Compacted cumulates revealed by electron backscatter diffraction analysis of plutonic lithics

E.M. Bertolett1, D.J. Prior2, D.M. Gravley1, S.J. Hampton1, and B.M. Kennedy1

1Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
2Department of Geology, University of Otago, PO Box 56, Dunedin 9054, New Zealand

ABSTRACT

Cumulates, exposed as plutonic lithics in a volcanic host, provide insight into the storage conditions, evolution, and eruptivity of an otherwise invisible magmatic system. Here, we present electron backscatter diffraction analysis of plagioclase-rich cumulates erupted from the Akaroa Volcanic Complex in New Zealand. Plagioclase {010} is clustered normal to foliation with girdle distributions of (100) and (001). This crystallographic preferred orientation does not definitively distinguish magmatic compaction from flow. However, the rotation axes of distortion for plagioclase observed in this study lie in the foliation plane, indicating that compaction drove both crystal organization and further deformation in the solid state. As such, we propose that these lithics represent cumulates formed first from uniaxial compression involving alignment of shaped grains by rigid rotation in magma, followed by grain distortion by dislocation creep and accompanying grain boundary migration associated with melt expulsion. Petrographic evidence of decreasing glass abundance with increasing fabric strength further confirms melt extraction. Our quantitative microstructural analysis on the preferred orientation and deformation of plagioclase grains in erupted gabbroic lithics is an important complement to more traditional geochemical approaches and improves our understanding of how crystal mush evolution is physically linked to melt extraction and, possibly, volcanic eruption.

INTRODUCTION

Plutonic lithics are sampled from magma bodies by volcanoes and, hence, form the important and elusive connection between magmatic and volcanic systems. Geochemical studies have dominated research in this field, beginning with Bowen (1928). Instead, we use microstructural analysis as a powerful, quantitative tool that directly relates physical crystal relationships within volcanic deposits to magmatic processes. This study is the first to link microstructural deformation within the magmatic system to erupted deposits via plutonic lithics, which provides a more complete picture of the evolution of magma from the plutonic to the volcanic realm.

Plutonic lithics (xenoliths, cumulates, enclaves) may represent the bulk liquid or the crystal residue of magmatic bodies that reached solid- or near-solid-state conditions. Crystal phases in plutonic lithics accumulate by crystallization, crystal settling, magmatic flow, and/or compaction (Sewell et al., 1993; Burt et al., 1998; Bacon et al., 2007; Graeter et al., 2015). In concert with these processes of crystal accumulation, interstitial melt can be extracted and stored separately (cf. mush model; Bachmann and Bergantz, 2008), and ultimately erupt.

In this study, gabbroic plutonic lithics were sampled from Goat Rock Dome, a trachyandesitic lava dome on the flank of the extinct Akaroa Volcanic Complex, South Island, New Zealand (Fig. 1A). Lithics were discovered following a rockfall event during the Canterbury Earthquake Sequence (September 2010). The lithics exhibit a strong foliation defined by framework-forming plagioclase (40%; Fig. 1B) and, to a lesser extent, pyroxene (13%) and olivine (14%). We use a combination of crystallographic preferred orientations (CPOs) and microstructures to determine the magmatic processes responsible for plagioclase accumulation and alignment.

ELECTRON BACKSCATTER DIFFRACTION ANALYSIS

The microstructures of lithics with the most conspicuous plagioclase alignment (e.g., Fig. 1B) were quantified using electron backscatter diffraction (EBSD). EBSD enables mapping of crystallographic orientations (Prior et al., 1999), which in the last decade has been applied more frequently to igneous rocks and has illuminated processes that include magmatic flow, cumulate and glomerocryst formation (i.e., synneusis versus crystal growth), and melt extraction (Žák et al., 2008; Beane and Wiebe, 2012; Satsukawa et al., 2013; Ji et al., 2014; Graeter et al., 2015; Fiedrich et al., 2017; Cheadle and Gee, 2017; Holness et al., 2017). The application of EBSD to plagioclase in plutonic lithics is limited but critical in determining how magmas separate and erupt—a problem that geochemistry alone is unable to solve without this textural context.

Goat Rock plutonic lithics contain elongate plagioclase crystals up to 10 mm long that define a planar foliation (all data that follow refer to plagioclase). EBSD maps were collected from entire polished thin sections of five samples (see the GSA Data Repository1) using a step size of 50 µm, with one sample (GR8b) remapped at a higher resolution (5 µm step). All CPOs are characterized by point maxima of the {010} perpendicular to foliation and great circle girdle distributions of {100} (Fig. 2A). Generally, poles to {001} are also distributed about a great circle. The following data in this paper refer to the representative sample GR8b.

Misorientations are differences in the crystal orientation of different points in a crystal lattice (Fig. DR2 in the Data Repository). Intragran misorientation transects reveal that individual plagioclase grains are continuously distorted by as much as 10°, corresponding to bent twin boundaries and undulatory or patchy extinction (Fig. 1C). Boundaries between plagioclase grains are irregular and in some cases lobate (Fig. 1C). Plagioclase crystals impinged on by other grains are common and are visibly bent (Fig. 1C).

The conventional approach of plotting misorientations of neighboring pixels gives large errors on rotation axis orientations, as
Figure 1. A: Map of Banks Peninsula in New Zealand (inset) showing the two main volcanic complexes: Lyttelton Volcanic Complex outlined by gray dashed circle, and Akaroa Volcanic Complex (AVC) designated by gray shading. Red square shows Goat Rock (43°43′13.48″S 173°3′58.48″E). B: Full thin-section image of sample GR8b with framework-forming plagioclase and interstitial clinopyroxene, olivine, and Fe-Ti oxides. C: Photomicrograph image with draped plagioclase grains and twins bent around impinging olivine outlined in black, lobate grain boundaries (white arrows), tapering twins (red line), and undulatory extinction (orange arrows).

ALIGNMENT AND DEFORMATION DURING UNIAXIAL COMPRESSION

Crystal Organization in Magmatic Fabrics

EBSD studies on magmatic fabrics have focused on minerals such as quartz, olivine, and biotite (Romeo et al., 2007; Žák et al., 2008; Beane and Wiebe, 2012; Graeter et al., 2015), whereas studies on magmatic plagioclase CPOs are rare (Satsukawa et al., 2013; Ji et al., 2014; Holness et al., 2017; Fiedrich et al., 2017). Observations of orthogonal cuts of Goat Rock lithics in hand sample are consistent with elongate plagioclase shapes in three dimensions (i.e., a > b > c). Plagioclases are mostly elongate normal to {010} (see the Data Repository) and have average axial ratios, measured in the thin section plane, of 2.7. This is likely an underestimate of the ratio of the long and intermediate axes in the plane perpendicular to {010}. Lithics have very distinct plagioclase CPOs (Fig. 2A) that are characteristic of elongate crystals that have been mechanically rearranged to form a foliation via uniaxial shortening (Fig. 3A; Axial-B of Satsukawa et al. [2013] and Type A of Ji et al. [2014]). Weak lineation fabrics may also have this CPO; however, elongate crystals in a flowing medium are generally characterized by clusters in all three directions ([100], [010], and [001]) orthogonal to each other (Fig. 3B). Goat Rock CPOs are best explained by elongate crystals that were free to arrange themselves within a foliation plane with no constraint on a preferred direction (Fig. 3A). Rotation axis orientations provide a means of definitively distinguishing CPOs that may be attributed to compaction or weak magmatic flow.

Magmatic Compaction versus Flow in the Solid State

An important distinction can be made between the organization of crystals under liquid-rich conditions and the intra-crystalline deformation that occurs with continuing stress after rheological lockup (Arzi, 1978; Paterson et al., 1989; Philpotts et al., 1999). The former is within the presence of melt, and any further crystal growth will reflect this stress (i.e., chemical zoning will by asymmetric; Holness et al., 2017), while the latter refers to the kinematics of crystallographic deformation in the solid or near-solid state.
The CPOs studied here have a cylindrical symmetry consistent with uniaxial compaction. Furthermore, microstructural indicators such as bent crystals and lobate grain boundaries indicate compaction accommodated by grain boundary migration in the dislocation creep regime (Fig. 1C; Rybacki and Dresen, 2000). As soon as a rigid framework of crystals is formed (<~33% crystals; Philpotts et al., 1996), grains interact (i.e., bend and rotate) during continued uniaxial compaction and remaining melt expulsion (Fig. 3). The spread of rotation axes related to plagioclase distortion in the foliation plane (Fig. 2C) is consistent with uniaxial stress and continued compaction in the solid state (Fig. 3A).

Under compaction, crystals are free to deform internally without the constraint of a secondary direction (other than the direction of uniaxial compression). Rotation axes of all twins will be related by a shared great circle (Fig. 2C), reflecting the plane in which compacting crystals can bend and rotate as they are compressed (Fig. 3A). In a system initially organized by magmatic flow, rotation axes will be aligned within the foliation plane; i.e., all points from each twin in a sample will plot in the same place (Fig. 3B). Sample GR8b rotation axes of all twins and crystals analyzed do not share the same orientation; instead they are dispersed across orientations connected by a great circle (i.e., a plane; Fig. 2C). This indicates that a uniaxial compressional stress controlled both the organization and deformation of plagioclase crystals, with no indication of magmatic flow or simple shear.

Compaction as an Adcumulate Forming Process

Extensive solid-state deformation (petrographic features; Fig. 1C) in a compacting regime suggests that Goat Rock plutonic lithic fabrics reflect adcumulate formation. Strong CPOs and the persistence of rotation axes indicative of uniaxial compression make it clear that Goat Rock plutonic lithics were subject to a compacting stress throughout both their organization and subsolidus deformation (i.e., cumulate formation during melt extraction; Hunter, 1996; Schmidt et al., 2012). While cumulate textures, due to their strength, may completely overprint initial crystal organization (Holness et al., 2017), we observe evidence of cumulative-forming processes creating both the initial CPO and further reduction in porosity necessary for cumulate formation (Fig. 3A). Petrographic observations of the cumulate lithic (sample GR8b) reveal no preserved inter-grain glass (i.e., interstitial melt; Fig. 4C). In contrast, a plutonic lithic with a similar but weaker CPO (sample GR14; Fig. 4A) and more silicic composition, hypothesized to have resided further “upwards”...
in the magmatic system, has 7% glass (Fig. 4B). We propose that compressional stresses acted on the system as crystals came together from settling through to deformation of the crystal pile during cumulate formation and a decreasing melt component (Table DR3 in the Data Repository; Bachmann et al., 2007, and references therein; Fiedrich et al., 2017).

The extraction and potential pooling of melt during porosity reduction (Bachmann et al., 2007; Bachmann and Bergantz, 2008; Cashman and Giordano, 2014; Cooper and Kent, 2014) are important stages in the development of magma that can ultimately erupt. The identification of features indicative of magmatic compaction and cumulate formation associated with decreasing residual melt provides compelling physical evidence for the segregation of the solid and liquid components of the magmatic system. In contrast to studies focusing on the plutonic realm of igneous complexes (Ji et al., 2014; Chedale and Gee, 2017; Holness et al., 2017; Fiedrich et al., 2017; Vukanovic et al., 2018), this study presents microstructural data on erupted plutonic lithics, providing insight into how magmas differentiate and melt segregates (in cumulate-forming processes) in a system that had a known and active volcanic counterpart.

CONCLUSIONS
Plagioclase CPOs and rotation axis distortion occur in the horizontal plane and define a foliation. These patterns are characteristic of uniaxial compaction of elongate plagioclase, both in the arrangement and near-solid-state deformation of grains. Rotation axis analysis reveals that uniaxial compression continued with decreasing porosity and associated melt expulsion, as seen in decreasing glass abundance in grain boundaries as grains came into contact and deformed. Microstructural analysis of the crystal residue left behind during melt extraction, as preserved in plutonic lithics, can elucidate physical processes occurring in the overlapping space between plutonic and volcanic systems.

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