A Geochemical control for erosion on the lava flow stratigraphy of the Akaroa volcanic complex, Banks Peninsula, NZ

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ABSTRACT

Analyzed transects reveal cyclic geochemical trends, which correspond to eruptive packages of lava flows on the Akaroa volcanic complex (AVC). Cyclic geochemical trends are a result of shallow crustal magma recharge producing defined eruptive cycles. A new primitive melt disturbs a layer of crystal mush causing the first flows of each eruptive package to be primitive (picrite to hawaiite) and zenocryst-rich while the last flows are evolved (hawaiite to benmorite) and aphyric. The stark difference in texture between porphyritic first flows and aphyric last flows match with the stark difference in erosional slope between bench slope and package slope in cross section. This study illustrates how the last (top) flows of eruptive packages define erosional bench surfaces with a shallow bench slope, suggesting a geochemical control on erosion for the AVC.

Keywords: eruptive packages, volcanic benches, cyclic geochemistry, erosion

INTRODUCTION

Detailed geochemical analysis of volcanic stratigraphy allows identification of eruption batches that would otherwise be difficult to discern. Much of the geologic history of a volcano can be interpreted by analyzing the petrologic evolution of its lava flows.
Banks Peninsula (BP) consists of two Miocene volcanic complexes that erupted alkalic to transitional volcanic rocks to produce four eruptive groups, two of which are composite shield volcanoes (Sewell 1988).

Earlier BP studies focused on developing a stratigraphic order for lava sequences using field observations, sparse mapping, and dating (Von Haast 1878, Stipp and McDougall 1968, Taylor and Price 1980, Sewell 1988). Once geochemical analysis began, focus turned to determining the source of BP magma in the context of intraplate volcanism, an under-studied process involving mantle plumes away from plate boundaries (Timm et al. 2009). In their shift to mantle source studies, BP researchers skipped over the link between the upper mantle and lava flows at the surface: the shallow crustal magma system that allows mantle melts to rise to the surface, evolving along the way.

Over the past five years, the Frontiers Abroad (FA) program has been mapping volcanic units in great detail on the AVC. Several recent studies began developing a model for the magmatic plumbing system in the AVC based on geochemistry, thin section petrography, and statistical analysis (Johnson 2012, Crystal 2013, Beckham 2015). These studies have begun to fill the knowledge gap between upper mantle and surface lava flows. This study uses eruptive packages to begin filling a spatial gap between medial and distal deposits on the flanks of the AVC. From 2012 to 2015, FA groups mapped and sampled distal lava flows at coastal or near-coastal outcrops. New 2016 samples from outcrops near present day summits provide medial data, which, combined with distal data, give new insight into both how flows travel down the flanks of the AVC and how these flows then erode to the present day landscape. Another FA study links eruptive packages to erosional benches (Worthington in prep). This study is
the first to use geochemistry and eruptive batches to provide a better understanding of lava flow erosion on the AVC.

GEOLOGIC BACKGROUND

Tectonic Setting

BP lies southeast of Christchurch, NZ off the South Island’s east coast with its older composite shield volcano, the Lyttleton volcanic complex, sitting northwest of its younger counterpart, the AVC (Figure 1). It sits on the Pacific plate away from the Alpine Fault, which forms the plate boundary with the Australian plate to the northwest. The volcanic units on BP are a result of intraplate volcanism whereby interactions between asthenospheric and lithospheric melts resulted in two successive detachment/delamination events in the form of Rayleigh-Taylor instabilities to trigger the upwelling that produced the Lyttleton (first, smaller event) and Akaroa (second, larger event) volcanoes along with two other eruptive groups (Mount Herbert and Diamond Harbour volcanics) (Timm et al. 2009).

Banks Peninsula Evolution

Early studies (Von Haast 1878, Stipp and McDougall 1968, Taylor and Price 1980, Sewell 1988) focused much of their fieldwork on the Lyttleton volcanic complex, mapping it as numerous units, while paying little attention to the larger Akaroa volcanic complex, mapping it as just a few units. Until recently, BP was thought to have been comprised mainly of two composite shields that formed around two individual large central vents. The most detailed map of BP was on a 1:100000 scale, and mapped the AVC as one formation split into several subgroups (Sewell et al. 1992). More recent
mapping performed on the Lyttleton volcanic complex shows the possibility of 15 separate vent locations based on valley ridge orientations (Hampton and Cole 2009). If the Lyttleton volcanic complex and the AVC are tectonically related, formed within the same geologic time period (mid- to late-Miocene), and are geochemically similar (Timm et al. 2009), then clearly the AVC may have contained multiple vents as well. Careful analysis of geomorphic features on the AVC suggests that, like Lyttleton, Akaroa did indeed contain multiple vents (Hampton 2010).

Johnson (2012), Crystal (2013), Beckham (2015), Goldrick (2015), and Shankle (2015) have characterized the geochemistry of lava flows in specific areas on the flanks of the AVC. Each has observed cyclic trends, which are preserved as eruptive packages evolving from picrite to benmorite over time. Johnson (2012) defined the dominant magmatic processes controlling chemical compositions of volcanic deposits on BP as crystal fractionation and an alkali-series magma evolution. Beckham (2015) supported Johnson’s crystal fractionation theory by analyzing six transects in the eastern bay area of the AVC and identifying batches of lava flows, which correspond to interpreted eruptive cycles. Beckham (2015) proposed a refined magmatic plumbing system for the AVC based on geochemical cyclicity and petrographic analysis of phenocryst textures. Barefoot (2015) used principle components analysis to analyze years of FA data and begin to geochemically define sectors which each originate from one of the multiple vents indicated by Hampton (2010). Barefoot’s (2015) study also revealed a possible correlation between lava flow geochemistry and slope changes. This study uses Beckham’s (2015) magmatic plumbing system model along with new medial transect data to support Barefoot’s (2015) link between bulk rock geochemistry and erosional morphology on the AVC.
METHODS

Data was retrieved from six peaks (Montgomery, Mt. Sinclair, Pigeon Bay Peak, Ellangowan, Purple Peak, and Stoney Bay Peak) (Figure 1) near Summit Rd in some of the highest regions of eastern Banks Peninsula. Mapping areas were selected to cover a spatially wide area around present day peaks. Additional data is presented from past fieldwork undertaken in Decanter Bay. Fieldwork on the peaks conducted in February 2016 for four days consisted of taking samples along transects with sufficient outcrop exposure. If possible, samples were taken at each erosional plateau. However, vegetation cover often prevented mapping groups from sampling along the entire transect, resulting in several data gaps (Figure 3). A total of 229 samples were taken from the six peak regions and 171 of them were submitted for whole rock geochemical analysis by the University of Canterbury’s XRF and had corresponding thin sections cut.

Transect geochemical data was then organized into stratigraphic order, analyzed, and separated into individual eruption batches according to geochemical trends (Figures 3, 4, 5, 6). Then transects were divided into batches based on patterns in their major element geochemistry. Batch divisions were defined by analyzing both rock type progressions and distinct shifts in oxide or trace element concentrations. Each batch begins with a more primitive rock type marking the start of an interpreted eruptive cycle. Specifically SiO$_2$, Al$_2$O$_3$, K$_2$O, P$_2$O$_5$, FeO, and MgO trends were used to define batch boundaries (with the addition of V, Zr, and Sr trace element trends used for Decanter Bay). Of the selected elements, positive SiO$_2$, K$_2$O, and Zr trends coupled with negative MgO, P$_2$O$_5$, FeO, V, and Sr trends distinguished the eruptive cycles. These negative correlations fits with fractionation as olivine, pyroxene, plagioclase, and iron oxides crystallize from a cooling magma the heavier elements will decrease in concentration as
lighter elements such as silica, alkalis, and incompatibles will increase. Data was plotted in IgPet2013 to observe specific geochemical trends between transects (Figure 2). Using GoogleEarth, volcanic benches were mapped and transferred to ArcGIS (Worthington in prep). These benches were then placed in stratigraphy next to geochemically defined eruption batches (Figure 7).

RESULTS

Transect rock types range from picrite basalt to mugearite, with no batches evolving through to benmorite (Figure 6). Batches 1 and 2 from Pigeon Bay Peak Transect 1 (Figure 3) along with batch 4 from Decanter Bay Transect (Figure 6) show the most prominent major element trends. For specific correlations between batches and volcanic benches, see Table 1.

Once the erosional volcanic bench map was transferred to ArcGIS, specific transects were analyzed with respect to the benches (Figures 7, 8). The only 2016 peak transect which perfectly matched the top of a batch to an erosional bench was Pigeon Bay Peak Transect 1 (hereafter refered to as PBPT1) (Figure 8). However, volcanic benches allow for rough correlations of multiple transects within a given sector of the AVC (Figure 7). Transects upslope from Little Akaloa and Decanter Bays have been correlated using the erosional benches (Worthington in prep). Benches are treated as marker horizons which help place small-scale transects next to each other in a large-scale stratigraphy. Erosional benches are used to roughly correlate transects, and then batch divisions (based on geochemical trends) allow refinement of bench placement within a correlated stratigraphy. Provided a complete stratigraphy, trace element data can be analyzed along the sequence to highlight overall trends. Errors are associated
with both GPS sample location accuracy and erosional bench mapping (which depends on DEM quality), which are not equivalent in scale.

**DISCUSSION**

**Eruptive Batches**

A geochemical control on BP erosion necessitates understanding of the shallow magma recharge model outlined by Beckham (2015). The model defines eruptive batches of lava flows, which record an eruptive cycle of the AVC. Each batch contains: (1) early stage picrite to hawaiite lava flows with zenocryst textures (sieved cores and resorption) that reflect magma recharge, (2) middle stage picrite to mugearite lava flows with less porphyritic textures than early stage lava flows, and (3) late stage hawaiite to benmorite lava flows with aphyric textures void of large crystals. Beckham’s (2015) theory is that when the magma chamber is undisturbed, crystals are allowed to settle to the bottom and form a layer of crystal mush. But when a new primitive melt is injected, it stirs up the crystal mush, and the vents erupt primitive yet porphyritic flows early in the batch. As the eruptions continue, the remaining magma evolves through fractionation, re-creating a base of crystal mush as the residual magma erupts producing more evolved yet aphyric flows later in the batch. Initial petrographic analysis of PBPT1 (Figure 3) supports Beckham’s (2015) model. Samples of early stage lava flows are picrites that could be grouped based on slightly evolving chemistries. However in thin section separation of these early stage lavas can be made as both zenocryst and groundmass components differ.

**Batches to Volcanic Benches** (refer to Figure 8)
Barefoot (2015) suggested that cyclic trends in geochemistry through lava flow stratigraphy correlate to present day slope changes on the AVC. Specifically, lava flow geochemistry controls erosion such that a series of volcanic benches mark lava flows that are less resistant to weathering and therefore make up a bench surface (Figure 8). The crux of this model depends on how porphyritic each flow is. The first four flows of PBPT1’s batch 1 are picrites, meaning they are primitive and have a porphyritic texture (because of a higher zenocryst load) according to Beckham (2015). The fifth, top flow is mugearite meaning it is significantly more evolved and aphyric in texture (because of the absence of zenocrysts) compared to the first four flows of the batch.

Field notes supported by bench mapping (Worthington in prep) indicate a bench surface (Figure 8) above the mugearite lava flow meaning it is more resistant to weathering than the four picrite lava flows below. The top lava flow of the package is more resistant to weathering because it represents a late stage lava flow with an aphyric texture (as discussed above). This aphyric lava flow has a fine-grained groundmass and low zenocryst size and population. The absence of zenocrysts combined with a fine-grained groundmass allows very little space for void spaces to become pores through weathering. Less weathering means more of the mugearite lava flow’s surface is preserved, forming a bench. The bench surface in plan view corresponds to the bench slope in cross section, which is shallower than the package slope (Figure 8). Due to this geochemical control, erosion over time of cyclic flow packages has resulted in the stair-step bench pattern observed today along ridges on the AVC.

This model assumes that a lava flow’s phenocryst (zenocryst in this case) load correlates positively to its degree of erosion. In reality, lava flow erosion could be controlled by a number of factors including groundmass texture, phenocryst size and content, and joint spacing. Lava flow geochemistry may directly or indirectly control all of
these erosion factors. Geochemistry determines the types of minerals in a lava flow’s groundmass and porphyry, which in turn controls their relative proportions and the extent of their growth. Rock chemistry could also have an effect on joint spacing since it may influence cooling rate, but a more detailed analysis would be necessary.

**Transect Stratigraphy and Medial to Distal Comparisons**

With further refinement of the volcanic bench model and more transect mapping, correlated transect stratigraphies (see Figure 7) can be constructed for each sector, which each corresponds to a central vent on the AVC. This would allow for overall analysis of geochemical trends for both major and trace elements, which would reveal a highly detailed history of the AVC’s central vent evolutions. However, fixed vent locations cannot be assumed. Vent locations most likely evolve over time similar to present day volcanoes (Figure 9). An evolving vent location (Figure 9B) means distal flows may be difficult to find. In fact, distal flows would have entered the ocean as the AVC grew during the late Miocene, so accessing them now would be incredibly costly. Also, as shown in Figure 9B, some transects might capture medial flows from a younger vent location along with proximal flows from an older version of that same vent. This could complicate the construction of a full transect stratigraphy.

**Future Work**

More transects with well-defined eruptive packages and volcanic benches are necessary to further support the volcanic bench model. Figure 7 outlines the beginning of a developmental model for a transect stratigraphy for the region between Pigeon Bay Peak and Decanter and Little Akaloa Bays. Future work can build on those correlated transects and construct similar models for other flank sections of the AVC. The region
between Stoney Bay Peak and Haylocks and Flea Bays already has several transects to be correlated using the techniques outlined here. This study did not include detailed petrographic analysis of thin sections. But for future transects, a thin section corresponding to each flow is crucial since phenocryst load and rock texture are the main concerns. Rock strength tests, particularly on the samples from batch 1 in PBPT1, may also aid in further refinement of the volcanic bench model.

**CONCLUSIONS**

- PBPT1 supports the model first proposed by Eric Barefoot (2015), which posits that lava flow composition controls erosion on BP such that large scale volcanic benches form where a more evolved, aphyric flow (Beckham 2015) at the top of an eruptive batch is less resistant to weathering.
  - More mapping is necessary to further support the volcanic bench model with additional transects that capture multiple eruptive packages.
- Now that these volcanic benches have been mapped (Worthington in prep), transects can be placed within a large scale lava flow stratigraphy (Figure 7). Such a stratigraphy will allow for analysis of overall trace element trends along with other geochemical variations to piece together an extremely accurate representation of the evolution of the AVC both spatially and geochemically.
- When transects are observed in relation to erosional benches, peak transects are placed below coastal transects despite being much higher in elevation. This highlights:
  - (A) The amount of erosion that has taken place within the central vent region,
o (B) that the slope of lava flows travelling down the northern flank of the AVC shallowed as they reached distal regions,

o and (C) the complications that arise when thinking of lava flows as being part of a stratigraphy.

• As Figure 9 illustrates, any given vent location can evolve over time making transect correlation difficult.

ACKNOWLEDGEMENTS

This project could not have succeeded were it not for a dedicated group who worked together. I would like to sincerely thank Mr. Benson Worthington for tediously constructing volcanic benches and Mr. Eli Orland for managing ArcGIS madness. Thanks must also go to Mr. Stephen Brown for performing bulk rock chemistry using XRF, Mr. Rob Spiers for his good humor and thin section preparation, and the whole UC Geological Sciences Department for being willing to work with a large group of inexperienced young geologists.

REFERENCES


Note: this manuscript is to be submitted to the *Journal of Petrology*
FIGURES AND CAPTIONS

Figure 1: Overview map of Banks Peninsula showing its location in NZ and the main volcanic units of BP. The inner Akaroa Harbour defines the AVC’s central vent region. 2016 peak mapping locations are marked by purple ellipses and labeled.
Figure 2: Total Alkali-Silica Diagram (Cox-Bell-Pankhurst 1979) with all 2016 transects plotted. Each shows a range of rock types from picrite to mugearite.
Figure 3: Pigeon Bay Peak’s first stratigraphic geochemical plot. Horizontal dashed lines represent batch dividers, vertical solid lines indicate related flows within a batch, and vertical dashed lines indicate unrelated flows between two different batches. 2016 trace element data is not available. For specific geochemical analysis and stratigraphic interpretation see Table 1.
Figure 4: Pigeon Bay Peak’s second stratigraphic geochemical plot. Horizontal dashed lines represent batch dividers, vertical solid lines indicate related flows within a batch, and vertical dashed lines indicate unrelated flows between two different batches. 2016 trace element data is not available. For specific geochemical analysis and stratigraphic interpretation see Table 1.
Figure 5: Stoney Bay Peak stratigraphic geochemical plot. Horizontal dashed lines represent batch dividers, vertical solid lines indicate related flows within a batch, and vertical dashed lines indicate unrelated flows between two different batches. 2016 trace element data is not available. For specific geochemical analysis and stratigraphic interpretation see Table 1.

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Decanter Transect

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Figure 6: Decanter Bay stratigraphic geochemical plot. Horizontal dashed lines represent batch dividers, vertical solid lines indicate related flows within a batch, and vertical dashed lines indicate unrelated flows between two different batches. For specific geochemical analysis and stratigraphic interpretation see Table 1.
Figure 7: Angled view of the eastern bays region of the AVC showing all analyzed transects from 2015 (Menzies, Little Akaloa, Stony Bay, Ducksfoot Bay, Lavericks Bay, and Lebons Bay) and 2016 (Pigeon Bay Peak 1 and 2) (modified from Beckham 2015). Green lines on both the map and transect correlation represent erosional benches (Worthington in prep). Not to scale.
Figure 8: A) Schematic model of Pigeon Bay Peak volcanic benches with field sample locations. Green lines correspond to bench markers from the aerial view (B). Notice the mugearite flow (characterized by PBP043) forms an erosional bench above the four
picrite flows and these five flows together form an eruptive batch (see Fig. 2A). B) Aerial view of Pigeon Bay Peak Transect 1 with flow colors that correspond to A.

Figure 9: A) Hypothetical model of the AVC assuming a fixed central vent location over time such that coastal transects represent distal lava flows. B) This (more likely) model assumes the central vent location evolves over time such that coastal transects only represent medial lava flows.

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<td>The transect contains the largest and most continuously evolving batches from 2016. Both batches 1 and 2 show consistent major oxide trends. In batch 1, Note the consistency in picrite compositions and then the sharp</td>
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change from PBP042 to PBP043 going from picrite to mugearite. Batch 1 represents one complete volcanic bench capped by the mugearite (PBP043) acting as the bench-forming flow.

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<td>The transect contains 10 flows, however, two locations had excessively weathered rock while PBP007 was never processed for the XRF. Stars denote missing data. Batch 1 evolves slightly along with batch 3, but neither batch correlated directly to a volcanic bench.</td>
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<td>The transect taken in 2015 contains three evolving batches (1, 4, and 5). None of them correlated to a volcanic bench, however the batch divider between 2 and 3 did correlate directly to a bench.</td>
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Table 1