. Methods

We analyzed magnetite plaquettes in a polished thin section of the CI Orgueil provided by the Field Museum. Imaging and mineral elemental compositions were obtained using the JEOL 7600F Field Emission SEM at NASA Johnson Space Center (JSC). EBSD patterns were obtained using a Zeiss SUPRA 55VP Field Emission SEM with a Bruker Quantax CrystAlign 400i EBSD system coupled with a Bruker *e*-Flash EBSD detector at JSC.

We removed focused ion beam (FIB) sections from each of the preselected magnetite crystals from Orgueil at Kyoto University. The FIB slices ($\sim 20 \times 20 \mu\text{m}$) of magnetite were then imaged by X-ray computed microtomography (XRCT) at SPring-8 Beam Line (2015A).

3. Results and Discussion

We studied the misorientation profiles of >10 magnetite stacks in Orgueil. The EBSD data show that the crystal orientation is fairly consistent within a single magnetite, however, this does not rule out the spiral configuration, as spiral dislocation induced crystal growth can result in constant crystal orientation within a single plaquette and is preserved from layer to layer [5]. Nevertheless, notable misorientations ($30\text{-}40^\circ$) were found between adjacent magnetite discs. The plaquettes appear to be comprised of discs with consistent rotation direction, which indicates a possible rotational feature.

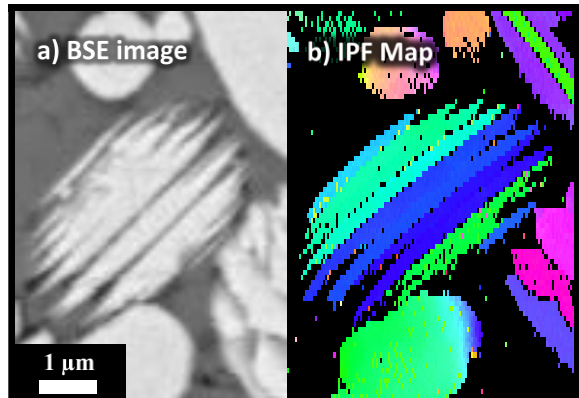


Figure 2: BSE image and inverse pole figure (IPF) map of a selected magnetite stack showing doublet feature in Orgueil.

Although the rotation direction is almost uniform within a given magnetite plaquettes, it is not consistent among different magnetite plaquettes. In order to gain a thorough understanding of the magnetite rotational feature, we studied the misorientation profiles of more magnetite plaquettes using EBSD. In addition, we investigated the internal structure of the magnetite plaquettes using XRCT to support our SEM observations.

We have observed that magnetite sometimes form plate-doublets, where the spacing between the plate-doublet is significantly smaller than the spacing to

the adjacent discs, likely formed by arrangement of discs with alternating aligned and anti-aligned magnetization (Figure 2a). The EBSD data indicate that the plate-doublets are of different crystal orientations, whereas the adjacent discs of the two neighboring plate-doublets share the same crystal orientation (Figure 2b). If magnetic orientation corresponds to the magnetite's crystal structure, the two magnetite discs in a plate-doublet would have their magnetization orientation anti-aligned. The misorientation in the crystal lattices and magnetic alignment between the magnetite plates possibly provide crystallographic control of asymmetric amplification of organics.

4. Conclusions

The remarkable morphology of magnetite plaquettes not only fascinates us by their striking appearance, but also their possible rotational feature that is now confirmed with EBSD analysis. These magnetite plaquettes are naturally asymmetric materials, effective catalyst of amino acid synthesis, and are associated with aqueous processing that is commonly involved in many amino acid formation mechanisms. Their possible involvement in the origin of homochirality which might have endowed the prebiotic world with an initial feedstock of asymmetric molecules for subsequent molecular evolution deserves further understandings.

Acknowledgements

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