Bulk Rock Chemistry and Erosional Morphology are Intimately Linked in Basaltic Landscapes

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Abstract

On Akaroa Volcano, rigorous confirmation of the presence of multiple eruptive centers remains elusive. Work to provide evidence for a sub-cone around View Hill on Akaroa revealed a heretofore unknown association between abrupt changes in bulk rock chemistry and decreased erodibility of bedrock. Preliminary findings suggest that stratigraphic variation in rock chemistry is reflected in subtle topographic features, however physical mechanisms for this phenomenon remain obscure. Regardless of cause, the discovered relationship between chemically differentiated lava batches and topography has analytical power for testing and refining constructional histories of the volcanic edifice. Packaging lava flows using this relationship can aid in the reconstruction of the primary volcanic morphology of deeply dissected shields. In addition, these results hold implications for conceptual models of landscape evolution in volcanic terrains.

Background

Banks Peninsula is a large collection of Miocene (Hampton 2010) volcanic deposits on the east coast of North Canterbury, New Zealand (see figure 1). Constructed of overlapping strata from multiple vents, the volcanic complex drapes over a basement of Cretaceous metasedimentary rocks (Hampton 2010). Since deposition, the edifice has been incised by streams, mantled by loess, and infilled with marine sediments. The loess and marine sediments are derived from material reworked from uplifted basement rocks in the Southern Alps (Hampton 2010). Deeply dissected, the current form of the volcano is dominated by a mosaicked and nested collection of large amphitheatre-headed valleys.

Debate surrounds the notion that Banks Peninsula volcanoes developed as a complex with multiple cones (Hobbs 2012). In initial observations and descriptive work, early reporters suggested that the Lyttleton and Akaroa volcanoes were discrete, singular cones, citing as evidence their large central calderas (Speight, 1944). Later refined and built upon by other authors (Sewell 1985), this interpretation was called...
into question by Hampton (2009), asserting that the Lyttleton volcano is, in fact, an overlapping set of up to 10 contemporaneous sub-cones. Using a similar procedure to Hampton, Hobbs (2012) extended this hypothesis to Akaroa Volcano, conducting a broad-scale analysis of erosional and primary volcanic features and identifying up to ten ‘sectors’ (Hobbs 2012). At the confluences of these sub-cones, ancient drainages incised wide valleys, which are now expressed in the modern landscape as amphibitres. The flanks of these sub-cones remain preserved between the mouths of the amphitheatre valleys as dip slopes mimicking the underlying form of the lava. French in origin, the geological term for these vestigial landforms is planêze.

However, it remains unclear whether each planêze corresponds to a single eruptive center. Work by Hampton (2009) on Lyttleton Volcano incorporated several coincident sets of erosional and hypabyssal features to suggest that deposits from different sectors can exist across several planêzes and also be discriminated from each other in a loose sense, but clear and rigorous identification of a single source vent and its associated deposits remains an unsolved problem.

One sector, hereafter referred to as the View Hill Sector (VHS) (see figure) is hypothesized to represent a single subcone. The VHS is a planêze bounded on two sides by amphitheater valleys and marked at the head by large fissure dike, and a trachyte dome (Eisenburg 2013, Rosen 2013). We expect that it is possible to discriminate between the VHS and adjacent sectors, thereby providing strong positive identification of a single sector (VHS) and its corresponding paleovent.

**Chemical Approaches**

Supposing that each vent has a different chemical signature, the multiple cone hypothesis predicts that samples collected from different sectors will cluster together solely based on their chemical properties. With a large dataset of bulk chemical data built up over many years by the efforts of the Frontiers Abroad Program, principal components analysis (PCA) is an attractive technique for answering this kind of question. PCA allows for the efficient compression of a large amount of variance into a few composite variables. PCA was conducted using a suite of bulk and trace element data from across Akaroa. Before analysis, the data
were subjected to a centered log-ratio transformation to remove the problem of dataset closure (Davis 2002).

In the case of Akaroa, 91% of the variance in major oxide composition can be expressed in three principal components. Observation of the first and third principal components (see figure 2) reveals that three basic chemical processes are present across the volcanic complex: (1) a low-alkali, variable silica magma series, (2) a high alkali, low silica magma series, and (3) chemical weathering. Most variation in the data is well explained by a simple TAS classification system, the same one as was used by Metcalfe (2013). The same analysis repeated for trace element concentrations yields similar interpretations, so a plot of that analysis has been excluded.

Both Hartung (2011) and Johnson (2012) identified the main the dominant magmatic processes in the Banks Peninsula volcanic complex. Crystal fractionation and alkali-series magma evolution are the main processes controlling chemical composition on Banks Peninsula. Hartung also identified a Daly gap (Hartung 2011) in the deposits on Akaroa volcano, suggesting that magma stagnated and became more alkaline before erupting as differentiated mush. Our analysis confirms and enhances the explanation put forth by previous workers.

We find that in addition to the main alkali magma evolution series, there is evidence of the less common nepheline-generating high alkali, low-silica magma series. On a principal components plot, the high-alkali lavas plot away from the main sequence and are well-described by TAS classification. We speculate that these samples represent an extreme enrichment in alkali minerals such as nepheline.

There is also a distinct signature of chemical weathering evident in major element chemistry across the volcano. Work on principal components reveals a wide scatter of points away from the main cloud that are not well-described by TAS classification. Of these points, two main populations were identified by visual clustering, and their locations on Harker diagrams were plotted along with the main-sequence lavas (see figure 3). It appears that one population is distinguished from the main sequence by elevated aluminum, iron, and reduced calcium. Our interpretation is that these anomalies record groundwater leaching through lavas. The second population is only differentiated by a high phosphorous anomaly, which we have similarly interpreted as chemical weathering, albeit a different process. Neither process was investigated in any great detail.
In addition, PCA reveals that sample locality is thoroughly uncoupled from rock chemistry. This confirms that if there were multiple eruptive centers and paleovents, they most likely drew from the same magma source, and there is not significant process variation across the volcano. Rock chemistry alone is therefore a poor predictor of provenance.

However, rock chemistry is germane to our question when framed in terms of stratigraphy. Johnson (2012) described alternations between high and low silica lava batches and theorized about cyclic melting processes in the parent magma system. Johnson's insight into batch mechanisms implies that chemically distinct batches should be contemporary, and as such, represent a discrete, continuous time surface of the volcano. This surface carries the potential for approximating the shape of the volcano at a discrete time in the evolution of the volcanic edifice.

This study confirms the same batch phenomenon along the flanks of Decanter Bay just outside the VHS. Rock samples were collected at every a’a outcrop intersecting the road on the northwest headlands of Decanter Bay (see figure 6). These samples were crushed and analyzed for major element composition, and organized in order of stratigraphy. We find two main batches, with the suggestion of other batches above and below the main group (figure 3). One distinction to make between our observations of the batch concept and those Johnson put forth is that ours does not reveal significant magma evolution within batches. Rather, each batch consists of a chemically similar population of deposits. We lack strong evidence for regular, long-term cyclicity, because transects are limited to the vertical extent of the lava stack under investigation. Portner (2013) suggests that these records can be extended by stitching together transects from the heads and mouths of valleys, but the authors are not convinced by his arguments.

**Geomorphological Approach**

Banks Peninsula is deeply dissected by fluvial incision, and large amounts of material have been excavated from the peninsula by rivers (Hampton 2010) Preliminary mapping reveals two main classes of river valleys occur across Banks Peninsula. Large catchments drain into wide, flat-bottomed bays with steep walls, boxy headlands, and wide amphitheater-style valley heads, e.g. Okain’s Bay and Akaroa Harbour. For a view of this morphology, see figure 5. Smaller catchments drain straight, narrow valleys with steep V-
shaped floors. These observations prompt close examination to determine what process differentiates catchment size and stream power in this setting.

Hampton (2010) postulated that the smaller, straight valleys constitute lines oriented back to an eruptive center. In fact, these were one of the primary indicators he used to hypothesize the existence of multiple cones. He further hypothesized that the large amphitheater valleys were once paleo-lows, facilitating increased runoff between cones. The specific mechanisms governing the formation of amphitheater-headed valleys in basaltic landscapes are still poorly understood, however increased runoff to certain streams due to inherited topography increases catchment size. The erosional history of Banks demands more study before the unique morphology here can be thoroughly explained.

Previous work on Banks Peninsula has used drainage networks to group lavas into convenient packages (Metcalf 2013). Besides providing information about attitude, packaging lavas according to morphology suggests that erosional topography has some underlying relationship to eruptive processes. To test this concept, relationships between drainage area to knickpoint migration and concavity and slope of longitudinal profiles are appropriate avenues to explore. Differences in the orientations and permeability of differently-dipping strata will affect the propagation of knickpoints and drainage areas across the landscape unequally compared to if the cone were uniform throughout.

One prominent feature on Banks Peninsula are parallel bands of high slope running along valley walls. These bands represent outcroppings of lava on the hillslope (see figure 5) and are ubiquitous across the peninsula. Alone, these bands of high slope indicate the presence or absence of outcrops, and may denote some hypabyssal features like dikes and extrusive features like domes (Hampton 2009, Eisenburg 2013). However they don’t reflect distinct lava packages a priori. These bands of high slope do frame the edges of planèzes, allowing for easy visual identification and separation of eroded features from preserved primary features (figure 5).

Longitudinal profiles on banks reveal different concavities and base levels for the two different classes of valleys. Knickpoints are also observed throughout the peninsula, and careful analysis of their distribution may provide some insights into the erosional processes at work. Even longitudinal profiles of ephemeral gullies demonstrate areas with high slope (figure 7).
**Coupling Morphology and Chemistry**

In order to test the assumption that slope is a convenient way to package lavas, it is necessary to demonstrate a connection between changes in the properties of lava and changes in slope. In Decanter Bay, rock samples along with descriptions and location information were collected along a transect on the northwestern headland (figure 6). Every ‘a’a deposit that was encountered was sampled, and its stratigraphic position recorded.

Using digital elevation models, a gully incised on the valley wall was identified, a longitudinal profile was extracted along it, identifying areas of high slope (see figure 7). It is important to note that these areas of high slope are not knickpoints because hillslope processes dominate in these gullies, which only experience periodic flow. Instead, they correspond to areas where rock is more resistant and therefore likely to outcrop on the surface.

Because sampling was not taken along the topographic profile, it is necessary to project the elevations of samples onto the longitudinal profile. This was done by calculating a distance from sample location to profile and assuming a 4° dip of the lava flow. The result is a stratigraphic log of sample properties directly connected to changes in topography. Areas of elevated slope were identified by calculating a smoothed slope along the topographic profile, and the elevations for these peaks were then compared to the same elevations in the chemical stratigraphy in figure 7.

It appears that within the resolution of the DEM and our sampling transect, dramatic changes in bulk rock chemistry correspond to areas of elevated slope. Recall that overall, these areas of slope also correspond with decreased erodibility. The causal relationships behind this association remain relatively unexplored. It is doubtful that chemistry itself is a driving factor, however it may reflect some other currently unknown mechanism. Our working hypothesis invokes a time lag in deposition to create an easily bondable substrate for subsequent lavas. Future work will be required to narrow our scope and investigate this question.

There are some transitions in chemistry that do not have changes of slope reflected in the topography, but it is important to note that near base level and the top of the headland, sedimentation processes can disguise contributions from the bedrock. For example, at the shore platform, marine sedimentation and slowed hillslope creep could contribute to a colluvial wedge that may mask any
outcropping lavas. Small land slips and loess mantling are in evidence on this part of Banks Peninsula, and could disguise slope variation on the boundaries of longitudinal profiles.

Regardless of mechanism, this association proves quite useful in reconstructing cone features on eroded shields. Provided that chemically similar lava batches are contemporary, this association also provides a way to build 3D time surfaces of the volcano.

**Conclusions**

This study does not attempt a rigorous identification of a paleo-vent on Banks Peninsula. Rather, this study provides an honest and careful assessment of the tools used and work done thus far in verifying the multiple eruptive center model on Banks Peninsula, put forth by Hampton (2009) and extended by Hobbs (2012). We evaluated the utility of multivariate statistics on Akaroa, confirming previous work and revealing two minor chemical processes not formally identified in this study area. However, multivariate methods provided little insight into provenance. Batch processes in lava emplacement were confirmed through careful stratigraphy. Elevated slope was shown to correspond to both primary volcanic features and erosional features.

The multiple cone hypothesis suggests that chemical stratigraphy should be non-conformable across sector boundaries. We have yet to examine chemical transects on either side of a sector boundary, but as a future project, this work suggests that such a correlation is possible and informative. New in this study is the discovery that chemical stratigraphy and topography are intimately linked on Banks Peninsula. It is our hope that this relationship will provide critical insight into the constructional history of Akaroa Volcano. Additionally, we expect that further investigation and study of the chemically distinct bluff phenomenon will provide insight into the landscape evolution processes on basaltic terrains.

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References


Figure 1: Geographic context of Banks Peninsula and the View Hill Sector.
Figure 2: Principal component scores of log-ratio transformed major element data. Coloring is by TAS classification, and outlier populations are marked with colored triangles. The main magma sequence present on Akaroa is denoted by the grey arrow, with lavas evolving to trachyte compositions. Overall, the variation presented in this projection is well explained by a simple TAS classification, with some minor anomalies. Interestingly, this analysis suggests that lavas recognized as trachy-andesites and dacites are actually more similar to benmorites than more evolved trachytes. This analysis allowed for the identification of data that plot away from the main series.
Figure 3: Harker diagrams demonstrating individual elemental associations with regard to the outlier populations identified using PCA. Note the elevated phosphorous in the purple population and wide scatter of the pink population away from the main sequence. This particular combination of elemental anomalies suggests chemical weathering.
Figure 4: Chemical stratigraphy of a transect in Decanter Bay, (see figure 6). Note the sharp transitions bounding sections of chemical similarity. The shortness of the record makes interpretation of patterns at the boundaries difficult. Two batches can be seen clearly here, and using cluster analysis, each batch can be rigorously discriminated from each other.
Figure 5: Combined slope and elevation raster of Banks Peninsula. Brighter areas correspond to both areas of high slope and areas of higher elevation. Overlay is amphitheatre-headed valleys on Akaroa. Note that View hill lies directly between two such valleys. The triangular remaining pieces are planèzes.
Figure 6: Sample locations and longitudinal profile in context at Decanter Bay on Banks Peninsula. The red box locates the map view in relation to the VHS.
Figure 7: Comparing chemical stratigraphy and slope of hillslopes demonstrates a connection between areas of increasing slope and dramatic changes in bulk chemistry. The fine sloping line is the longitudinal profile of the gully mapped in figure 6. The fine black line below it is the slope at each point on the profile. The dark red line is a moving average smoothing of slope. The dotted lines connect the two peaks in slope with their corresponding elevation and then relate that elevation to the chemical stratigraphy. Chemical stratigraphy of most major elements are included, but some minor constituents like phosphorous were excluded. Samples were projected onto the longitudinal profile assuming a dip of 4°.