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Quantitative textural analysis of ilmenite in Apollo 17 high-titanium mare basalts

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Abstract

Quantitative textural analysis is a powerful tool in the investigation of basalt crystallization. We present the first comprehensive crystal size distribution analysis of Apollo 17 high-titanium lunar basalts, with a focus on ilmenite. Crystal size distributions of ilmenite, pyroxene, plagioclase, olivine and armalcolite were determined for 18 high-Ti mare basalt samples from the Apollo 17 mission. A subset of the ilmenite size distribution (size bins of <0.6 mm in length) reflects growth at post-eruption or post-emplacement cooling rates. Growth of these small ilmenite crystals is controlled by cooling rate and not bulk composition or ilmenite abundance. CSD characteristics tied to cooling rate determined by experiments yield estimates of cooling rate in natural samples. Matrix ilmenite grew at rates up to 250 °C/h, while most samples contained phenocrysts that originated in environments cooling at <3 °C/h. Textural characteristics of ilmenite phenocrysts are used to develop a relative stratigraphy for the samples within a lava flow based upon comparisons with terrestrial analogues.

1. INTRODUCTION

While titanium is sparse in terrestrial basalts (typically containing 2–3 wt.% bulk rock TiO_2 or less), lunar mare basalts may contain up to 14 wt.% TiO_2 (e.g., Neal and Taylor, 1992), and basaltic mare glasses can contain up to 17 wt.% TiO_2 (e.g., Shearer et al., 1990). As a result, Ti-rich minerals (i.e., ilmenite, armalcolite, and Ti-spinel) play a more pronounced role in the crystallization of lunar basalts compared to terrestrial basalts. Ti-rich spinel can be found as inclusions in olivine, particularly in Type C basalts classified by whole-rock chemistry, but is soon replaced by armalcolite and ilmenite (Papike et al., 1976). In particular, lunar basalts with >6 wt.% TiO_2 ("high-Ti") typically contain more than 10 modal percent ilmenite (*cf.* Papike et al., 1976). Basaltic samples indirectly allow the nature of the lunar interior to be evaluated and crystallization processes are reflected in the morphology and size distribution of major phases. Thin sections of mare basalts are slices of truth, windows into the complex processes visited upon these igneous rocks. Petrographic observations are bolstered by the non-destructive creation of crystal size distributions (CSDs). The robustness of this crystal stratigraphy method has been demonstrated in terrestrial and lunar basalts alike (e.g., Cashman and Marsh, 1988; Day and Taylor, 2007; Hui et al., 2011; O'Sullivan, 2012; Fagan et al., 2013). These previous studies focused on low-Ti basalts where, for example, Hui et al. (2011) showed Apollo 14 chemical groups – interpreted as separate lava flows – had unique plagioclase CSDs reflecting distinct textures and petrogeneses. In the low-Ti mare basalts, ilmenite is a minor phase and was not the focus of study.

The Apollo 11 and Apollo 17 missions returned samples of high-Ti mare basalts and, recently, high-Ti basalts have been described in regolith samples and as breccia clasts from Apollo 16 (Zeigler et al., 2006; Fagan and Neal, 2012, 2014). Apollo 17 basalts make up a larger sample

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set and are the more texturally diverse suite, and have been classified both on the basis of chemistry and texture. The five known whole-rock chemical groups (Types A, B1, B2, C, and D; Rhodes et al., 1976; Neal et al., 1990) experienced a similar history of shallow-level fractionation and crystallization following separation from unique sources. There is also a textural continuum ranging from vitrophyric to micro-gabbroic that is independent of whole-rock chemistry. Type D is an exception, as it is defined by one 22-gram sample (79001,2187; Ryder, 1990). Multiple but similar threefold textural classification schemes have been proposed for Apollo 17 high-Ti basalts (Papike et al., 1974; Brown et al., 1975; Warner et al., 1975b; see comparison by Dymek et al., 1975). In this study, the textural naming conventions of Brown et al. (1975) are used, which are: **Type 1A** quenched olivine-porphyritic ilmenite basalt (Fig. 1a); **Type 1B** slower-cooled, olivine-poor (<5 vol.%), plagioclase-poikilitic ilmenite basalt (Fig. 1b); and the relatively rare **Type II** olivine-free, low-Mg ilmenite basalt similar to Apollo 11 low-K type basalt – Brown et al. (1975) describe only two samples with this texture (75035 and 75055). The comparison to Apollo 11 basalts is based solely on major element chemistry of bulk sample analysis. There is a textural continuum between textural Types 1A and 1B, and all three petrographic types are present in each chemical group. The Apollo 17 sample set here includes eight textural Type 1A basalts (fine-grained olivine-porphyritic) and ten textural Type 1B basalts (coarse-grained plagioclase-poikilitic). The sample petrography of textural Type 1A and 1B basalts is summarized below.

The eighteen Apollo 17 high-Ti basalts studied here were collected from various stations over the Apollo 17 landing site (Fig. 2). The numbering convention used has the first digit "7" representing the Apollo *Seven*teen mission and the second number corresponding to the particular station where the sample was acquired. If the second digit is "0" it was collected around the Lunar Module, denoted by the solid white circle in Fig. 2. If the second digit is "1" it was collected at Station 1. If the second digit is >1, the sample was collected at that station or between it and the previous one. Over 120 samples of high-Ti basalt have been described from the Apollo 17 site (Ryder, 1992; Neal and Taylor, 1993b,c; Meyer, 1994). To date 48 Type A, 14 Type B1, 39 Type B2, 7 Type C, and 1 Type D basalts have been defined on the basis of whole-rock chemistry from samples returned by the Apollo 17 mission (e.g., Neal et al., 1990; Donohue, 2013). There are still several coarse grained samples that were originally classified as "Type U" (Rhodes et al., 1976) because a representative whole-rock analysis was not possible.

In high-Ti basalts, ilmenite is an early and prolonged crystallizing phase (e.g., Brown et al., 1975; Dymek et al., 1975; Papike et al., 1976). Thus, the size and distribution of ilmenite should prove valuable in defining crystallization histories. Early studies of high-Ti analogues calibrated

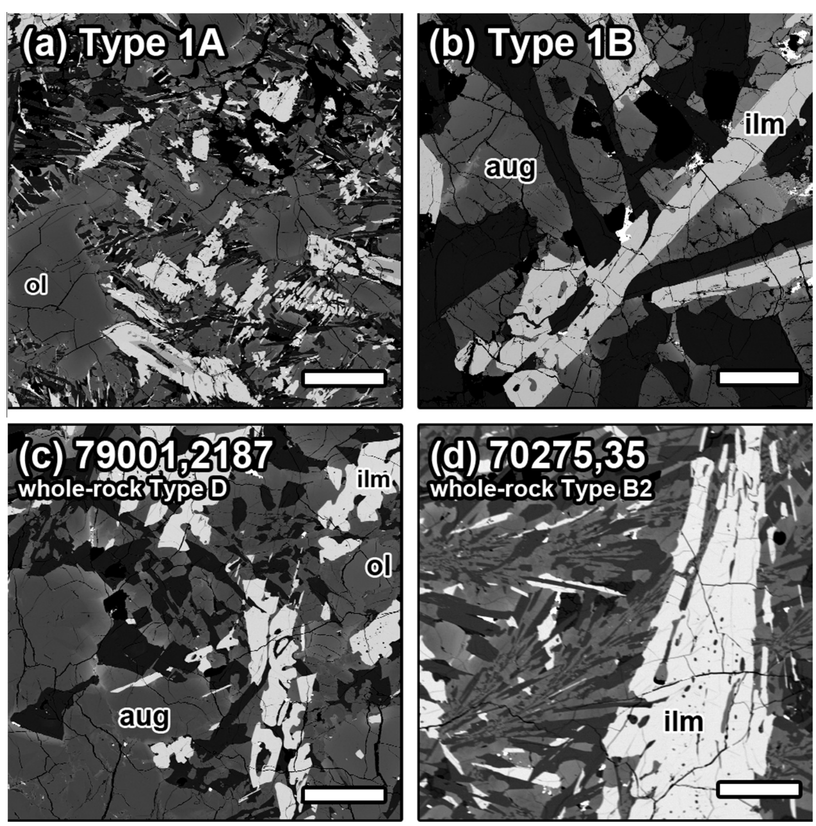

Fig. 1. Representative textures in backscattered electron (BSE) photomicrographs. (a) BSE image of olivine microporphyritic textural Type 1A basalt 79516,9. (b) BSE image of plagioclase poikilitic textural Type 1B basalt 75015,52. (c) BSE image of whole-rock Type D basalt 79001,2187 which has a texture intermediate between textural Types 1A and Type 1B. (d) BSE image of portion of 70275,35 highlighting the variation in ilmenite size in the fine-grained region. Scale bar is 0.2 mm in all images.