Late-Stage Trachyte Volcanism on Banks Peninsula: Physical and Petrologic Constraints

John A. Albright[1,2]
1. Geology Department, Pomona College, Claremont, California 91711, USA
2. Department of Geological Sciences, University of Canterbury, Christchurch 8041, New Zealand

ABSTRACT

Previous studies of the Akaroa Volcanic Complex on Banks Peninsula, New Zealand, have revealed a series of late-stage, dike-fed trachyte domes on the flanks of the volcano that are constrained to a fairly narrow range of elevations. While numerical models may be able to simulate the physical conditions necessary to create such a constraint, such models would need to match basic parameters from the volcano itself, namely the pressure within the original magma chamber and the flow directions in the resulting dikes. By analyzing thin sections from the domes and one exposed feeder dike, this study seeks to assess the feasibility of collecting these parameters for future research. While results concerning the flow directions and shapes of the dikes were inconclusive without additional sampling, previous studies suggest that lateral flow in a blade-shaped dike is the most likely scenario. Moreover, while the trachytic mineralogy of the domes lack the specific assemblages needed for traditional geobarometry, the presence of volcanic glass could potentially allow for pressure calculation using MELTS modelling software. Ultimately, a numerical model of the Akaroa system is still feasible as the subject of future research despite the difficulties posed by the trachyte mineralogy.

INTRODUCTION

As civilization continues to expand into volcanically-active regions, an increasing amount of property, infrastructure, and human life will be threatened by volcanic hazards. Such threats, however, do not necessarily originate at the summit or center of a given volcano, since magmatic intrusions such as dikes and sills can feed large and potentially dangerous eruptions up to several kilometers away from their host system's main vent (Poland et al. 2008). These intrusions in turn reflect the structure, eruptive behavior, and stress state of the surrounding volcano (Porreca et al. 2006). A more complete understanding of how different underlying physical conditions affect the formation and propagation of late-stage magmatic intrusions could therefore allow for better assessment and management of the associated volcanic hazards.

Complementing field-based studies, numerical models of volcanic systems can provide additional insights into subsurface stresses and their effects on local magma plumbing systems (Grosfils 2007). For instance, Hurwitz et al. (2009) used numerical modelling software to calculate the stress state below Summer Coon, an eroded stratovolcano in southern Colorado, during the emplacement of a set of surrounding radial dikes. Assuming dikes that open against the least compressive stress, this model was able to constrain where and how the dikes could propagate. By basing their model on parameters (e.g. edifice shape, magma pressure) gathered from the volcano itself by Poland et al. (2008) and others, Hurwitz et al. were able to match both the dikes' positions along the base of the edifice and their path through the subsurface.

The goal of this study is to determine the viability of a similar numerical model for a set of trachytic dikes in the Akaroa volcanic complex, an eroded intraplate shield volcano that forms the eastern end of Banks Peninsula, New Zealand (Timm et al. 2009). These dikes feed a set of six lava domes distributed across the volcano (Figure 1, Table 1) whose evolved trachytic compositions suggest relatively late-stage formation (Dorsey 1988). With the exception of one dike connected to the Panama Rock dome, however, these dikes are not exposed at the surface but are instead inferred from the positioning of their domes to have extended radially from the complex center (Dorsey 1988) before erupting either at (Curtin 2012) or near (Dorsey 1988) the volcano surface.

Unlike Summer Coon, where the dikes were vertically constrained to the base of the edifice (Poland 2008), the Akaroa domes all lie at elevations between 400 and 700 m above sea level, well above the volcano's base (Gaddis 2014). While Dorsey (1988) attributes these shared elevations to formation during the same phase of volcanism, more recent studies (Hobbs 2012, Gaddis 2014) suggest an alternative model with several eruptive centers, each independently evolving to trachyte over its lifespan. Under this new model, then, the similar elevations should be a result of persistent, underlying physical conditions.

Like the model from Hurwitz et al. (2009), a numerical model for the Akaroa dikes would need to be constrained by measurements and parameters from the volcano itself in order to be relevant and applicable in further study of the region. Using the Summer Coon model as a template, this preliminary study of Akaroa would need to consider: the location, orientation, size, and distribution of the dikes; the magma crystallization pressure and temperature; the magma flow direction; and the shape of the overlying edifice. While spatial data concerning the dikes have already been compiled by Gaddis (2014), the shape of the edifice remains uncertain, with early single-vent models (Shelley 1988) being challenged by more recent models with multiple eruptive centers (Hobbs 2012). Leaving edifice shape as an independent variable, then, the dikes' pressures and flow directions become the most important factors left to constrain.

GEOLOGIC SETTING

Banks Peninsula lies southeast of Christchurch on the east coast of New Zealand's South Island and is predominantly comprised of two eroded Miocene shield volcanoes, Lyttelton and Akaroa. The older Lyttelton Group volcanics (10.6-12.4 Ma) form the northwestern section of the peninsula, bordering Christchurch, while the younger Akaroa Group (8.8-9.4 Ma) dominate to the southeast (Timm et al. 2009). The rest of the peninsula was formed in a series of smaller eruptions, both during the transition of active volcanism from Lyttelton to Akaroa (i.e. the 8.3-9.1 Ma Mount Herbert Volcanic Group) and afterwards (e.g. the 6.8-8.4 Ma Diamond Harbour Volcanic Group and the 7.3-8.1 Ma Church Volcanics) (Timm et al. 2009, Dorsey 1988). This entire sequence of volcanic rocks overlies a basement of Triassic Torlesse greywacke, Cretaceous McQueens Volcanics, and Paleocene Charteris Bay Sandstone (Dorsey 1988) (Figure 2).

Both complexes formed as a result of intraplate volcanism, most likely due to two separate lithospheric delamination events since they lack evidence for either extensional tectonics or a mantle plume (Timm et al. 2009). Each volcano underwent at least two phases of volcanism, with the main edifice-building basalts, mugearites, and hawaiites, being cut and overlain by later-stage dikes and vents, which can reach trachytic compositions (Price and Taylor 1980). As previously mentioned, while early models for the formation of these volcanoes assumed single, central vents (e.g. Shelley 1988), more recent geomorphological and geochemical studies have shown evidence of multiple vents on both Lyttelton (Hampton 2010) and Akaroa (Hobbs 2012, Gaddis 2014). Despite these physical similarities, however, the Akaroa complex overall shows more alkalic compositions (Price and Taylor 1980) with lower concentrations of SiO_2 (Timm et al. 2009) than the Lyttelton complex.

Dikes in the Akaroa complex range in composition from basalt to trachyte, with ~85% or more having benmoreitic or trachytic compositions. They range between 0.1 m to 20 m in thickness, with thicker dikes showing more consistent orientations along their lengths and more abrupt terminations (Dorsey 1988). In general, these dikes display a radial pattern focused on a broad zone near the center of the volcano (Dorsey 1988), though more recent work by Gaddis (2014) has shown that the dikes in different sectors of the peninsula focus on slightly different zones within this central region. While none of the dikes have been observed to feed lava flows, one dike exposed at Panama Rock, a feature located 3 km west of Le Bons Bay (Curtin 2012), is directly connected to and presumably fed a nearby trachyte lava dome (Dorsey 1988).

The Panama Rock dome is one of six trachytic domes found on the flanks of the Akaroa volcano, the other five being located at View Hill, Pulpit Rock, Ellangowan, and Devils Gap (which has 2 domes, Jr. and Sr.) (Figure 1). While these other domes are not connected to exposed feeder dikes at the surface, the example from Panama Rock and their elongate shapes parallel to the local dike trends suggest that they are similarly fed by radial dikes (Dorsey 1988). While their sharp contacts with the country rock and the lack of extrusive features such as autobreccias suggest that these domes were near-surface intrusions (Dorsey 1988), evidence from Panama Rock suggests that this specific feature may have been extruded at the surface while confined to the crater of a preexisting scoria cone (Curtin 2012).

METHODS

Sample Collection

Three oriented samples were collected from the exposed trachyte dike at Panama Rock, one from the dike's southeastern side (JA1) and two from its top (JA2, JA3) and were cut approximately parallel to the plane of the dike. These samples were then supplemented with preexisting thin sections used in previous studies of the aforementioned trachyte domes (Curtin 2012, Garvin 2013, Dorsey 1988, Eisenberg 2013, Maher 2015) (Table 2). Due to availability of these thin sections, the majority of the samples came from the Panama Rock dome and both Devil’s Gap domes.

Geobarometry and Mineralogy

One of the key factors in the Summer Coon numerical model of Hurwitz et al. (2009) is the pressure within the original magma chamber from which the dike or dikes emerged. This value not only constrains the range of depths at which the chamber could lie, it also measures how much pressure was lithostatic and how much was overpressure due to incoming magma. Such pressures are calculated through geobarometry, which looks at the point compositions of specific minerals within the rock in order to determine the state of pressure-dependent chemical reactions. These methods, however, are prone to some inherent uncertainty, and each geobarometer is very dependent on a specific assemblage of minerals being in chemical equilibrium (Powell 1985).

While collecting the necessary compositional data is outside the scope and technical capability of this study, then, the mineralogy of the collected samples can be used to determine the viability of different geobarometers in later studies. Each thin section was studied in both plane-polarized (PPL) and cross-polarized (XPL) light in order to determine the minerals present in both the groundmass and phenocryst assemblages.

Flow Directions

As Poland et al. (2008) note, the direction of flow within a dike can constrain its shape and the possible paths the magma took to reach its final position. Poland et al. (2004), for instance, used the preferred orientations of plagioclase crystals con constrain the subhorizontal flow direction of the Summer Coon dikes, showing them to be blade-shaped as opposed to planar or fan-shaped (Figure 3). Similar studies on Banks Peninsula, both of trachyte dikes in the Lyttelton complex (Shelley 1985) and of the Panama Rock dome (Garvin 2013), have shown that the alignment of groundmass plagioclase laths in these rocks can record the orientation of magma flow.

The three oriented thin sections from the Panama Rock dike were qualitatively examined in both PPL and XPL in order to determine the direction of flow alignment in the plagioclase groundmass. While a more quantitative analysis of the samples using ImageJ processing software was attempted, in initial results the software was unable to reliably filter the plagioclase crystals from their surroundings.

RESULTS

Mineralogy

Table 3 summarizes each sample studied, listing the minerals present in both the phenocrysts and the groundmass in order of descending abundance. The typical mineral assemblage across all of the sampled domes included phenocrysts of alkali feldspar and/or clinopyroxene (Figure 4A) in a matrix of plagioclase laths, anhedral clinopyroxene, an opaque mineral (most likely magnetite (Dorsey 1988)), and glass (Figure 4B). However, View Hill and Pulpit Rock had only one sample each and there were no samples from Ellangowan.

While the plagioclase-dominated groundmass is present in every sample, the specific textures can vary greatly in size, alignment, and clarity of crystal boundaries (Figures 4A, 4C). The relative abundance of accessory minerals also varies between samples, some having more pyroxene and others having more magnetite. Two samples from Devil's Gap (DGJ1 and DG5a) also contain a red mineral, most likely aenigmatite, which was found in previous studies of the Akaroa trachytes (Dorsey 1988). Small amounts of matrix glass were present in most, but not all, samples, typically in the form of small round beads the remained extinct or at a constant color in cross-polarized light.

The samples also show varying degrees of secondary weathering in the form of a red-brown staining iron oxide, which is most commonly associated with magnetite and pyroxene (Figure 4B, 4F). This could in part be due to the original locality and freshness of each particular sample, but this relationship cannot be determined since the majority of the samples were collected from previous studies.

While the phenocryst assemblage of alkali feldspar and/or clinopyroxene stayed fairly consistent across the different samples, they also varied in texture and size, some with smaller euhedral crystals (Figure 4A) and others with larger, more fractured subhedral crystals (Figure 4C). Some phenocrysts also developed rims and other disequlibrium textures (Figure 4E). While one sample contained a single phenocryst of amphibole (Figure 4D), the rim of magnetite and the lack of similar pheocrysts suggest that this crystal is not in equilibrium with the main rock and could possibly be a xenocryst.

Flow Directions

Of the three oriented thin sections, the two collected from the top of the dike (JA2, JA3) show plagioclase laths oriented northeast-down, while the sample from the dike wall (JA1) has a northeast-up fabric (Figure 5, top). Assuming flow towards the dome, which was fed by this dike, these results suggest that magma was flowing diagonally upward through the dike before curving downward at the top of the dike (Figure 5, left).

DISCUSSION

Comparison to Summer Coon

While Akaroa and Summer Coon are both volcanoes that have eroded away to reveal an underlying network of radial dikes, the two features remain distinct in a number of ways that prevent direct comparisons between them. First of all, both the dikes and the main edifice at Summer Coon are much more silicic than those at Akaroa, with compositions ranging from basaltic andesites to rhyolites and dacites in comparison to Akaroa's basalts and tracytes. This difference in composition is directly reflected in the two volcanos' morphology, Summer Coon being a steeper stratovolcano to Akaroa's broader shield (Poland et al. 2008, Dorsey 1988). Before erosion, Akaroa was also significantly larger than Summer Coon, with an estimated volume of ~1200 km^3 over a 50 km diameter in comparison to Summer Coon's ~110 km^3 and 14 km diameter (Timm et al. 2009, Poland et al. 2008). These distinctions are important to highlight in any attempt to create a numerical model of the Akaroa system, not only to differentiate the model from that of Hurwitz et al. (2009) but also because they could potentially underlie the aforementioned differences in dike morphology.

Feasibility of Geobarometry

Due to their simple trachytic mineralogies, samples from the Akaroa dikes and domes are most likely incompatible with most traditional geobarometers. In their study of magma chamber pressures recorded in the Summer Coon dikes, for instance, Parker et al. (2005) used the Al-in-hornblende geobarometer of Johnson of Rutherford (1989), which depends on hornblende in equilibrium with melt, biotite, quartz, sanidine, plagioclase, titanite, and an iron oxide, many of which are not present in the studied samples. Even though hornblende, the most important mineral in this method, is present in one sample, that crystal is unique among the entire set of samples and has a rim of magnetite that implies disequilibrium. Importantly, however, the study by Parker et al. (2005) shows that geobarometry is possible even when the sample comes from an intrusion and not the original magma chamber, assuming a porphyritic rock whose crystals began growth before the dike formed.

While alternative pyroxene-based geobarometers exist, these techniques require mineral assemblages that also include phases like garnet, quartz, or olivine (e.g. Moecher et al. 1989), none of which are present in the Akaroa samples. Another alternative barometer suggested by Whitney and Stormer (1977) looks at how sodium is divided between plagioclase and alkali feldspars, two minerals that are abundant in the trachyte dikes. Powell and Powell (1977), however, argued that this method overlooks the effects of different impurities within the feldspars, creating significant errors. Moreover, the two-feldspar geobarometer has seen little use in the literature despite its age and may not be applicable in modern studies.

Gualda and Ghiorso (2014) suggest a different, more modern alternative to traditional geobarometry through the use of MELTS, a numerical modelling software. This method relies on the coexistence of quartz, feldspar, and volcanic glass preserved within the matrix or as inclusions within other grains. Because the glass was in equilibrium with the mineral phases at the time of emplacement, its composition records the chemical state of the system relative to the minerals' pressure-dependent solubility curves. While these Akaroa trachyte samples do not contain quartz, they still contain the critical glass phase alongside plagioclase, alkali feldspar, and clinopyroxene, all of which can be modeled in MELTS. A similar geobarometer could therefore potentially use a plagioclase-pyroxene-glass or a pyroxene-alkali feldspar-glass assemblage (Guilherme Gualda, personal communication, May 26, 2015).

Dike Flow Direction and Geometry

The oriented thin sections from Panama Rock dike indicate conflicting flow orientations, suggesting a curved flow direction as shown in Figure 5. The small sample size, however, calls into question the reliability of these results, which could be a result of localized anomalies or turbulence in the magma flow. In particular, the flow along the top of a dike can segment from the underlying intrusion, creating flow patterns that are not indicative of the entire dike at large (Poland et al. 2004).

Even discounting the two samples from the top of the dike and assuming the remaining sample JA1 is not subject to any local anomalies, the observed diagonal flow direction could still reflect two different flow patterns within the dike as a whole; it could either be an upward branch of a dike that is primarily moving laterally (Shelly 1988) or simply a result of a net diagonal motion (Figure 5, right). These two patterns, in turn, would reflect two different shapes for the dike as a whole, with diagonal flow in a fan-shaped dike and lateral flow in a blade-shaped dike (Figure 3).

Poland (2008), however, argues that planar or fan-shaped dikes with large height to length ratios, particularly those with evolved compositions like rhyolite, tend to freeze while still close to their sources and are unable to propagate very far. Moreover, Shelley (1988) found that the analogous Lyttelton dike swarm was dominated by blade-shaped dikes with predominantly lateral flow. Although more extensive sampling is required to definitively determine the flow direction in the Panama Rock dike and similar dikes across Akaroa, then, a lateral flow direction is the most likely.

The blade-shaped dikes suggested by predominantly horizontal flow directions are characterized by a zone of steep, vertical motion near the volcano's center before an abrupt shift to lateral motion at a certain elevation (Figure 3). This shift from upward to outward motion could be caused either by a zone of neutral buoyancy or a stress barrier past which the magma can no longer move upward (Poland 2008). The existence of such a barrier could therefore explain the fairly constant elevation of the trachyte lava domes.

CONCLUSIONS AND FUTURE RESEARCH

The eroded nature of the Akaroa volcano gives a unique opportunity to study the complex systems of dikes and intrusions that occur beneath volcanic edifices. A better understanding of the physical processes that control the formation and growth of these features would not only allow for easier comparison with other features, it would also allow for better assessment of the risks associated with dike-fed flank eruptions that can occur kilometers away from the main edifice.

While numerical modelling has been used to great effect at Summer Coon, a similarly eroded complex in Colorado, a model for the trachyte lava domes at Akaroa requires key pieces of information from the volcano itself, namely the magma pressure within the original reservoir and the flow direction in the feeder dikes, in order to be accurate and applicable. Based on thin sectioned samples for several of the domes, the trachyte mineralogy of these late-stage intrusions lack the specific assemblages needed for most traditional geobarometers. The presence of glass inclusions in the matrix however, could potentially allow for a new method of geobarometry using MELTS software. The characterization of magma flow within the Panama Rock dike, on the other hand, was primarily limited by a lack of samples instead of mineralogy, although a lateral flow direction is most likely.

Future research will collect additional samples from Panama Rock in order to better constrain both the mineralogy and the magma flow direction within the dike. Using point compositions from these samples, collected with either EDS or microprobe analysis, MELTS software will then be used to calculate the magma pressure. These calculations will be based either on a plagioclase-pyroxene-glass assemblage in the groundmass or a pyroxene-alkali feldspar-“glass” assemblage, using the phenocrysts and an average bulk composition for the groundmass to approximate the coexisting melt. With these two methods creating end member constraints on the possible pressures, COMSOL software will then be used to recreate the model of Hurwitz et al. (2009) for the Akaroa volcanic complex, hopefully uncovering the physical constraint behind the shared elevation of the lava domes.

ACKNOWLEDGEMENTS

Many thanks to Darren Gravley, Sam Hampton, Eric Grosfils, Jade Star Lackey, and Guilherme Gualda for advising on this project, to Rachel Beane, Michelle Gavel, Lorelei Curtin, Oliva Truax, Emily DiPadova, and Sean Maher for help with sample collection, to Rob Spiers for making the thin sections, to Kerry Swanson for help with the photomicrographs, and to the rest of the Frontiers Abroad 2015 class for their general help and support.

WORKS CITED

Curtin, Lorelei. "Origin and evolution of Panama Rock dike and dome, Banks Peninsula, New Zealand." Christchurch: University of Canterbury, 2012.

Dorsey, C. J. "The geology and geochemistry of Akaroa volcano, Banks Peninsula, New Zealand." Thesis. Christchurch: University of Canterbury, 1988.

Eisenberg, Jane L. "Structural and Geochemical Characterization of a Trachy-Andesitic Cryptodome: View Hill, Banks Peninsula, New Zealand." Christchurch: University of Canterbury, 2013

Gaddis, Emily. "Magma Propagation and Stress Influences: A Spatial Analysis of Akaroa's Primary Volcanic Features." Christchurch: University of Canterbury, 2014.

Garvin, Jennifer. "Dome Formation of Panama Rock Banks Peninsula, New Zealand: Using Joint and Flow Banding Relationships." Christchurch: University of Canterbury, 2013.

Grosfils, Eric B. "Magma reservoir failure on the terrestrial planets: Assessing the importance of gravitational loading in simple elastic models." *Journal of Volcanology and Geothermal Research* 166 (2007): 47-75.

Gualda, Guilherme A. R. and Ghiorso, Mark S. "Phase-equilibrium geobarometers for silicic rocks based on rhyolite-MELTS. Part 1: Principles, procedures, and evaluation of method." *Contributions to Mineralogy and Petrology* 168 (2014): 1033.

Gualda, Guilherme A. R. Personal communication. May 26, 2015.

Hampton, S.J. "Growth, Structure, and Evolution of the Lyttelton Volcanic Complex, Banks Peninsula, New Zealand." Thesis. Christchurch: University of Canterbury, 2010.

Hobbs, Daniel J. “Remote Sensing Geomorphology of Akaroa Volcano and Detailed Mapping of Okains Bay, Banks Peninsula, NZ.” Christchurch: University of Canterbury, 2012.

Hurwitz, Debra M. et al. “The characteristics of magma reservoir failure beneath a volcanic edifice.” *Journal of Volcanology and Geothermal Research* 188 (2009): 379-394.

Johnson, Marie C. and Rutherford, Malcolm J. “Experimental calibration of the aluminum-in -hornblende geobarometer with application to Long Valley caldera (California) volcanic rocks.” *Geology* 17 (1989): 837-841.

Maher, Sean. “Emplacement Mechanisms in Two Eroded Lava Domes at Devil’s Gap, Banks Peninsula, New Zealand.” Christchurch: University of Canterbury, 2015.

Moecher, D. P. et al. “Calculation and application of clinopyroxene-garnet-plagioclase-quartz geobarometers.” *Contributions to Mineralogy and Petrology* 100 (1988): 92-106.

Parker, D.F. et al. “Origin of rhyolite by crustal melting and the nature of parental magmas in the Oligocene Conejos Formation, San Juan Mountains, Colorado, USA.” *Journal of Volcanology and Geothermal Research* 139 (2005): 185-210.

Poland, Michael P. et al. “A model for radial dike emplacement in composite cones based on observations from Summer Coon volcano, Colorado, USA.” *Bull Volcanol* 70 (2008): 861-875.

Poland, Michael P. et al. “Patterns of magma flow in segmented silicic dikes at Summer Coon volcano, Colorado: AMS and thin section analysis.” *Earth and Planetary Science Letters* 219 (2004): 155-169.

Porreca, M. et al. “Geometric and kinematic features of the dike complex at Mt. Somma, Vesuvio (Italy).” *Earth and Planetary Science Letters* 245 (2006): 389-407

Powell, R. “Geothermometry and geobarometry: a discussion.” *J. geol. Soc. London* 142 (1985): 29-38.

Powell, Marjorie and Powell, Roger. “Plagioclase-alkali feldspar geothermometry revisited.” *Mineralogical Magazine* 41 (1977): 253-256.

Price, R.C. and Taylor, S.R. “Petrology and Geochemistry of the Banks Peninsula Volcanoes, South Island, New Zealand.” *Contributions to Mineralogy and Petrology* 72 (1980): 1 -18.

Shelley, David. “Determining paleo-flow directions from groundmass fabrics in the Lyttelton radial dikes, New Zealand.” *Journal of Volcanology and Geothermal Research* 25 (1985) 69-79.

Shelley, David. “Radial dikes of Lyttelton Volcano – their structure, form, and petrography.” *New Zealand Journal of Geology and Geophysics* 31 (1988): 65-75.

Timm, Christian et al. “Geochemical Evolution of Intraplate Volcanism at Banks Peninsula, New Zealand: Interaction Between Asthenospheric and Lithospheric Melts.” *Journal of Petrology* 50 (2009): 989-1023.

Whitney, James A. and Stormer, J.C. “Two-Feldspar Geothermometry, Geobarometry in Mesozonal Granitic Intrusions: Three Examples from the Piedmont of Georgia.” *Contributions to Mineralogy and Petrology* 63 (1977): 51-64.

FIGURES

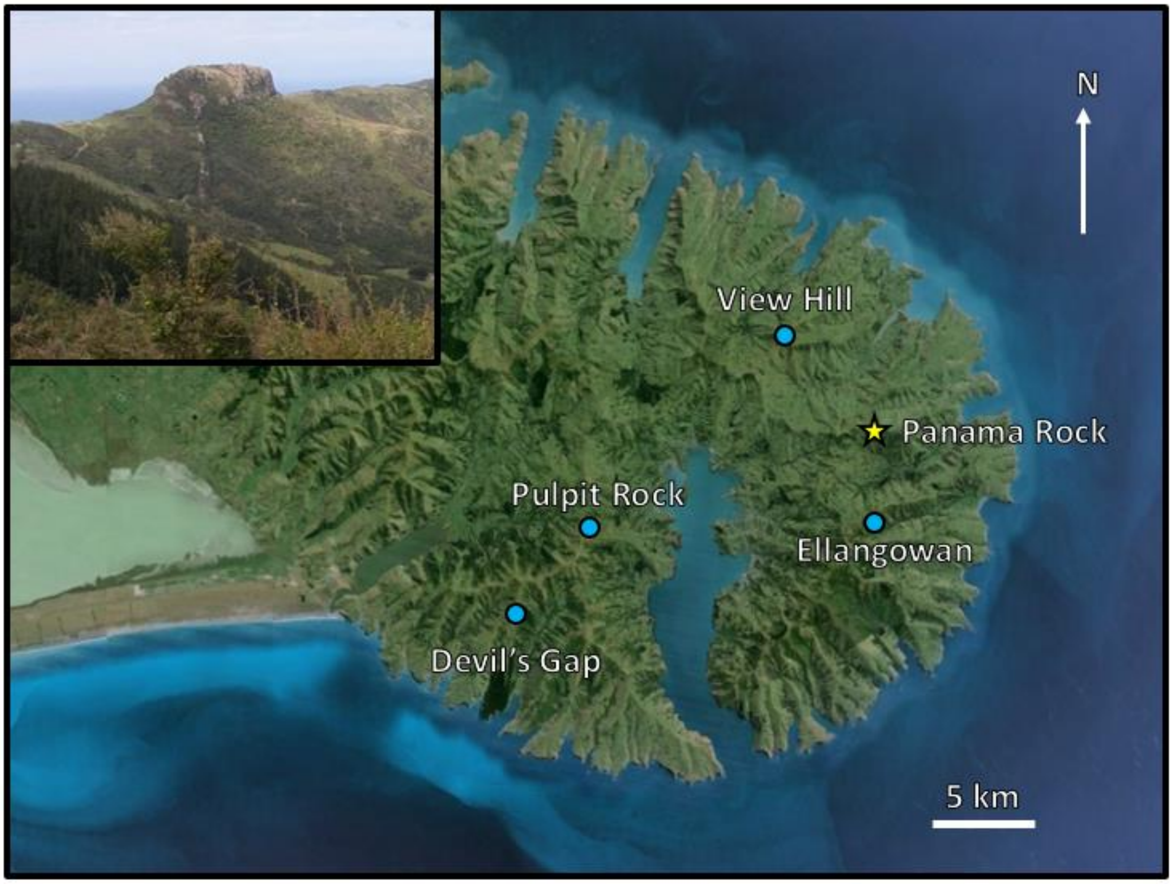

Figure 1: Map of Banks Peninsula with late-stage trachytic lava domes highlighted and labeled. Inset: Photograph of Panama Rock dome, showing the exposed feeder dike.

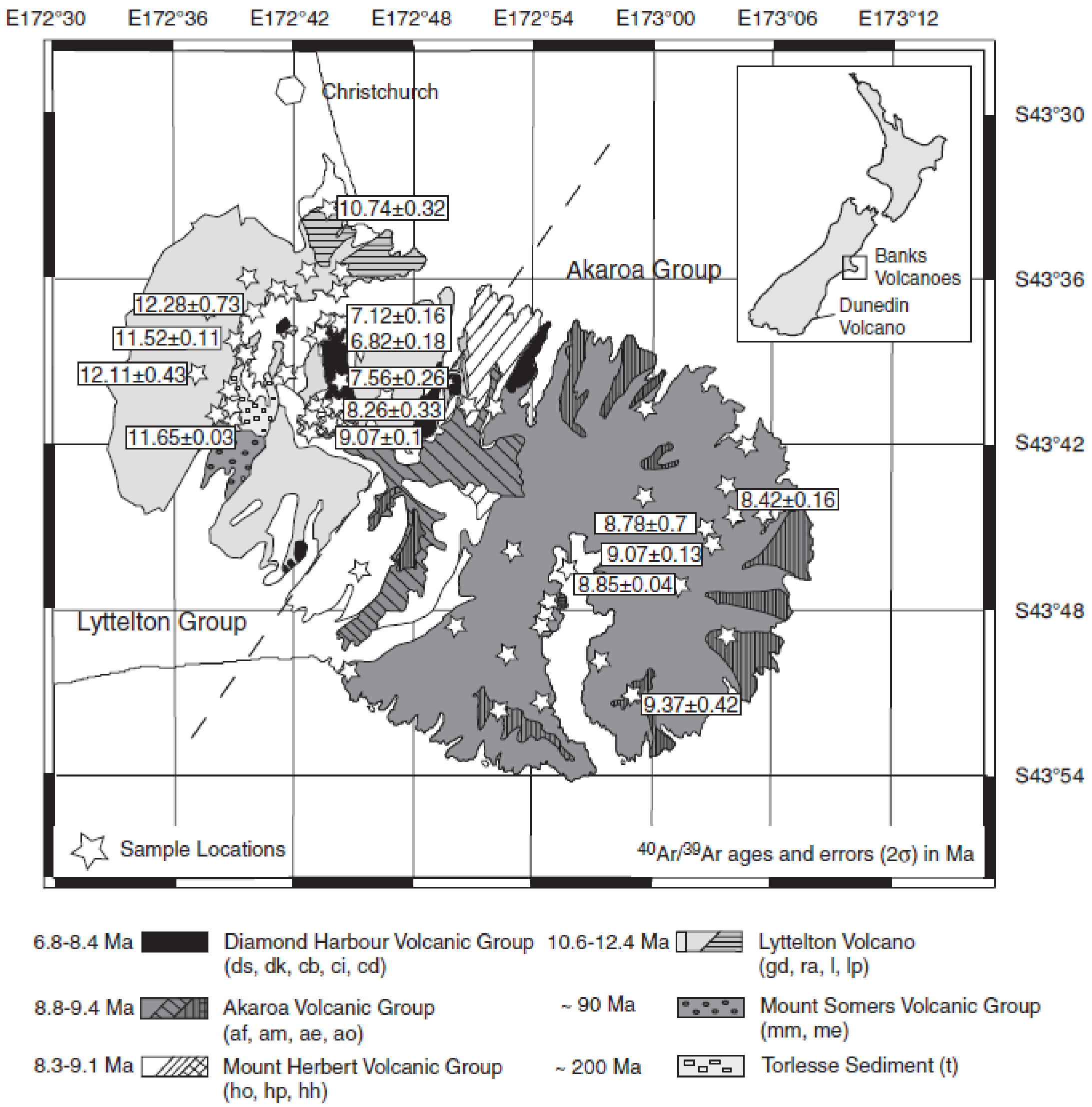

Figure 2: From Timm et al. (2009). Simplified geologic map of Banks Peninsula, showing the Lyttelton and Akaroa Volcanoes as well as related units and their ages.

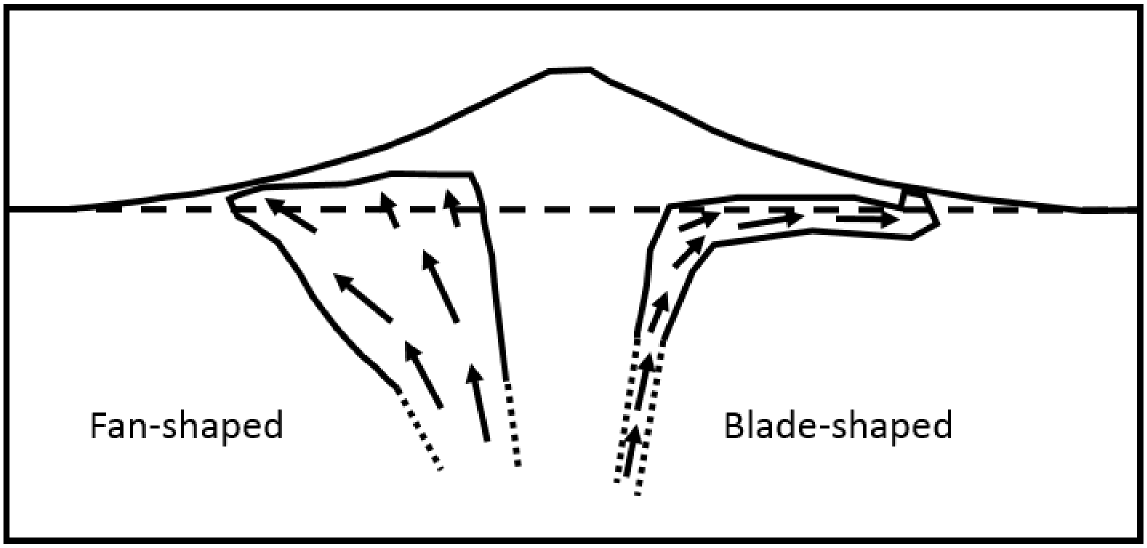

Figure 3: Adapted from Poland et al. (2008). Two possible models of dike emplacement, showing different dike shape and flow orientations

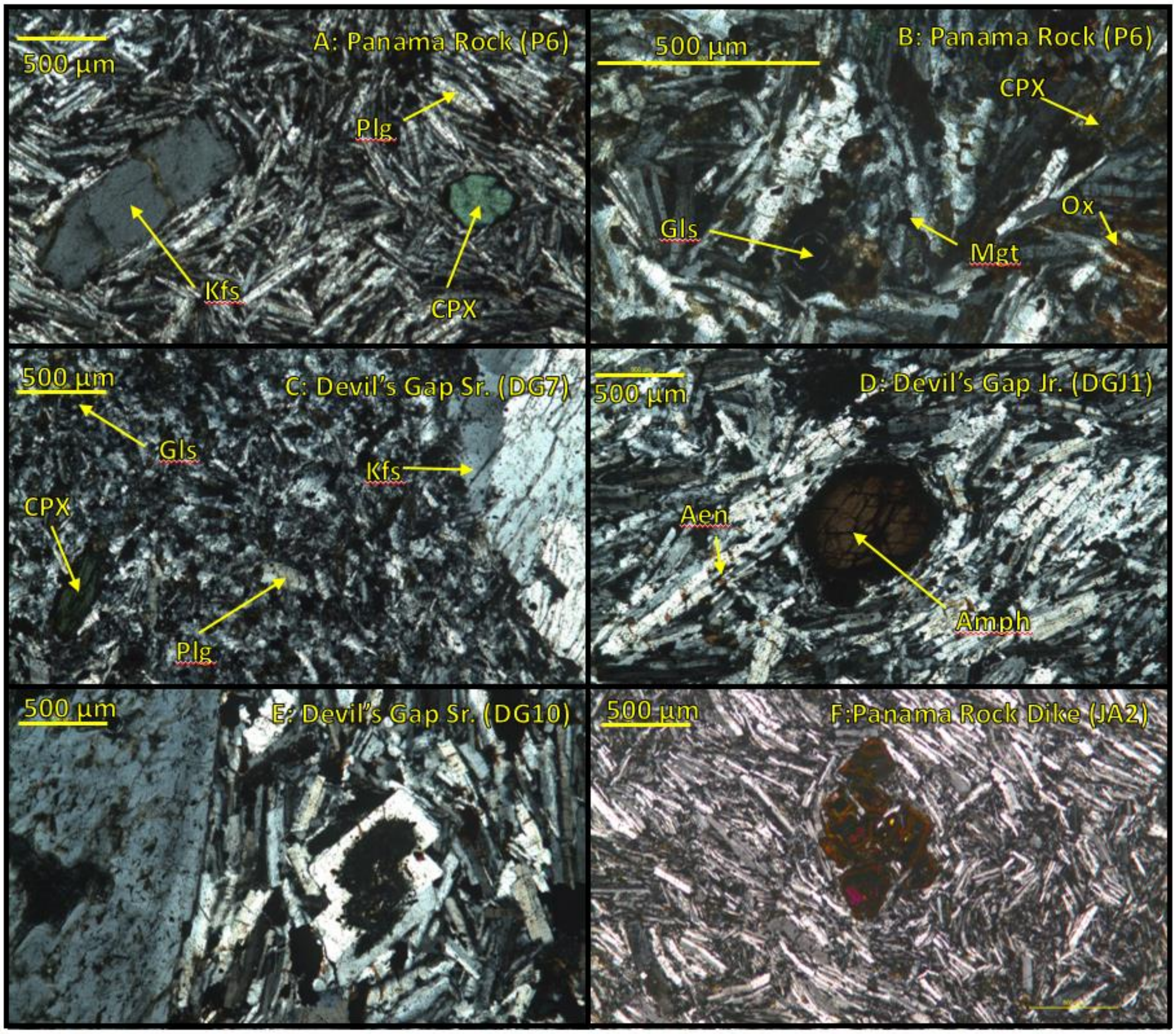

Figure 4: Photomicrographs of selected trachyte thin sections (XPL). Kfs = alkali feldspar, Plg = plagioclase, CPX = clinopyroxene, Amph = amphibole, Mgt = magnetite, Ox = Fe oxide, Gls = glass, Aen = aenigmatite.

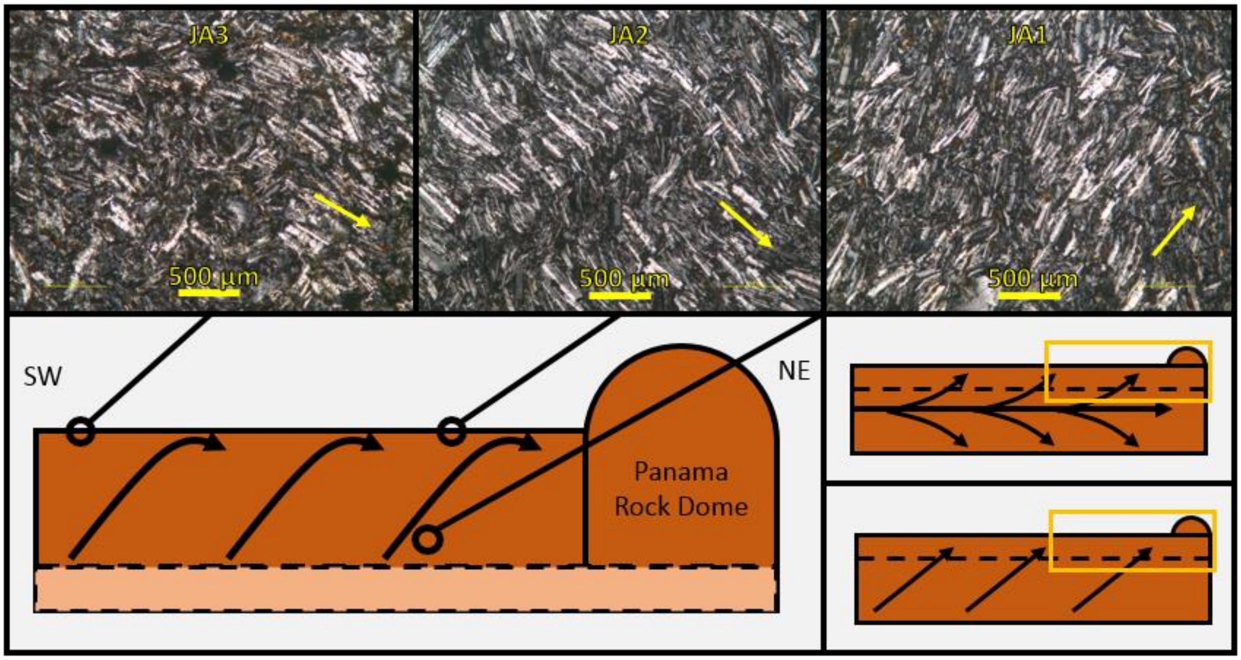

Figure 5: Top: Photomicrographs of oriented thin sections from Panama Rock dike showing flow alignment of plagioclase groundmass laths (yellow arrows) (XPL). Bottom: Conceptual model of magma flow direction based on relative locations of oriented samples (black circles). Right: 2 possible models for how observed flow could reflect larger flow direction in the dike.

TABLES

Name	X Coordinate	Y Coordinate	Elevation
Panama Rock Dome	1603466	5156432	583
Ellangowan Dome	1603529	5151971	503
Devil's Gap Sr.	1585782	5147373	590
Devil's Gap Jr.	1586650	5147373	481
Pulpit Rock Dome	1589655	5151575	414
View Hill Dome	1599096	5161005	738

Table 1: Adapted from Gaddis (2014). List of late-stage trachyte domes on Akaroa alongside coordinates and elevations.

Sample	Source	Feature	Orientation	Groundmass	Phenocrysts
JA1	Original	Panama Dike	Yes	Plg, CPX, Mgt, Ox	Kfs, CPX, Mgt
JA2	Original	Panama Dike	Yes	Plg, CPX, Mgt, Ox, Gls	Kfs, CPX
JA3	Original	Panama Dike	Yes	Plg, Mgt, Ox, CPX, Gls	Kfs, CPX
BP31	Curtin 2014	Panama Dome	No	Plg, CPX, Mgt, Ox	Kfs
BP33	Curtin 2014	Panama Dome	No	Plg, CPX, Mgt, Gls	CPX

P5	Garvin 2013	Panama Dome	Yes	Plg, CPX, Mgt, Ox, Gls	Kfs
P6	Garvin 2013	Panama Dome	Yes	Plg, CPX, Mgt, Ox, Gls	Kfs, CPX
P7	Garvin 2013	Panama Dome	Yes	Plg, CPX, Mgt, Ox, Gls	CPX
P9	Garvin 2013	Panama Dome	Yes	Plg, CPX, Mgt, Ox, Gls?	CPX
DG1a	Maher 2015	Devil's Gap Sr.	No	Plg, CPX, Mgt, Ox, Gls	Kfs, Mgt
DG3	Maher 2015	Devil's Gap Sr.	No	Plg, CPX, Mgt, Ox	Kfs
DG4	Maher 2015	Devil's Gap Sr.	No	Plg, CPX, Mgt, Ox, Gls	Kfs, CPX
DG5a	Maher 2015	Devil's Gap Sr.	No	Plg, CPX, Mgt, Ox, Gls, Aen	Kfs
DG6a	Maher 2015	Devil's Gap Sr.	No	Plg, CPX, Mgt, Gls, Ox	Kfs, CPX
DG6b	Maher 2015	Devil's Gap Sr.	No	Plg, Mgt, Ox, CPX, Gls	Kfs, CPX
DG7	Maher 2015	Devil's Gap Sr.	No	Plg, CPX, Mgt, Ox, Gls	Kfs, CPX, Mgt
DG10	Maher 2015	Devil's Gap Sr.	No	Plg, Mgt, Ox, CPX, Gls	Kfs, Mgt, Gls?
DG11	Maher 2015	Devil's Gap Sr.	No	Plg, Mgt, Ox, CPX, Gls	Kfs, Mgt, CPX
DGJ1	Maher 2015	Devil's Gap Jr.	No	Plg, CPX, Mgt, Ox, Aen, Gls	CPX, Gls, Amph, Kfs, Mgt
DGJ2	Maher 2015	Devil's Gap Jr.	No	Plg, CPX, Mgt, Px, Gls	?
3111	Dorsey 1988	Pulpit Rock	No	Plg, Mgt, Ox, CPX, Gls?	Kfs
TRD VH1	Eisenberg 2013	View Hill	No	Plg, CPX, Mgt, Ox, Gls	CPX

Table 2: List of all thin sections analyzed for this study with observed mineralogies. Kfs = alkali feldspar, Plg = plagioclase, CPX = clinopyroxene, Amph = amphibole, Mgt = magnetite, Ox = Fe oxide, Gls = glass, Aen = aenigmatite.