Origin and evolution of Panama Rock dike and dome, Banks Peninsula, New Zealand

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ABSTRACT
Structural and geochemical studies of lava domes can provide insight into their origin and stages of their formation. Understanding dome-forming eruptions are critical, as the highly explosive eruptions from rhyolite domes have claimed many lives. In this study, an eroded dome on Banks Peninsula, New Zealand, was characterized through various geochemical and structural methods. The dome in question was found to have been formed endogenously in the crater of a scoria cone, fed by a radial dike from the larger Akaroa volcanic complex. The curious concentric jointing exhibited in certain areas of the dome can be loosely correlated to a higher obliquity of flow in this region; however, further studies are needed to better understand this relationship.

INTRODUCTION
The study of lava domes has become increasingly significant as population increases near dome-forming volcanoes, because the sudden collapse of lava domes has left many people vulnerable to pyroclastic flows and other volcanic hazards. Dangerous lava domes generally form in more silicic environments than the one studied in this paper, but an understanding of these systems is crucial in order to preserve human lives.

Historically, active domes have been studied in various locations around the world. There are four different types of lava domes, whose classifications are based on observations made during their formation as well as analog laboratory experiments:

- spiny/Pelean (i.e. Mt. Pelée, Santiaguito), lobate (i.e. Mt. St. Helens, Katmai, Pinatubo, Redoubt), platy (i.e. Mt. Merapi, Soufrière), and axisymmetric (i.e. Medicine Lake, Newberry). These distinctions are generally made based on morphology, surface texture, and eruptive mechanisms, including eruption rate, cooling rate, and yield strength of the lava (Fink and Anderson 2000, Fink 1998).

In this study, whole-rock geochemistry via XRF and macro- and micro-scale structures were analyzed to reconstruct the formation of the Panama Rock dome and dike on Banks Peninsula, New Zealand (Figure 1). Panama Rock provides an excellent
example for study as it has been partially eroded, allowing for the interior structures of
the dome to be easily accessed. The goal of this study is to fully characterize Panama
Rock geochemically and structurally, and to determine the relationship between the dome
and the dike. Field relationships, jointing patterns, and micro-scale flow and shear
structures provide insight into the origin of the dome, the type of dome, and the
mechanics of dome growth.

GEOLOGIC SETTING

Banks Peninsula is located to the southeast of Christchurch on the South Island of
New Zealand (Figure 1). It is made up of two Miocene-aged volcanoes, Lyttelton and
Akaroa. Although they are intraplate volcanoes in nature, they cannot be attributed to
either an extensional tectonic regime or a mantle plume. Their formation has been
attributed to delamination of the lower crust (Timm et. al. 2009); melts related to
subduction underneath Gondwana before its breakup “re-fertilized” the bottom of the
lithosphere with high-density mantle material. This created a large density differential
between the lower lithosphere and the asthenosphere on which it sat. The negative
buoyancy of the lower lithosphere caused it to detach from the crustal material above,
allowing hot asthenosphere to rise and partially melt due to decompression. This melt
interacted with surrounding rocks, creating the complicated chemistry that is expressed
today.

Based on this theory, Banks Peninsula is believed to represent two delamination
events; the first created the Lyttelton volcano, active from 11.0 to 9.7 million years ago,
while the second, larger event created the Akaroa volcano, active from 9.3 to 8.0 million
years ago (Hampton 2009). Both of these volcanoes had two main phases of activity—a
large building phase followed by an interval of late-stage volcanism (Price and Taylor
1980). Three main types of features can be seen on both volcanoes: constructional
features, including lava flows, scoria cones, and domes; hypabyssal features such as dikes
and sills; and erosional features, which form valley orientations and ridge patterns
(Hampton 2009).

Although they are similar in structure, the compositions of Lyttelton Volcano and
Akaroa Volcano vary greatly. Each volcano exhibits its own suite of basalt-trachyte lavas
and dikes, which grew progressively more alkaline over time (Price and Taylor 2009).
Akaroa has overall lower SiO$_2$ concentrations and trace element and isotope chemistry suggest the source was a carbonated eclogite in a peridotite matrix. Lyttelton volcano, however, has rocks of higher SiO$_2$ content, and geochemistry suggestive of mixing between asthenospheric (Akaroa-type) melts with lithospheric pyroxenite melts (Timm et al 2009).

One feature on Akaroa volcano, Panama Rock, located 3 km west of Le Bons Bay, is a dome approximately 250 m long by 150 m wide that is intersected by a 4 m-thick dike. The dome is separated into two parts; an inner dome and an outer amphitheater. The dike terminates inside the amphitheater, but is not exposed between the amphitheater and the inner dome (Figure 2). The eroded center allows for an excellent view of the jointing pattern around the amphitheater, which seems to trend with the overall shape of the dome. The rock it is made of is an apheric trachyte mostly composed of dark grey groundmass with few (<10%) feldspar phenocrysts.

METHODS

Strike and dip measurements were taken along various jointing planes around all accessible parts of the dome (Figure 2). Four samples were taken; one from the inner core of the dome, one from the outer amphitheater, one from the slope alongside the dome, and one from the dike (Figure 2). The three dome samples were oriented. The whole-rock geochemistry of each sample was analyzed via X-Ray Fluorescence, using the Philips PW2400 Sequential Wavelength Dispersive X-ray Fluorescence Spectrometer at the University of Canterbury. Samples were prepared and analyzed via the fused disk method outlined in Hartung 2011. Oriented thin sections were prepared from samples 1-3, and an unoriented thin section taken from sample 4.

RESULTS

Geochemistry and Texture

The three samples collected from the dome and the sample from the dike all fall into the trachyte range, based on their total alkali to total silica ratio (Figure 3). All samples lack defined texture at the hand-sample scale; they are >97% dark grey apheric groundmass, with the occasional feldspar phenocryst. The phenocrysts show no preferred alignment. The trachytic texture observed in the groundmass of the samples at the thin section-scale is defined by the alignment of the feldspar crystals, which make up
90% of the groundmass. The rest of the groundmass is made up of a few augite and olivine crystals, and fractures coated with oxidized iron. The thin sections were taken in the vertical plane, oriented north-south. The general trend of the crystal alignments were measured as degrees from horizontal, and are plotted on Figure 4. No textural domains were observed in individual thin sections, and no thin sections in the horizontal plane were taken. Phenocrysts were present in all samples most of which have multiple fractures at 90-degree angles to the edges of the crystals (typical feldspar cleavage). No vesicles were observed.

Structure

The macro-scale structures observed at Panama Rock are defined by jointing patterns, and three domains can be defined: platy jointing, columnar jointing, and irregular jointing. The platy jointing is present around the outer amphitheater and down the eastern side of the dome. Columnar jointing is observed on the western edge of the dome and in the dike. The inner dome is irregularly jointed.

DISCUSSION

Lava and Dome Type

The geochemical and textural data are typical of Akaroa volcano’s late activity trachytes. The magma feeding these eruptions is the most mature seen on Banks Peninsula, implying a long fractionation process and/or increased interaction with host material. The large amount of brittley deformed feldspar crystals that have been aligned implies that most, if not all, of the crystals were already formed upon eruption, and were aligned by internal flow of the lava. During cooling, the deformation changes for more ductile processes (flow) to brittle processes, causing the crystals to fracture. The high crystallinity of the lava upon eruption causes it to be much more viscous than its chemistry implies.

In order to typify the dome that Panama Rock was originally, results were compared to Fink and Griffiths’ classifications. Previous work on this subject includes a study in Central Italy (Cimarelli and Rita 2006). The evidence for an endogenous dome, or cryptodome, includes the obvious deformation and uplift of the sedimentary cover above, while an exogenous dome was formed via the superimposition of lava flows, dipping away from the source. In the Italian case the contact zones between the dome and
the sedimentary cover were well exposed; however, the local geology of Panama Rock precludes these observations from being made.

Usually it would be unexpected for lava of Panama Rock’s composition to form a dome, as dome-forming lavas are felsic and highly viscous in nature. However, it is possible that the high crystallinity caused the lava to be viscous enough to behave like a rhyolite lava. It is unlikely that the dome was spiny, platy, or lobate, as it lacks radial features; these domes all have a central core, from which between a few and a dozen lobes/spines are emplaced laterally. Panama Rock, on the other hand, has a distinctly concentric morphology, with a relatively regular elliptical shape. Panama Rock’s tall profile makes it also unlikely that it was an axisymmetric dome. Because it does not fit in any of these classifications, this study concludes that the dome was either a cryptodome, or its morphology was constrained by some other means not accounted for in Fink and Griffith’s study.

**Inner Dome, Outer Dome, and Dike Relationship**

Previous studies have suggested that the formation of domes on Akaroa volcano is due to the intersection of radial dikes with the dip-slope of the flank of the volcano (Weaver and Sewell 1986). This seems likely, as the dike trends approximately 240°, towards the center of Akaroa volcano, and is exposed at the current surface, underneath Panama Rock, where it terminates. It had been previously thought that Panama Rock was formed by the extrusion of two overlapping domes fed by the dike (Hobden 1990). However, observations made during this study suggest otherwise. The separation between the outer amphitheater and the inner dome seem to be related to the jointing patterns—the outer amphitheater is either platy jointing or columnar, while the central core is irregular. It seems more likely that this was one continuous dome, with the central portion representing the top of the conduit that fed the dome. The difference between the columnar jointing and platy jointing probably has to do with the proximity to the cooling margin, whether that is the country rock or a previously cooled part of the dome. This implies multiple endogenous filling phases.

Based on these interpretations, a new model for the formation of Panama Rock is presented. The presence of scoria deposits to the west and northeast of Panama Rock suggest that perhaps a scoria cone provided the constraints on the shape of the dome.
If, in the late stage of the scoria cone’s life, its eruption style became more effusive, it is probable that a lava dome could form in the crater. The walls of the crater would provide a buttress against which the steep sides of the dome could form, and cause a possibly lobate dome to appear more elliptical (Figure 5).

**Dome Formation Mechanics**

Flow indicators in lavas can be preserved in shallow intrusions and analyzed structurally, similar to studies performed on metamorphic rocks. It is assumed that the crystals rotate into an alignment that decreases resistance to flow, and thus the alignment can be used as a proxy for flow. However, the high crystal concentration could also impede rotation, causing inconsistent results (Smith 2002).

Flow was observed in three dome samples. The sample that showed the most obliquity was collected from the portion of the dome with the most pronounced platy jointing. This is consistent with Shelley (1985)—extreme obliquity of flow results in shear planes nearly parallel to dike walls. Assuming this can be applied to the dome situation, the areas with a flow direction more oblique to the roof of the dome contained pronounced shear planes parallel to the roof, resulting in the platy, “onion-skin” jointing.

**FUTURE RESEARCH**

Possibilities for further research would mainly focus on a more detailed micro-structural study of Panama Rock and its associated dike. Shelley (1985) provides detailed instructions on determining flow directions in the dikes of Lyttleton volcano, and it would be interesting to see if these methods could be applied to both the dike and dome. This requires thin sections cut parallel to the wall of the dike or dome, which were unavailable for this study. If more samples were available, as well, it is possible that domains of crystal alignment and concentration could be identified, which have further implications for flow and shear in the dome (Smith 2002). With continued research, the model for shear and strain in a growing dome presented by Buisson and Merle (2002) could be tested.

**ACKNOWLEDGMENTS**
Many thanks to Darren Gravely, Samuel Hampton, Paul Ashwell, Shane Cronin, Joshua Johnson, Daniel Hobbs, and Gabe Lewis (field assistant) for their contributions to this project.

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Figure 1. Map of Banks Peninsula, Panama Rock located at red dot.
Figure 2. A) Map of Panama Rock. Yellow dashed line indicates dike, green circles indicate outer amphitheatre and inner dome. B) Inset shows strikes and dips of joint planes. Stars indicate sites where samples were taken.
Figure 3. Green triangles are 4 samples from Panama Rock Dike and Dome.
Figure 4. Orange lines show direction of flow observed in thin section. Flow in sample 1 dips 37 degrees S, while flow in samples 2 and 3 dip 2 degrees to the N.
Figure 5. A) Large-scale model of dome (orange) formation; the dome fills in the crater of a scoria cone, fed by a dike on the flanks of Akaroa Volcano. B) Model of intra-dome lava flow (black arrows), which explains the orientation of joint planes (blue lines) in Figure 2.