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Magnetite (U–Th)/He dating and its application to the geochronology of intermediate to mafic volcanic rocks

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Abstract

We present a new approach to dating intermediate to mafic volcanic rocks using magnetite (U–Th)/He geochronology. Magnetite is common in volcanic rocks that typically do not contain easily datable minerals such as sanidine or zircon. Analytical procedures for producing magnetite (U–Th)/He ages have been developed, including mineral separation, sample air-abrasion to correct for α-ejection effects, He extraction/measurement, sample dissolution, and anion-exchange column chemistry procedures. Dated magnetite crystals were non-skeletal, euhedral to subhedral, and 100–300 μm in size. To test the reliability of this new geochronometer, four basaltic to andesitic samples lacking sanidine or zircon were dated by both magnetite (U–Th)/He and whole-rock $^{40}Ar/^{39}Ar$ methods. For two samples, the ages from the different geochronometers are in excellent agreement (<1%). A third sample with a poorly behaved $^{40}Ar/^{39}Ar$ age spectrum affected by ^{39}Ar recoil yielded a well-defined magnetite (U–Th)/He age that is consistent with $^{40}Ar/^{39}Ar$ age data from similar nearby volcanic rocks. The final sample, however, exhibited a near 40% discrepancy between the two methods, despite yielding reproducible magnetite (U–Th)/He ages. In all cases, the multi-aliquot magnetite (U–Th)/He ages ($n>7$) exhibit 3–11% (2σ) variation about the mean age, indicating that reproducibility for magnetite (U–Th)/He ages is comparable to that of apatite and zircon (U–Th)/He analyses. In order to assess the He retentivity, we conducted a single magnetite helium diffusion experiment, yielding a well-behaved Arrhenius relationship and a closure temperature of ~250 °C ($dT/dt = 10$ °C/myr). Magnetite's high He retentivity coupled with (U–Th)/He age reproducibility demonstrates good potential for magnetite (U–Th)/He dating as an alternative volcanic geochronometer, particularly in cases where samples yield inconclusive or uninterpretable $^{40}Ar/^{39}Ar$ ages.

Keywords: (U–Th)/He; magnetite; helium; thermocrhonology; geochronology; volcanic

1. Introduction

Mafic to intermediate extrusive rocks are the most common volcanic rock types on the earth's surface, dominating the upper oceanic crust as well as many tectonically active portions of the continental crust. Reliable geochronology of these rocks is critical for resolving a wide range of geologic problems, including paleomagnetic time-scale calibrations, chronostratigraphic constraints on evolutionary and paleoclimatic history, as well as tectonic timing and rate studies. Despite their widespread occurrence and importance in unraveling temporal aspects of earth processes, precise dating of mafic to intermediate volcanic rocks is often hindered by the aphanitic nature of these rocks and the

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absence of commonly dated phases. The most commonly employed technique for constraining the eruption ages of such rocks has been ground-mass or whole-rock K–Ar or $^{40}Ar/^{39}Ar$ geochronology. However, analytical and geological complications, such as ^{39}Ar recoil or excess ^{40}Ar can result in poorly-behaved and difficult to interpret age data when using these techniques. The ability to reliably date aphantic mafic to intermediate volcanic rocks requires geochronologists to resolve these problems and/or develop alternative geochronologic methods.

In this study, we present results from (U–Th)/He dating of magnetite that demonstrate the potential the technique has as an alternative method to dating mafic to intermediate composition volcanic rocks. Magnetite is found in nearly all types of extrusive rocks and is common in intermediate to mafic volcanic rock types that typically do not contain minerals such as sanidine, zircon, and biotite. (U–Th)/He dating of apatite and zircon from quickly cooled volcanic standard samples has been carried out extensively to monitor laboratory procedures (House et al., 2000; Reiners and Farley, 1999; Farley et al., 2002; Min et al., 2006; Aciego et al., 2003; Blackburn et al., 2005; Stockli et al., 2005). Several studies have built on these efforts and have explicitly employed (U–Th)/He geochronometry to time the cooling of xeno- and phenocrystic minerals in volcanic rocks, thus demonstrating that the (U–Th)/He system can provide reliable age constraints on a wide range of minerals and volcanic rocks to constrain eruption ages (Min et al., 2006; Aciego et al., 2003; Blackburn et al., 2005; Stockli et al., 2005; Blondes et al., 2007; Schmitt et al., 2006) . We developed analytical procedures to date magnetite by the (U–Th)/He method, including mineral separation, sample abrasion, ^{4}He extraction/measurement, sample dissolution, and anion-exchange column chemistry protocols. To test the reliability of this geochronometer, four magnetite bearing basaltic to andesitic volcanic rocks from the western Basin and Range Province, United States were dated by magnetite (U–Th)/He geochronometry.

2. Analytical techniques

2.1. Sample characterization and mineral separation

For this study, only euhedral to subhedral magnetite grains or equidimensional magnetite fragments were selected for (U–Th)/He analysis, avoiding composite grains showing complex intergrowth of magnetite with other mineral phases or aphantic groundmass. Samples for this study were selected after careful characterization of magnetite size and texture using standard thin section and backscattered electron (BSE) imaging techniques. Analyzing equigranular magnetite grains as opposed to skeletal or vein-like magnetite growth is an important distinction to be made to avoid complications related to α-implantation or ejection effects (Haggerty, 1991). A photomicrograph of sample 12-7-01C shows three representative euhedral magnetite grains with no skeletal intergrowth (Fig. 1A). Detailed BSE imaging of magnetite crystals from the same sample shows similar euhedral habits, corroborating the lack of complex intergrowth, and reveals a non-spongy internal grain texture with few mineral inclusions and no obvious exsolution textures (Fig. 1B).

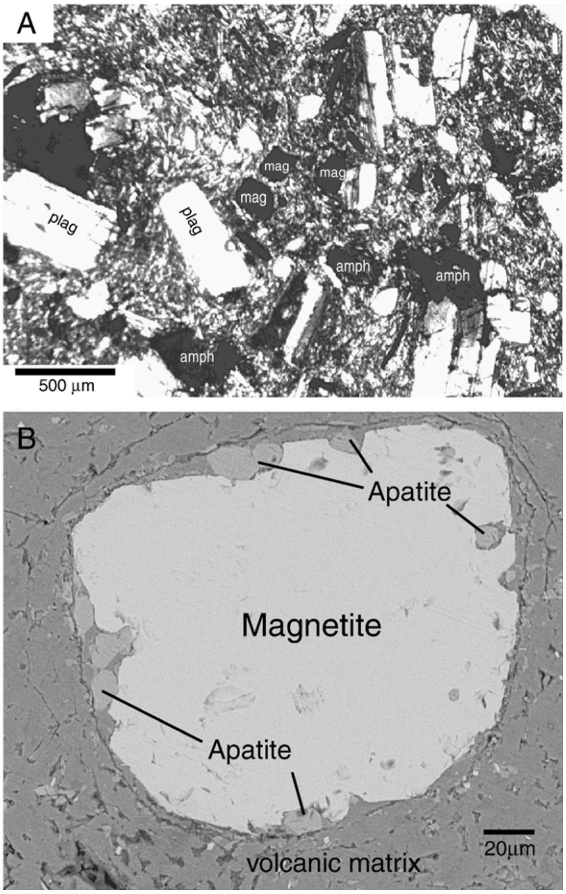

Fig. 1. (A). Photomicrograph of three magnetite grains in a standard thin section from sample 12-7-01C. These large magnetite grains are representative of magnetite grains dated by (U–Th)/He methods. Fig 1 (B) Back Scatter Electron imaging of a magnetite grain from sample 12-7-01C. BSE imaging supports interpretation that grains are non-composite, non-skeletal, and euhedral to anhedral in shape. Small apatite grains concentrate along the edges. Mechanical abrasion of magnetite grains removes the outer 20–30 µm affected by alpha implantation from these apatite grains and surrounding matrix.