A Geochemical Analysis of Akaroa Volcano Flank Eruptives

Lucas R. Zeller[1], Samuel J. Hampton[2]

[1] *Department of Geology, Amherst College, Amherst, Massachusetts*
[2] *Department of Geologic Sciences, University of Canterbury, Christchurch, New Zealand*

I. Abstract

Evidence of flank eruptions are common geologic features on Akaroa Volcano, typically in the form of scoria deposits and eroded scoria cones. This study collates major-element geochemical data from eight scoria deposits on Akaroa's flanks ranging in elevation from sea level to 525 meters. Additional data from lava flow transects in the areas of Laverick's Bay, LeBon's Bay, and View Hill were collated to examine alongside the scoria deposits in those locations. The scoria deposits comprised a wide range of chemical compositions, unrelated to their elevation or the surrounding central-vent lava flows (in the case of Laverick's Bay and LeBon's Bay). View Hill lava flows and scoria were determined to be sourced from a nearby fissure eruption, providing evidence of flank activity capable of forming high-volume lava flows on Akaroa Volcano. Methods to identify flank-derived lava flows from observations made while in the field and from geochemical data are proposed based on the View Hill geology and setting.

II. Introduction

Scoria cones, the most common volcanic feature on land, are small volcanoes that form from the eruption of low-viscosity and generally basaltic magma onto the Earth's surface, building up into the shape of a cone (Vespermann & Schmincke 2000). They can be found on flat surfaces in monogenetic volcanic fields, as parasitic cones on the flanks of larger shield or composite volcanoes, and on small ocean islands formed by hotspot volcanism. Cones are made of a wide range of eruptive material ranging from lava rocks and bombs, welded and non-welded breccias and lapilli, and small amounts of volcanic ash (Kereszturi & Nemeth 2012).

Flank scoria cones are fed by dikes that radiate from either the central magma chamber or a shallower reservoir and can also provide information about the complex inner plumbing of a volcano (Acocella and Neri 2003). Flank vents form for a variety of reasons, including magma intrusion into zones of weakness created by local seismic activity or because of lateral movement of magma under the regional gravitational stress of the volcano itself

(Acocella & Neri 2003) (Shelley 1988). No universal relationship or "tipping point" has been identified for the influences of gravity and tectonics, but distinct patterns and characteristics are associated with each (Macaferri 2011, Acocella & Neri 2003). In a volcano's early stages, magma will rapidly propagate upwards through conduits with V-type (vertical and upward) movement (Geshi 2008). If a closed conduit and significant edifice load exists, magma will fracture through the conduit wall laterally and propagate outward with L-type (for lateral and outward) movement (Geshi 2008). Differential magmatic evolution has been linked to these different types of intrusions (Geshi 2008).

This study aims to characterize the geochemistry of scoria deposits on Akaroa's flanks and to find relationships (if any) among the cones and their surrounding lava flows. This will allow for better understanding of the plumbing system, flank eruptions, and the link between these eruptions and the central-vent eruptions.

III. Geologic Background

Banks Peninsula, located on the east coast of the South Island of New Zealand, is made of the remains of two large composite shield volcanoes: Lyttelton Volcano (12.3-10.4 Ma) and Akaroa Volcano (9.4-6.7 Ma) (Hampton & Cole 2009). These volcanos, along with smaller volcanic groups on the peninsula (Mt. Herbert and Diamond Harbour), are the result of Cenozoic intraplate volcanism and crustal extension and thinning associated with continental rifting and breakup (Timm 2009). Early models depicted the volcanoes as forming from single vents (Shelley 1988), but more recent studies have suggested that the volcanoes are each the product of multiple eruptive centers (Hampton 2010, Hobbs 2012). The Akaroa volcanic deposits are predominantly picrite through benmorite basalt flows, with frequent scoria deposits and trachytic domes with basaltic to trachytic dikes at higher elevations (Johnson 2012). Geochemical studies have indicated cyclic fluctuations in basaltic compositions of lava flows, believed to be the result of the underlying magma chamber being periodically replenished (Johnson 2012, Beckham 2015).

IV. Methods

Eight scoria deposit locations were identified by searching through a database of field samples and observations collected by previous Frontiers Abroad geology students from 2012 to 2015. For each location identified, a single sample was chosen to represent the entire cone. Although magma composition is not constant throughout a flank eruption or scoria cone formation, all samples were bomb- or spatter-derived, allowing for the cones to be compared based on these stages of their formation. Samples were chosen only if they were clearly identified as being scoria and if coordinate locations existed for their location. Geochemical analysis had previously been done on some samples by past Frontiers Abroad students. For other samples the actually hand samples were located and analyzed for major and trace element data.

To better understand the context of scoria cones, surrounding lava flows were selected from the database of past Frontiers Abroad field data by plotting flow location on ArcGIS and selecting flow transects surrounding the selected scoria deposits. Stratigraphic order of lava flows and scoria deposits were determined by consulting geological maps of previous students. Reliable transects were found for three of the scoria deposits: Lebon's Bay, Laverick's Bay, and View Hill. For all others, the surrounding lava flows had either not been sampled or the quality of data collection was not reliable enough to be used.

Igpet2012 was used to plot and compare the chemical compositions of the scoria deposits and lava flows. Google Earth and ArcGIS were used to study the setting and surrounding features of each sample.

V. Results

Sampled scoria deposits are all basaltic in composition, ranging from picrate basalt in Laverick's Bay to benmorite in Okain's Bay (Figure 1) and 43.8 to 55.5 silica wt% (Table 1). The five scoria samples deposited at or near current sea level (0-150m) range from picrite basalt to benmorite. Scoria deposited at higher elevations ranged from picrate basalt to mugearite.

The three lava flow transects chosen were in LeBon's Bay, Laverick's Bay, and View Hill. The LeBon's Bay transect (Table 2) consists of eight lava flows. Stratigraphically, one flow was deposited before the formation of the scoria cone and the other were all deposited after the scoria cone formation. This is based on the flow paths of the seven later flows wrapping around the scoria cone, while the first flow does not (Figure 2). The flows range in composition from picrite basalt to mugearite (45.3 – 52.5 silica wt%), and the scoria composition is hawaiite (49.7 silica wt%) (Figure 3). The two flows stratigraphically surrounding the scoria sample are picrite basalt (46.6 silica wt%) and borderline picrite basalt/hawaiite (48.4 silica wt%).

The Laverick's Bay transect (Table 3) consists of six lava flows, all of which stratigraphically overlie the scoria cone. The flows range from picrite basalt to mugearite (46.7 – 51.7 silica wt%) and the scoria composition is a less evolved picrite basalt (43.8 silica wt%) (Figure 4). The scoria composition lies well outside of the compositions of the surrounding lava flows, representing a much less evolved magma than the flows.

The third lava flow transect was taken from View Hill (Table 4), consisting of eleven flows. There is little variation in the composition of these flows, with the eleven samples (Figure 5) clustering near the border between hawaiite and mugearite (47.7 to 49.4 silica wt%). The scoria composition (49.3 silica wt%) is very similar to the lava flows, and plot within the same cluster (Figure 5).

VI. Discussion

Chemistry and Elevation

Scoria deposits on Akaroa Volcano display a broad range of chemical compositions similar to the range shown by lava flows. There is no distinct marker or trend among scoria deposits that sets them apart from central-vent flows (e.g. typically more or less evolved). Additionally, there is no relationship between elevation of the scoria deposits and their chemical composition (Figure 1). Scoria deposits at low elevation (near sea level) and high elevation do not have any distinct chemical differences or trends. This suggests that elevation is not a main controlling factor in the chemical composition/evolution of flank eruptions. The changing central magma chamber composition is likely to have a more active role in determining the composition of scoria eruptions. As the magma travels laterally from the central magma chamber/conduit toward the volcano's flanks the variable paths and speeds that it travels through the surrounding rock before being erupted is also likely to affect the scoria's chemistry by controlling the mineral crystallization and degree of evolution undergone by the magma post- separation from the main chamber (Geshi 2008). The location at which magma separates from the central conduit is likely to have an effect on these paths and distances which it travels, and will also impact the elevation at which the magma is erupted as scoria (Acocella and Neri 2003). In this way, there may be a link between the elevation of scoria and its chemical composition, but the underlying mechanisms are more complex and not readily understandable without further work and understanding of the plumbing systems.

Laverick's Bay and LeBon's Bay

Looking at the Laverick's Bay and LeBon's Bay scoria deposits in the context of their surrounding lava flows further highlights Akaroa's complex plumbing system. In Laverick's Bay (Figure 4) the scoria was formed from a magma that was much less evolved than the lava flows that were erupted from the central vent soon afterwards. The LeBon's scoria (Figure 3) was deposited in the middle of a period in which the central magma chamber was systematically evolving through fractional crystallization, resulting in more evolved lava flows being deposited on top of more primitive flows (Beckham 2015). The scoria is representative of a more evolved magma than would be expected, based on its stratigraphic location among the flows. The chemical separation between these scoria deposits and their surrounding lava flows shows that the relationship between the magma fuelling the scoria eruptions and lava flows is very complicated and it is difficult to interpret the connection between the two. Due to these complexities Akaroa's flank eruptions cannot be assumed to be chemically related to central vent eruptions.

View Hill

The View Hill lava flows and scoria deposits lie along a E-W running ridge that also features a fissure and trachytic dome which all appear to cross cut each other (Thieringer 2015) (Figure 6). Previous studies have identified relationships between the fissure and lava flows, but did not address the scoria in their interpretation (Thieringer 2015). This setting is fundamentally different from LeBon's Bay and Laverick's Bay (whose lava flows were from a central vent source). The lack of variation among the View Hill lava flows and scoria deposit suggest that they were formed from the same magma, and their chemical similarities to the nearby fissure point to them being sourced from this fissure. The features at View Hill are similar to many flank eruptions on Mount Etna, the currently active Italian stratovolcano, which frequently produce high volume lava flows along with scoria deposits (Figure 7) (Andronico et al. 2005).

This is the first evidence of lava flows on Akaroa's flanks that are not sourced from the central vent. Previously models have assumed that all lava flows were central-vent flows, not accounting for the possibility of flank eruptions being capable of producing high volume lava flows. This possibility should be kept in mind when making future interpretations about lava flow sequences on Akaroa's flanks. It may be possible to distinguish between flank-eruption lava flow sequences and central-vent lava flows based on the chemical similarities and differences among the flows and taking into account the surrounding geologic features.

In the field these comagmatic, flank-derived lava flows may be identified by being a local high point, higher in elevation than surrounding features (such as a ridge). This is caused by the lava flows being deposited above and alongside scoria, which is preferentially weathered and eroded away, leaving the lava flows standing as a ridgeline or local elevation peak. These observations can be further supported in the lab by clustering of the geochemistry of the lava flows and nearby scoria deposits, while other central-vent flows will have more variation in their chemical compositions.

VII. Conclusions

Akaroa scoria deposits do not have a distinct chemical marker that distinguishes them from lava flows, and there is no trend relating their eruption elevation to their chemical composition. These flank eruptions cannot be assumed to be chemically related to central vent eruptions, due to the complex plumbing system underlying the volcano. The View Hill field site provides evidence that flank events were capable of forming high volume lava flows, contradicting the assumption that all lava flows on Akaroa were sourced from central-vent eruptions. Further work should investigate other locations in which flank eruptions have caused significant lava flows and assess their similarities to modern flank eruption flows on Mount Etna.

References

Acocella, V. and Neri, M. (2003). What makes flank eruptions? The 2001 Etna eruption and its possible triggering mechanisms. Bull Volcanology. 65: 517-529.

Andronico, D., Branca, S., Calvari, S., Burton, M., Caltabiano, T., Corsaro, R. A., ... & Spampinato, L. (2005). A multi-disciplinary study of the 2002–03 Etna eruption: insights into a complex plumbing system. Bulletin of Volcanology, 67(4), 314-330.

Beckham, E (2015). Magmatic Evolution of the Akaroa Volcanic Complex, Eastern Banks Peninsula. Retrieved October 5, 2015, from http://www.frontiersabroad.com/research/geology-research-projects/

Geshi, N. (2008). Vertical and lateral propagation of radial dikes inferred from the flow-direction analysis of the radial dike swarm in Komochi Volcano, Central Japan. Journal of Volcanology and Geothermal Research, 173(1), 122-134.

Hampton, S. J. (2010). Growth, Structure and Evolution of the Lyttelton Volcanic Complex, Banks Peninsula, New Zealand: A Thesis Submitted in Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Geology at the University of Canterbury (Doctoral dissertation, University of Canterbury).

Hampton, S. J., & Cole, J. W. (2009). Lyttelton Volcano, Banks Peninsula, New Zealand: primary volcanic landforms and eruptive centre identification. Geomorphology, 104(3), 284-298.

Hobbs, D. (2012) Remote Sensing Geomorphology of Akaroa Volcano and Detailed Mapping of Okains Bay, Banks Peninsula, NZ. University of Canterbury.

Johnson, J. E. (2012). Insights into the Magmatic Evolution of Akaroa Volcano from the Geochemisty of Volcanic Deposits in Okains Bay, New Zealand. In Geological Society of America Abstracts with Programs (Vol. 44, No. 7, p. 560).

Kereszturi, G., & Németh, K. (2012). Structural and morphometric irregularities of eroded Pliocene scoria cones at the Bakony–Balaton Highland Volcanic Field, Hungary. Geomorphology, 136(1), 45-58.

Maccaferri, F., Bonafede, M., & Rivalta, E. (2011). A quantitative study of the mechanisms governing dike propagation, dike arrest and sill formation. Journal of Volcanology and Geothermal Research, 208(1), 39-50.

Shelley, D. (1988). Radial dikes of Lyttelton Volcano—their structure, form, and petrography. New Zealand journal of geology and geophysics, 31(1), 65-75.

Timm, C., Hoernle, K., Van Den Bogaard, P., Bindeman, I., & Weaver, S. (2009). Geochemical evolution of intraplate volcanism at Banks Peninsula, New Zealand: interaction between asthenospheric and lithospheric melts. Journal of Petrology, 50(6), 989-1023.

Thieringer, P (2015). Geochemical Evolution of the Akaroa Volcanic System in View Hill, Banks Peninsula. Retrieved October 5, 2015, from http://www.frontiersabroad.com/research/geology-research-projects/

Vespermann, D., & Schmincke, H. U. (2000). Scoria cones and tuff rings. Encyclopedia of Volcanoes. Academic Press, San Diego, 683, 694.

Figures and Tables

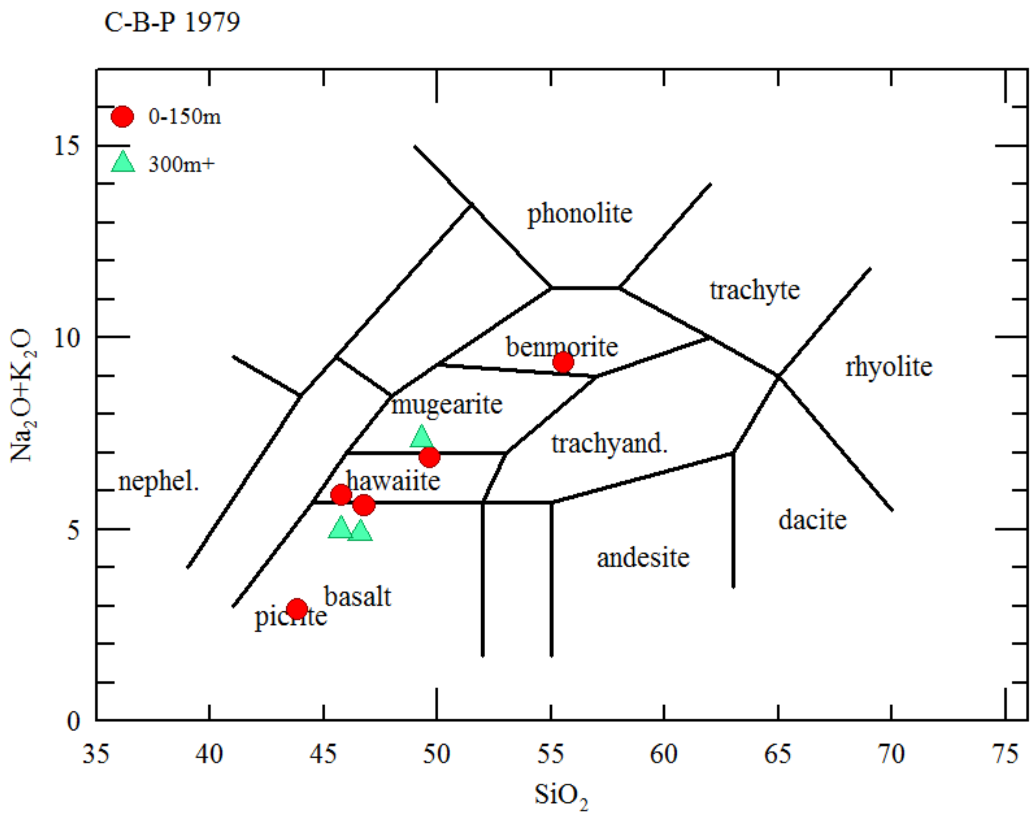

Figure 1. TAS diagram showing the compositions of each scoria sample. Samples are labelled according to elevation of the scoria deposits: red circles deposited from 0 to 150 meters, green triangles deposited above 300 meters (up to 525m).

Figure 2. Geologic map of the lava flows in LeBon's Bay, showing how flow LLB25 was the first flow that was diverted around the scoria cone, meaning it was the first flow deposited after cone formation.

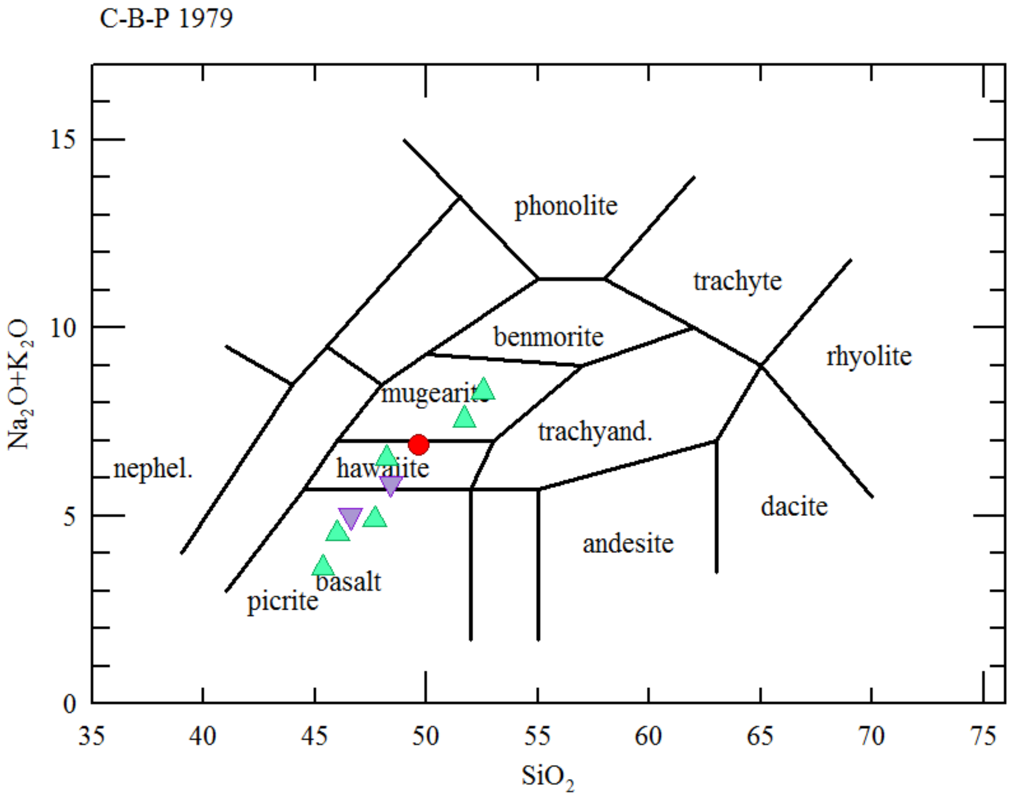

Figure 3. Composition of LeBon's Bay scoria (red cirlce) and surrounding lava flows (purple and green triangles). The two purple triangles stratigraphically surround the scoria deposit.

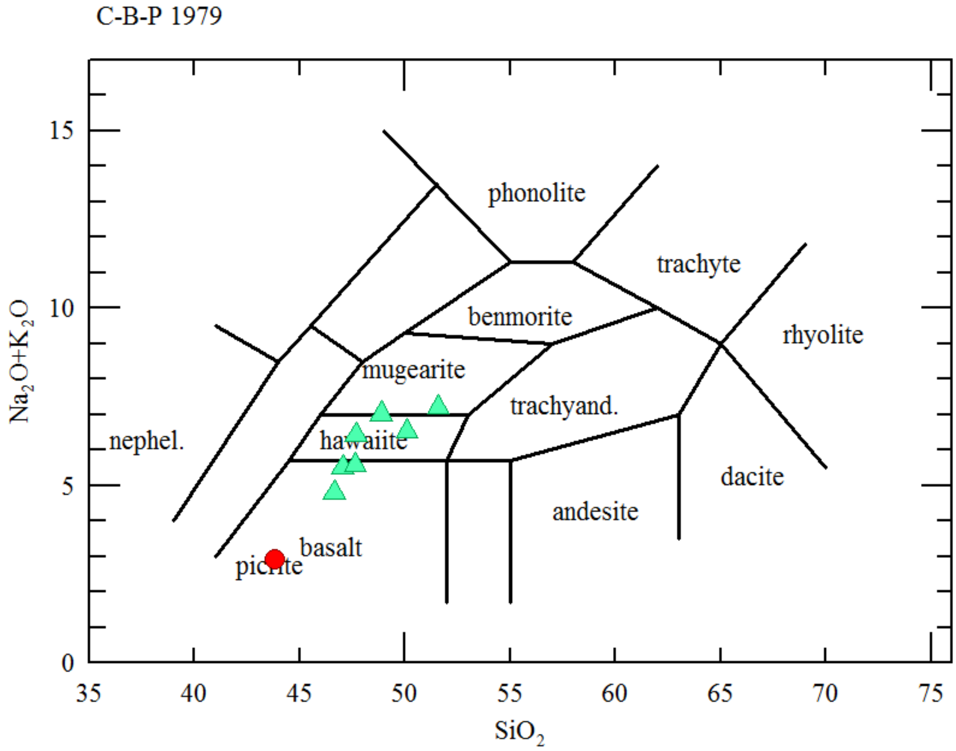

Figure 4. Composition of Laverick's Bay scoria (red circle) and surrounding lava flows (green triangles)

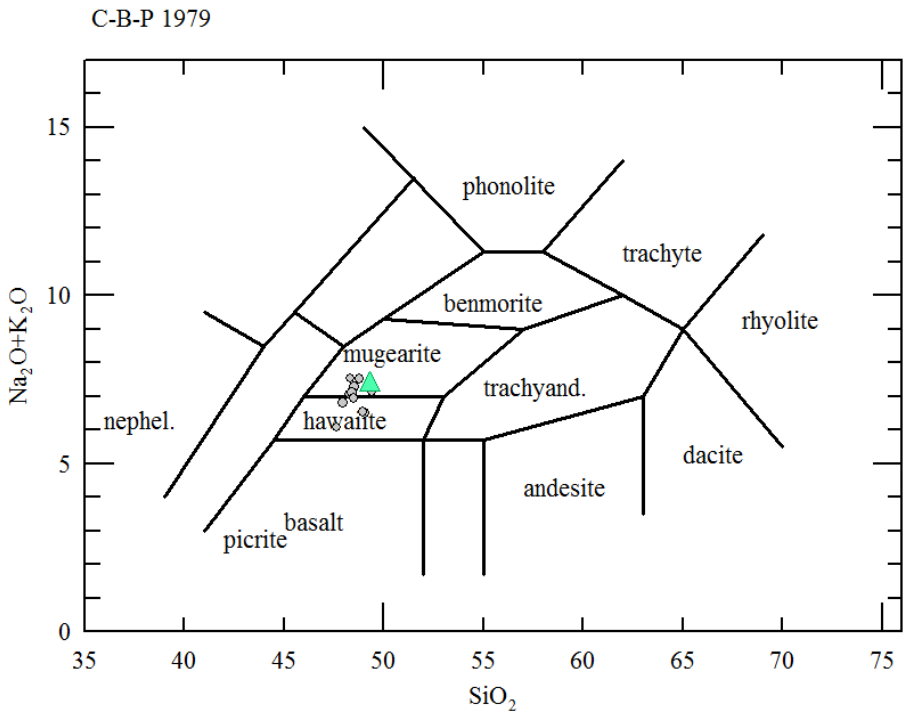

Figure 5. Composition of View Hill scoria (green triangle) and surrounding lava flows (grey dots)

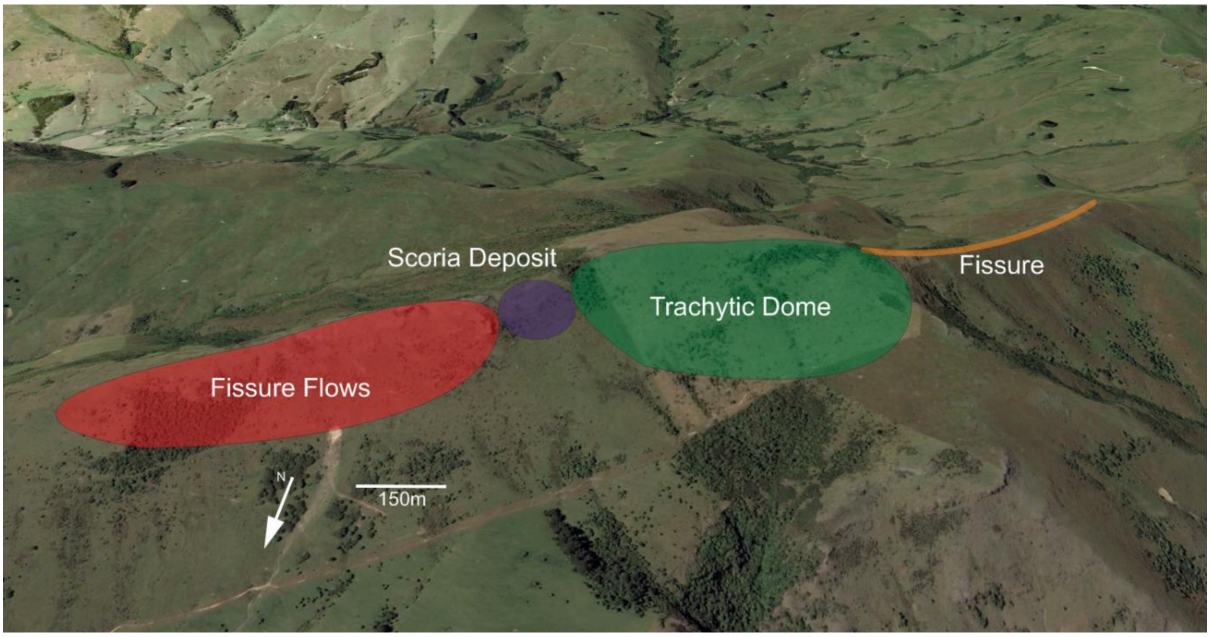

Figure 6. View Hill, showing the locations of its associated features. The fissure, running approximately East-West, deposited scoria on its sides, eventually focussing its activity in to the East, resulting in fissure- sourced lava flows. The trachytic dome later rose along the same plane of weakness as the fissure (Thieringer 2015).

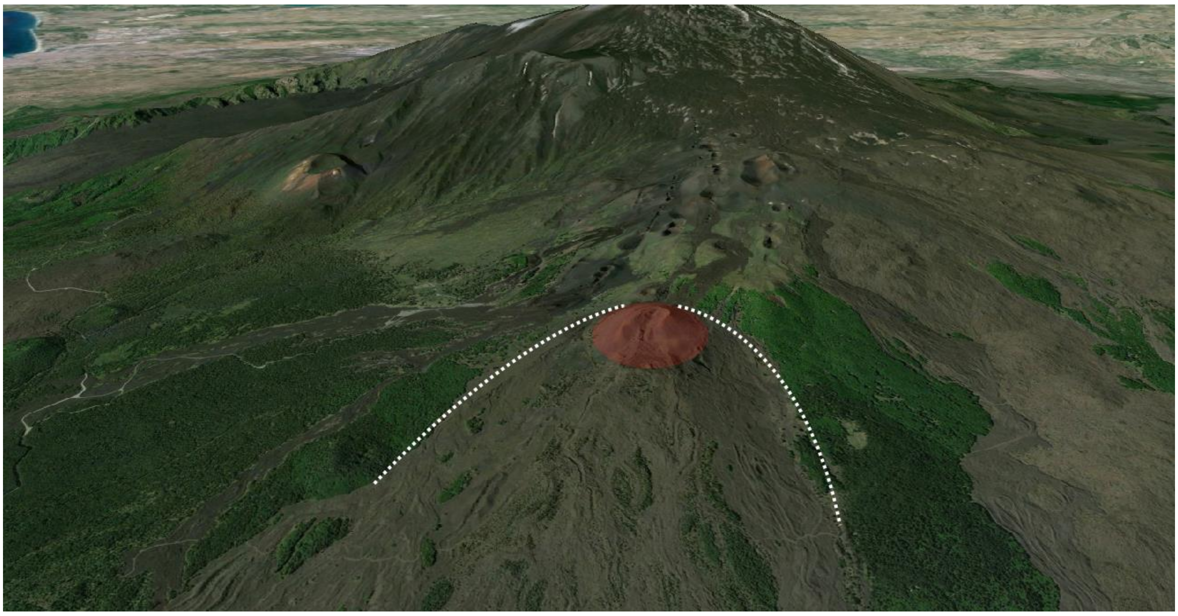

Figure 7. Example of lava-forming flank eruptives on Mount Etna. Scoria cone highlighted in red and subsequent flank-derived lava flows outlined in white.

Sample	Sample	Elevation	Coordinates	
Label	Location	m	X	Y
51ELABP	Akaloa	1	1599579	5164177
LAWBP6	Akaloa	5	1599690	5164758
JK-SC-17	Okain's	20	1605712	5161831
LLB12	LeBon's	44	1607625	5157255
LAV6SC	Laverick's	131	1607442	5159250
ST12GR5	Goat Rock	375	1605219	5159097
39VHBP	View Hill	409	1598509	5161948
PRSC	Panama Rock	525	1603049	5156500

Table 1a. Elevation and locations of all eight scoria deposits

Sample	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
Label	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
51ELABP	45.78158	4.222019	19.45545	16.6761	0.140974	1.931448	5.203692	4.377399	1.508525	0.702812	2.79	100
LAWBP6	46.77907	3.755969	19.3775	15.0982	0.149669	2.314263	6.336989	4.360752	1.268619	0.558966	1.67	100
JK-SC-17	55.55	1.45	19.25	9.48	0.14	0.76	3.38	6.49	2.87	0.63	2.2	100
LLB12	49.6814	3.115465	19.05913	13.66467	0.224164	2.051724	4.316196	5.125677	1.762179	0.999398	3.41	100
LAV6SC	43.82	4.29	21.01	16.2	0.21	4.39	6.42	2.35	0.56	0.75	6.25	100
ST12GR5	46.59	3.91	19.3	14.95	0.19	2.93	6.51	3.21	1.69	0.72	2.36	100
39VHBP	49.29	2.27	17.12	12.55	0.2	3.12	6.91	5.59	1.77	1.18	0.19	100
PRSC	45.73	4.05	18.13	15.45	0.2	3.82	6.94	3.35	1.64	0.68	3.83	100

Table 1b. Chemical compositions of all eight scoria samples

Sample	**Sample**	**SiO2**	**TiO2**	**Al2O3**	**FeO***	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**	**P2O5**	**LOI**	**Total**
Label	**Feature**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
LLB 28	lava	46.6016	3.475896	16.05752	13.3896	0.172995	5.460836	9.235723	3.802886	1.200964	0.601982	-0.1	100
LLB12	scoria	49.6814	3.115465	19.05913	13.66467	0.224164	2.051724	4.316196	5.125677	1.762179	0.999398	3.41	100
LLB 26	lava	48.39786	2.969741	17.32032	12.64069	0.18943	4.049192	7.747587	4.250649	1.622683	0.811843	0.17	100
LLB 25	lava	52.52414	2.179074	17.96177	12.51207	0.152918	1.203219	4.15996	5.709256	2.600604	0.996982	0.53	100
LLB 23	lava	51.70053	2.171437	17.63695	12.30752	0.16985	2.136856	5.220602	5.138219	2.419601	1.098432	1.54	100
LLB 22	lava	48.2049	2.876951	17.04225	12.6111	0.217467	3.890468	7.605367	4.866078	1.65295	1.03247	-0.25	100
LLB 35	lava	46.00063	3.983643	16.54947	14.76667	0.184672	4.721317	8.629874	3.374834	1.168914	0.619971	1.31	100
LLB 36	lava	45.36194	3.318284	15.47426	14.29275	0.168931	8.060413	9.273095	2.750153	0.860743	0.439421	0.53	100
LLB07	lava	47.6788	2.851877	16.48944	13.25272	0.183306	5.814142	8.307508	3.585101	1.318588	0.518523	1.12	100

Table 2. Chemical compositions of LeBon's Bay lava flows and scoria, in descending stratigraphic order.

Sample	**Sample**	**SiO2**	**TiO2**	**Al2O3**	**FeO***	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**	**P2O5**	**LOI**	**Total**
Label	**Feature**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
LAV6SC	scoria	43.82	4.29	21.01	16.2	0.21	4.39	6.42	2.35	0.56	0.75	6.25	100
LAVE/EA	lava	50.1	2.42	19.78	11.57	0.16	2.24	6.48	4.85	1.67	0.72	1.5	100
LAV-F	lava	47.67	3.25	17.03	12.49	0.2	4.09	8.02	4.83	1.61	0.81	-0.2	100
LAV-G	lava	47.65	3.4	17.85	13.34	0.17	3.68	7.53	3.99	1.6	0.79	0.98	100
LAV-H	lava	46.65	3.53	17.12	13.24	0.18	4.83	9.04	3.53	1.27	0.62	0.51	100
LAV-4(J)	lava	51.58	2.12	17.87	12.27	0.21	2.18	5.42	5.08	2.12	1.16	1	100
LAV-O	lava	48.87	2.39	17.12	12.77	0.22	3.33	7.17	5.24	1.78	1.12	-0.26	100

Table 3. Chemical compositions of Laverick's Bay lava flows and scoria, in descending stratigraphic order.

Sample	Sample	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Label	Feature	%	%	%	%	%	%	%	%	%	%	%	%
39VHBP	scoria	49.29	2.27	17.12	12.55	0.2	3.12	6.91	5.59	1.77	1.18	0.19	100
1VHBP	lava	47.65	3.09	17.34	12.66	0.18	4.59	7.65	4.47	1.62	0.75	0.14	100.00
4VHBP	lava	49.06	2.31	16.83	13.32	0.23	3.47	6.95	4.60	1.90	1.33	0.21	100.00
5VHBP	lava	48.32	2.29	17.13	12.93	0.23	3.28	6.96	5.66	1.88	1.30	-0.04	100.00
6VHBP	lava	48.78	2.27	17.02	12.78	0.23	3.23	6.90	5.65	1.86	1.29	-0.87	100.00
7VHBP	lava	48.52	2.31	17.06	12.94	0.23	3.31	7.01	5.46	1.83	1.31	-0.56	100.00
8VHBP	lava	48.95	2.38	17.46	13.18	0.22	3.19	6.79	4.62	1.92	1.28	0.54	100.00
9VHBP	lava	47.96	2.41	17.22	13.14	0.24	3.58	7.30	4.98	1.83	1.31	0.70	100.00
10VHBP	lava	48.29	2.40	17.07	12.98	0.23	3.50	7.18	5.25	1.82	1.29	-0.51	100.00
12VHBP	lava	49.40	2.16	17.21	12.78	0.23	3.13	6.74	5.14	2.01	1.21	0.24	100.00
13VHBP, 14VHBP	lava	48.41	2.38	16.99	12.94	0.23	3.47	7.17	5.30	1.82	1.28	-0.49	100.00
15VHBP	lava	48.49	2.38	16.99	12.92	0.22	3.49	7.27	5.06	1.89	1.29	-0.80	100.00

Table 4. Chemical compositions of View Hill lava flows and scoria, in descending stratigraphic order.