Epitaxial relationships of clinopyroxene-hosted magnetite determined using electron backscatter diffraction (EBSD) technique

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ABSTRACT

Crystallographic relationships between exsolved phases and their hosts are typically characterized using transmission electron microscopy (TEM) or single crystal X-ray diffraction (XRD). In this investigation, electron backscatter diffraction (EBSD) was used to determine the epitaxial relationships of exsolved laths of magnetite in clinopyroxenes from three sampling sites in the Cretaceous Messum Complex of Namibia. Two orientations of magnetite inclusions are found with their long axes subparallel to [100] and [001] of the host clinopyroxene. Inclusions subparallel to [100], have [T10] // [010], (T11) // (010), and [112] // [010]. Inclusions subparallel to [001], have [T10] // [010], (111) // (100), and [T12] // [001]. The EBSD-derived orientation relationships agree well with previous TEM and XRD studies on similar materials.

The crystallographic relationships obtained with EBSD are used in conjunction with optimal phase boundary theory to determine the exsolution temperature of the magnetite inclusions, which is of importance to paleomagnetic studies. For one sample, this temperature (840 ± 50 °C) can be compared with that (865 ± 25 °C) derived from a more widely used cation exchange geothermometer. Thus it appears clear that exsolution occurred well above the Curie temperature of pure magnetite (580 °C).

INTRODUCTION

The electron backscatter diffraction (EBSD) technique has emerged as a method for rapidly determining lattice orientations of minerals exposed in polished thin sections (see review by Randle and Engler 2000). Most EBSD work on minerals published to date has been applied to petrofabric analysis in deformed rocks. We report here an application of EBSD to the determination of lattice orientations across coherent and semi-coherent phase boundaries produced by exsolution. Relative lattice orientations are critical to the application of the theory of optimal phase boundaries (Bollman 1970; Robinson et al. 1977) and to the calculation of exsolution temperatures based thereupon (Fleet et al. 1980). Although lattice orientations are routinely obtained by TEM and single-crystal XRD methods, EBSD is significantly less cumbersome and not as labor intensive.

Pyroxene and plagioclase in mafic plutonic and metamorphic rocks commonly contain oriented, highly elongated Fe-Ti oxide lamellae. In the case of clinopyroxenes collected from gabbros of the Messum Complex, Namibia, these inclusions comprise Ti-poor magnetite important in paleomagnetic and rock magnetic studies for their unusually stable magnetizations (e.g., Renne et al. 2002 and references therein). Interpretation of paleomagnetic data acquired from such rocks requires a detailed understanding of: (1) the formation temperature of the magnetite inclusions, (2) the timing of magnetization, and (3) the effects of extreme magnetic anisotropy. Determination of the orientation of the magnetite lattice with respect to the clinopyroxene host is a step-pleing stone to addressing all three of these issues. The epitaxial relationships between clinopyroxene and magnetite were first determined using single-crystal XRD (Bown and Gay 1959). Fleet et al. (1980) were the first to describe the orientation of magnetite with respect to its clinopyroxene host as a proxy for the temperature of exsolution (see discussion below). This geothermometer was later adapted to TEM studies by Doukhan et al. (1990) and Besson and Poirier (1994) to infer exsolution temperatures in metamorphic diopside and clinopyroxene phenocrysts, respectively. Doukhan et al. (1990) also suggested a balanced reaction involving hydrogen as a reactant and magnetite and tremolitic amphibole (which they observed) as products:

\[
(Ca,Mg,Fe^{2+})_{3}(\text{Si}_{2-3x/4}\text{O}_{10}) + x/4\text{H}_2 \rightarrow 3x/4\text{Fe}_2\text{O}_3 + (1-3x/2)\{(Ca,Mg,Fe^{2+})_{2+y/4}\text{Al}_{2-y/4}\text{Si}_{2-y/4}\text{O}_{10}\} + x/4(Ca,Mg,Fe^{2+})_{3-y/4}\text{Al}_{2-y/4}\text{Si}_{2-y/4}\text{O}_{10}(\text{OH})_{3}
\]

where \(y = 8x/(2 – x)\).

Equation 1 is the first relationship, of which we are aware, to show from a phase compositional perspective that an exsolution origin for both the magnetite and amphibole is plausible. Earlier studies argued for an oxidation origin for the magnetite inclusions and proposed reactions similar to that of Morse (1975):

\[
3\text{FeSiO}_3 + 1/2\text{O}_2 = \text{Fe}_3\text{O}_4 + 3\text{SiO}_2
\]

However, the abundant silica expected from Equation 2 is not observed as either nonstoichiometric Si or as a Si-rich phase within clinopyroxenes containing oriented magnetite inclusions, and thus, there is little support for an oxidation origin for the inclusions.

The samples for this study were collected from gabbros of

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