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Petrology and rock magnetism of the gabbro of Troodos ophiolite

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ABSTRACT

In order to determine the nature of remanence carriers of the layered gabbro of the Troodos ophiolite, Cyprus, we report optical and electron microscopic observations, together with rock magnetic and paleomagnetic experiments. Above all, the study aims to understand and clarify the time of magnetic acquisition relative to the brittle deformation of the oceanic crust manifested by the ridge-transform intersection (Solea graben and the Arakapas transform). Petrographic examination of pyroxene grains revealed isolated magnetite inclusions ranging in size from single-domain (SD) to multi-domain (MD) and in addition, MD pyrrhotite inclusions residing in veins and cracks. Thermal demagnetization and thermomagnetic procedures indicate two components, low and high temperature. We argue that the low temperature component, <350 °C, and the high component, <580 °C, are the contribution of the pyrrhotite and magnetite, respectively.

The SD magnetite inclusions exsolved in pyroxene are the dominant carriers of magnetic remanence in Troodos Gabbro. The initial formation of these inclusions occurred via exsolution reaction at temperatures between 520 and 850 °C, above the Curie temperature of pure magnetite during the solidification of the magma. Therefore, acquisition of remanent magnetization of the Troodos gabbro took place during the earliest stages of crustal accretion, before any brittle deformation associated with the spreading ridge and the transform fault occurred.

1. Introduction

Rock magnetic studies of oceanic crust by and large focused on the relative contribution of each layer to the oceanic magnetic anomalies and how that contribution is changing with age and distance from the spreading ridge (e.g., Gee and Kent, 1999, 2007; Kent et al., 1978; Wang and Van der Voo, 2004; Zhou et al., 1997 and references therein). Most of the studies focused on the extrusive rocks (dyke and pillow lava complex), whereas less attention was paid to the deeper intrusive (gabbro) layer. In addition, most of the samples are from drill cores or dredged materials. The gabbroic layer carries a significant portion of the oceanic crust magnetization (Feinberg et al., 2005; Gee and Kent, 2007), and provides crucial information about the most primary geodynamical processes of crustal accretion and deformation.

Previous rock magnetic studies (Davis, 1981; Kent et al., 1978; Renne et al., 2002) demonstrated that in many cases magnetization of gabbroic rocks is carried by SD particles even though these rocks are slowly cooled. SD particles have a 10–100 times stronger thermoremanet magnetization than MD inclusions. Minute magnetite inclusions have been commonly observed in pyroxenes in mafic and ultramafic rocks and the magnetic significance of this association to the bulk magnetic properties of the rock has been demonstrated. Evans et al. (1968) were one of the first to identify SD magnetite inclusions in pyroxene grains in the gabbroic rocks. They found that these inclusions carry a stable thermoremanence with characteristics similar to those of the total rock and concluded that these inclusions are single or pseudo-single domain (PSD) magnetite. Fleet et al. (1980) investigated magnetite inclusions in pyroxene grains in granulite rocks from Grenville province. Davis (1981) showed that magnetite rods in plagioclase are the primary carrier of stable natural remanent magnetization (NRM) in ocean floor gabbros. Selkin et al. (2000) studied the plagioclase hosted magnetite inclusions in the Archean Stillwater complex. Renne et al. (2002) and Feinberg et al. (2004, 2005, 2006) studied the oriented, highly elongated, magnetite inclusions in clinopyroxene crystals in gabbros of Messum Complex, Namibia as the main carrier of NRM.

Rock magnetic properties indicate that most of these inclusions are single domain. Four studies report magnetic properties of Troodos gabbros. Abelson et al. (2001, 2002) studied the anisotropy of magnetic susceptibility (AMS) of massive as well as layered gabbro. Granot et al. (2006) used remanent magnetization to reconstruct 3D crustal deformation of Troodos gabbro and showed that vertical axis rotations increase away from the spreading axis. This hints that most of the brittle deformation postdated the acquisition

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of magnetization. Granot et al. (2007) measured reliable absolute paleointensities. All four studies show stable and primary NRM and some clues for very small magnetite grains. Yet, none of them intimately combined the petrography and petrology with rock and paleomagnetic observations.

Ebert et al. (in preparation) used paleomagnetic vectors to study the brittle deformation associated with the Solea oceanic spreading ridge and the Arakapas transform fault (Fig. 1). They found that the remanence magnitization vectors measured in the gabbro differ significantly from those acquired by the upper crust. Therefore, it is essential to delineate the time of remanence acquisition in order to determine whether it is earlier than the deformation process. In this paper we demonstrate that the characteristic remanence magnetization (ChRM) is the primary magnetization residing mostly in SD and PSD inclusions of magnetite in the pyroxene crystals. A secondary small component of chemical remanent magnetization (CRM) resides in isolated large MD inclusions of pyrrhotite. Above all, the study aims to understand and clarify the time of magnetic acquisition relative to the brittle deformation of the oceanic crust caused by the Solea spreading ridge and the Arakapas transform fault. The maximum depth of brittle failure of the oceanic lithosphere is between 500 and 600 °C isotherm according to the presence of earthquakes along oceanic transform faults (Abercrombie and Ekstrom, 2001).

2. Methods

In order to characterize the petrographic and magnetic properties of the layered gabbro of Troodos Ophiolite, fresh samples were collected as hand samples and oriented field-drilled cores. Hand samples were used to prepare thin sections for petrographic analyses and a mineral separate for rock magnetic measurements. Thin sections were prepared from the hand-sample gabbro; it was also crushed and sieved and plagioclase and pyroxene single crystals larger than 2 mm were hand-picked. NRM and vector analysis of the oriented cores were studied for directional paleomagnetic analysis. The results with structural implications will be reported and discussed in a following paper (Ebert et al., in preparation).

2.1. *Petrographic characterization*

Eight thin sections of the gabbro and four separated pyroxene grains were examined using an Electron Probe Micro Analyzer (EPMA, JEOL JAX 8600) at the Institute of Earth Sciences and the Environmental Scanning Electron Microscope (E-SEM, Quanta 200) at the Nano-characterization center, the Hebrew University of Jerusalem. Four pyroxene grains were selected by examining hysteresis loops (see below). The four representative grains were mounted in epoxy and polished to expose a section of the pyroxene grains. The magnetic ore inclusions were detected by backscattered-electron imaging (BSI). Each sample was analyzed using the EPMA with an acceleration voltage of 15 kV and a beam current of 10 nA. Counts were collected for 60 s using a focused electron beam. The X-rays were collected using a Pioneer-Norvar Energy Dispersive Spectrometer (EDS). All phases were analyzed for Si, Al, Mg, Fe, Ca, Na, S, V, Cr, Ti, using silicate and oxide standards. The data were corrected using ZAF/PROZA correction procedure software. The BSI were taken from the E-SEM with accelerating voltage of 15 kV and 25 kV providing imaging at the resolution of 3.5 nm.

2.2. *Rock and paleomagnetic characterization*

Rock magnetic properties were determined on both standard paleomagnetic samples and plagioclase and pyroxene single crystals.

Curie temperature (Tc) was determined for three samples (two pyroxene samples and one plagioclase sample, 1000 mg each) using a fully computer-controlled Variable Field Translation Balance (VFTB) to obtain thermomagnetic curves between room temperature and 621 °C at the paleo- and rock magnetism laboratory, GFZ Potsdam, Germany. The VFTB combines the principles of classical horizontal Curie balance and an alternating gradient force magnetometer. The pyroxene samples yielded reversible heating and cooling curves whereas magnetization of the plagioclase sample was too weak for further analysis.

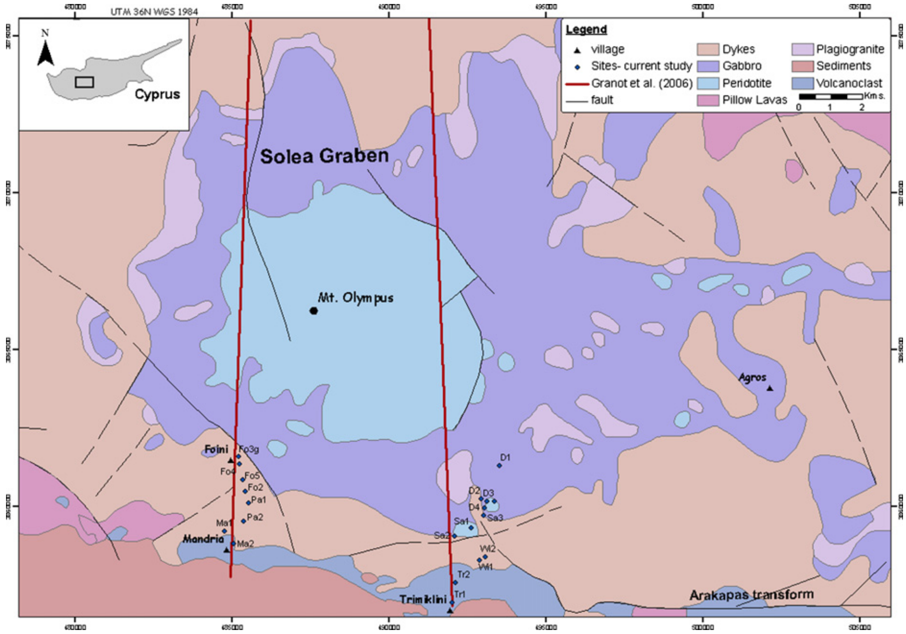

Fig. 1. Troodos geological map (after Cyprus Geological Survey Department 2005). Upper inset is the location map. Solid (red) lines are the Solea spreading axes. Granot et al. (2006). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)