Vesicular changes between pahoehoe and aa lava flows:
A case study of the lagoon section in Okains Bay, New Zealand

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ABSTRACT

There are three basaltic lava flows: pahoehoe, toothpaste, and aa lava flows. Pahoehoe (smooth, billowy, or ropy) can transition into aa (rough, jagged, spinose, and clinkery) lavas if a critical relationship between viscosity and shear strain rate is reached. Toothpaste lava is transitional between the two. Vesicles are more spherical in pahoehoe lavas and more irregular in aa lavas due to deformation from shear stress. It has been observed that there is a decrease in vesicularity and an increase in vesicle deformation across the pahoehoe-aa transition. The lava flows exposed along the lagoon in Okains Bay, New Zealand have not yet been described and doing so will add to the scientific community's knowledge about how vesicularity is affected by transitions from pahoehoe to aa lavas.

GEOLOGICAL SETTING

Okains Bay is located in the northeast portion of Banks Peninsula, which is southeast of Christchurch, New Zealand (Fig. 1). Banks Peninsula is composed of three main volcanoes: Lyttelton Volcano (11.0-9.7 Ma) in the west, Akaroa Volcano (9.3-8 Ma) in the east, and the Mt. Herbert Volcanic Group (9.7-8 Ma) in the center (Hampton and Cole, 2009). Late stage activity includes the Church-type lavas (8.1-7.3 Ma) and the Diamond Harbour Volcanic Group (7-5.8 Ma) on eroding flanks and degraded volcanoes (Hampton and Cole, 2009). Okains Bay belongs to the Akaroa Volcano Group, whose composition range from basalt to mugearite (Price and Taylor, 1980).

In Okains Bay, a lagoon has cut into some old lava flows from the Akaroa Volcano Group, leaving a nice exposure of several lava flows. The lateral exposure of these lava flows allows detailed examination of transitions from pahoehoe to aa lava flows.

BACKGROUND

There are three generally recognized basaltic lavas: pahoehoe, toothpaste, and aa lava flows (Fig. 2) (Macdonald, 1953; Rowland and Walker, 1987). End members pahoehoe and aa lava flows have been defined as “the type of lava…characterized by a smooth, billowy, or ropy surface…[and aa] as the type characterized by a rough, jagged, spinose, and generally clinkery surface”, respectively (Macdonald, 1953). Toothpaste lava flows are common in transitions from pahoehoe to aa lava flows (Rowland and Walker, 1987). They, also called “spiny pahoehoe (Peterson and Tilling, 1980), include both primary lava lobes and lava “extruded from rootless openings or boccas…on pahoehoe flows usually late in an eruption” (Rowland and Walker, 1987).

Below, the structure and vesicles of pahoehoe, toothpaste, and aa lava flows are described; a summary can be found in Table 1.

Structure of Pahoehoe Lava Flows

Regardless of variation in chemical composition or thickness, thin pahoehoe lava flows (<10 m) can be characterized with 3 zones (Fig. 3): upper and lower vesicular zones with a nonvesicular or dense zone in between the two (Aubele, et al., 1988). The upper and middle zones typically make up 50% and 40% of the total vertical section, respectively, and the lower zone typically 30-40 cm (Aubele, et al., 1988). The change in vesicle abundance between the upper and lower zones with the middle zone is generally quite sharp (Aubele, et al., 1988).

Distinguishing internal features of pahoehoe lava flows include the presence of lava tubes, smooth spheroidal vesicles (Macdonald, 1953), and the presence of many small flow units (Nichols, 1936; Walker, 1971).

Structure of Toothpaste Lava Flows

Toothpaste lava has been well described from the 1960 Kapoho lava of Kilauea Volcano, Hawaii as a transition from pahoehoe to aa (Rowland and Walker, 1987). In the literature, it has also been referred to as “fine aa” (Jones, 1943), “semi-hoe” (Malin, 1980), and “drawn-surface pahoehoe” (Foster and Mason, 1955). Its features are due to the lava’s higher viscosity than that of pahoehoe and a slower flow rate than that of aa (Rowland and Walker, 1987). Unlike pahoehoe, centimeter-scale spines are drawn out of the surface of toothpaste lava with the direction of the lava flow, with vesicles in the upper part of the spines exhibiting features caused by this surface drag (Rowland and Walker, 1987). Toothpaste lava and proximal-type aa (aa lava flows can be divided into proximal-type aa and distal-type aa) are alternative types that emerge from lavas of similar viscosities (Rowland and Walker, 1987). Aa is formed when the lava emerges from the broken surface rapidly and toothpaste lava is formed when the surface resists being teared apart by the emerging lava (Rowland and Walker, 1987). Thus, the difference between toothpaste lava and aa is that the former is characterized by an unbroken, rigid crust. Toothpaste-lava units can form either at the flow surface or at the front of a lava flow (Rowland and Walker, 1987). The surface of these toothpaste-lava tongues can be broken into slaty plates, separated due to "the coalescence of gas bubbles beneath them and become stacked when the tongues encountered an obstacle", usually standing subvertically (Rowland and Walker, 1987).

Structure of Aa Lava Flows

As stated before, aa lava flows can be divided into proximal-type aa and distal-type aa (Rowland and Walker, 1987). Proximal-type aa moves forward "with a rolling caterpillar-track motion" whereas distal-type aa gets the rubbly features from the "uprise of the massive flow interior on inclined shear zones (ramp structures)" (Rowland and Walker, 1987). Proximal-type aa is more vesicular than distal-type aa due to shearing mechanisms that eliminate the gas bubbles (Walker, 1989). Aa lava flows can generally be divided into three zones: an upper and a lower zone of breccia (Macdonald, 1953) and a middle zone of massive lava (Cas and Wright, 1987).

Structural Changes in Pahoehoe-Aa Transitions

Pahoehoe can change to aa once critical relations, such as the irreversible and inverse relation between viscosity and rate of shear strain, are reached (Fig. 4) (Peterson and Tilling, 1980). Modes of this transition include: 1) "spontaneous formation of relatively stiff clots in parts of the flowing lava where shear rate is highest", 2) "fragmentation and immersion of solid or semi-solid surface crusts of pahoehoe by rolling movements of the flow", and 3) "sudden renewed movement of lava stored and cooled within surface reservoirs" (Peterson and Tilling, 1980). As a result, autobrecciation is a characteristic of the pahoehoe-aa transition (Polacci, et al., 1998).

This transition from pahoehoe to aa is irreversible; however, secondary pahoehoe flows can break out of the surface of a stationary aa flow (Guest, et al., 2012). This has been observed at Mount Etna, Sicily, and Kilauea Volcano, Hawaii (Guest, et al., 2012; Hon, et al., 2003). At Mount Etna, secondary pahoehoe flows resulted from long duration eruptions where lava tubes are formed and there is a change in slope (Guest, et al., 2012). When slope shallows, lava pressure is increased in the tube, allowing breakouts to occur (Guest, et al., 2012).

Vesicles in Pahoehoe and Aa

Vesicles are formed because gas bubbles are trapped as silicate melts are solidifying (Aubele, et al., 1988). This is because the thermal diffusion coefficient of silicate melts is four orders of magnitude higher than the diffusion rate of gases in silicate melts, allowing the cooling thermal wave responsible for the solidification of the flow to travel faster than the gases (Aubele, et al., 1988).

Vesicles in pahoehoe often are regular spheroids while vesicles in aa usually are irregularly shaped, caused by continued movement and deformation during the final phases of solidification (Peterson and Tilling, 1980). In pahoehoe, vesicles in the upper and lower zones tend to increase in size and decrease in vesicle density (number of vesicles per unit area) closer to the middle zone (Aubele, et al., 1988; Walker, 1989). A review of the literature has not found a similar description of vesicles in aa.

Vesicle Changes in Pahoehoe-Aa Transitions

In their 1998 study of transitions from pahoehoe to aa lava flows at Kilauea Volcano, Hawaii, Polacci, et al. used the method of quantifying vesicular changes by capturing images of hand samples along three mutually perpendicular planes. The planes were oriented along the flow direction, across the flow direction, and parallel to the flow surface. Using NIH Image and Dapple software, the vesicularities (area fraction of vesicles per unit area), the vesicle number densities, and individual vesicle areas were measured. Then it was able to calculate the equivalent diameter (the diameter of a circle with the same area as the vesicle) and the deformation parameter $D=(1-b)/(1+b)$, where 1 and b are major and minor axes of vesicles (; Taylor, 1934). It was shown that as pahoehoe lava flows transition into aa lava flows, there is a general decrease in vesicularities and vesicle densities as well as a general increase in vesicle deformation. These changes were at their highest right before the transition due to the increase in shear strain rate (Duraiswami, et al., 2003). This may be exemplified by the fact that bubble loss through the flow has been observed for active pahoehoe and aa flows; the former due to bubble loss at flow surfaces and the latter due to shearing and bubble collapse (Polacci, et al., 1998).

METHODS

In the field, the height of each outcrop was measured and flows were subdivided into units depending on their vesicularity. Units were described in terms of vesicle density, the maximum and/or average vesicle size, and the shape of the vesicles (spherical or elongate). Hand samples were taken from a transitional flow, in which pahoehoe transitions into aa and then breaks out into pahoehoe again.

Based on an extensive literature review, a spectrum of basaltic lava flows (with pahoehoe and aa as endmembers) including lithology and vesicular zonation and characteristics was created. Using this, the type of flow exposed at each outcrop was determined. Then the changes in the vesicles throughout each lava flow as they progressed along the pahoehoe-aa spectrum were described.

Samples from the section in which a transitional flow turns into a pahoehoe break-out were cut along three mutually perpendicular planes: 1) vertical plane along the flow direction, 2) vertical plane across the flow direction, and 3) horizontal plane parallel to the flow surface. The flow direction was determined based on the orientation of the vesicles. Vesicularities and vesicle number densities were determined from binary images created from photos of these samples created by the NIH program ImageJ.

RESULTS

Following the lagoon to the ocean, the lava flow transitions from pahoehoe to aa and breaks out into pahoehoe again (Fig. 5).

Description of Lava Flows

The first pahoehoe outcrop had seven distinct flow units with a range of 0-40% vesicularity and the vesicles ranged from 1 to 5 mm in diameter. The vesicles were mostly spherical with a few elongate ones.

As the flow moved upward into a subvertical structure, parts of the flow became slaty, indicative of increased shear strain, and the pahoehoe flow transitioned into aa as breccia was formed (Fig. 6). In this chaotic environment, vesicularity had a range of 5-

30% and size had a range of <1-5 mm. Both spherical and elongate vesicles were present.

About 20 meters later, pahoehoe broke out of the aa. The upper 100 cm had an average flow unit height of 5 cm, 15% vesicularity, and spherical vesicles between <1 and 2 mm in size. The lower 50 cm had an average flow unit height of 9 cm, 20-25% vesicularity, and spherical vesicles between <1 and 2 mm in size.

Further down, the flow units became larger. The top meter of this outcrop had 25% vesicularity with 3 mm irregular but rounded vesicles. The bottom meter had 15-20% vesicularity with <1-2 mm spherical and elongate vesicles.

The next section had evidence of shear planes (Fig. 7). The top 30 cm had a vesicularity range of 15-30% and a size range of 1-4 mm, both decreasing downward. Vesicles in this zone were spherical. The next 30 cm had a vesicularity range of 10-30% and a size range of <1-6 mm, the former decreasing and the latter increasing downward. This zone was slaty and vesicles were elongate. The bottom 70 cm had a vesicularity range of 40-45% and a size range of 1-3 mm. These vesicles were spherical.

The next section had three flow units. The top was 25-30% vesicular, had an average vesicle size of 8 mm (though the largest found was 8 cm), and had elongate vesicles. The next zone was 10% vesicular with 1 cm elongate vesicles. The bottom zone had 25% vesicularity with 5 mm elongate vesicles.

Hand Sample Data

Vesicularity decreased as pahoehoe approached aa, remained relatively same as pahoehoe transitioned into aa, continued to decease until pahoehoe broke out of aa and it increased (Fig. 8). Vesicle number density increased as pahoehoe approached aa, decreased as pahoehoe transitioned into aa, continued to decrease until pahoehoe broke out of aa and it increased (Fig. 9).

DISCUSSION

Since none of the outcrops reveal the full vertical section of the lava flows (the middle nonvesicular and lower vesicular zones are not seen), comparison to the established model of the three-zoned pahoehoe lava flow is not possible. However, changes in vesicularity as pahoehoe progresses can be examined. It seems that the range of vesicularity decreases as pahoehoe progresses. The range was high before and as pahoehoe transitioned into aa until pahoehoe broke out of aa. The shape of the vesicles also changed from more spherical to more elongate and irregular. In areas where pahoehoe becomes slaty, vesicularity and vesicle size decrease.

The hand samples show that right at the transition from pahoehoe to aa, vesicularity remains relatively constant and vesicle number density decreases. Before this, vesicularity had been decreasing, which agrees with Polacci, et al.'s argument. Vesicle number density, however, had been increasing. The Polacci, et al. paper states that images of each sample were taken in three different planes in order to determine the three-dimensional morphology of vesicles; however, not all three planes are accounted for in the figures on vesicularity and vesicle number density. This may explain the discrepancy between our different findings. It would be interesting to take a look at the data not included in their paper for comparison. In addition, pahoehoe is generally made up of many flow units of varying vesicularities so the samples I took may not be representative of the entire flow at that point. Perhaps vesicularity should be determined for each flow unit and then a weighted average (based on the volume each flow unit contributes to the flow) can be calculated for a more representative value for vesicularity. On the other hand, the fact that there is a sharp increase in vesicularity and vesicle number density as pahoehoe broke out of the aa shows that there is a change in rheology.

For a more detailed study of this area, thin sections can be made to determine how microlite crystallinity changes in the transition and after the pahoehoe break out.

REFERENCES

Aubele, J. C., L. S. Crumpler and W. E. Elston. (1988). Vesicle Zonation and Vertical Structure of Basalt Flows. *Journal of Volcanology and Geothermal Research, 35*, 349-374.

Cas, R. A. F. and J. V. Wright. Volcanic successions, modern and ancient: a geological approach to processes, products, and successions. Allen & Unwin, London; Boston.

Duraiswami, R. A., G. Dole, and N. Bondre. (2003). Slabby pahoehoe from the wester Deccan Volcanic Province: evidence for incipient pahoehoe-aa transitions. Journal of Volcanology and Geothermal Research, 121, 195-217.

Foster, H. L. and A. C. Mason. (1955). 1950 and 1951 Eruptions of Mihara yama, Oshima volcano, Japan. *Geol Soc Am Bull, 66,* 731—762

Guest, J. E., A. M. Duncan, E. R. Stofan, and S. W. Anderson. (2012). Effect on slope on development of pahoehoe flow fields: Evidence from Mount Etna. *Journal of Volcanology and Geothermal Research, 219-220*, 52-62.

Hampton, S. J. and J. W. Cole. (2009). Lyttelton Volcano, Banks Peninsula, New Zealand: Primary volcanic landforms and eruptive centre identification. *Geomorphology, 104(3-4),* 284-298.

Hon, K., C. Gansecki, and J. Kauahikaua. (2003). The transition from ‘A’a to pahoehoe crust on flows emplaced during the Pu’u ‘O’o-Kupaianaha eruption. In: Heliker, C., D. A. Swanson, and T. J. Takahashi (Eds.), The Pu’u ‘O’o-Kupaianaha eruption of Kilauea Volcano, Hawai'i: The first 20 years: USGS Prof. Paper, 1676, pp. 89-103.

Jones, A. E. (1943). Classification of lava surfaces. *Trans Am Geophys Union*, Part I, 265—268.

Macdonald, G. A. (1953). Pahoehoe, aa, and block lava. *American Journal of Science, 251,* 169-191.

Malin, M. C. (1980). Lengths of Hawaiian lava flows. *Geology, 8*, 306--308

Nichols, R. L. (1936). Flow units in basalt. J Geol, 44, 617-630.

Peterson, D. W. and R. I. Tilling. (1980). Transition of basaltic lava from pahoehoe to aa, Kilauea Volcano, Hawaii: Field observations and key factors. *Journal of Volcanology and Geothermal Research, 7*, 271-293.

Polacci, M., K. V. Cashman, J. P. Kauahikaua. (1999). Textural characterization of the pahoehoe-‘a‘a transition in Hawaiian basalt. *Bulletin of Volcanology*, *60*, 595-609.

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

Rowland, S. K. and G. P. L. Walker. (1987). Toothpaste lava: Characteristics and origin of a lava structural type transitional between pahoehoe and aa. *Bulletin of Volcanology, 49*, 631-641.

Taylor, G. I. (1934). The formation of emulsions in definable fields of flow. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, 146(858),* 501-523.

Walker, G. P. L. (1971). Compound and simple lava flows and flood basalts. *Bulletin of Volcanology, 35,* 579-590

Walker, G. P. L. (1989). Spongy pahoehoe in Hawaii: a study of vesicle-distribution patterns in basalt and their significance. *Bulletin of Volcanology, 51*, 199-209.

FIGURES

Figure 1.

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decompressor
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Figure 2

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Figure 3.

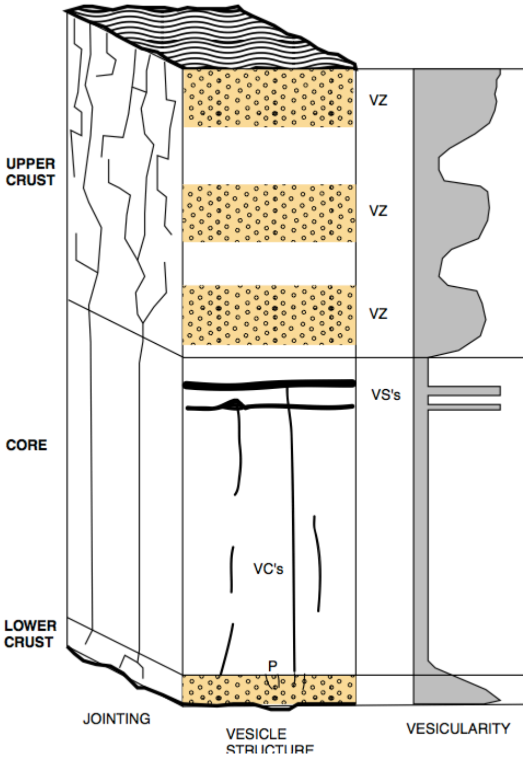

Figure 4.

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Figure 5.

Figure 6.

Figure 7.

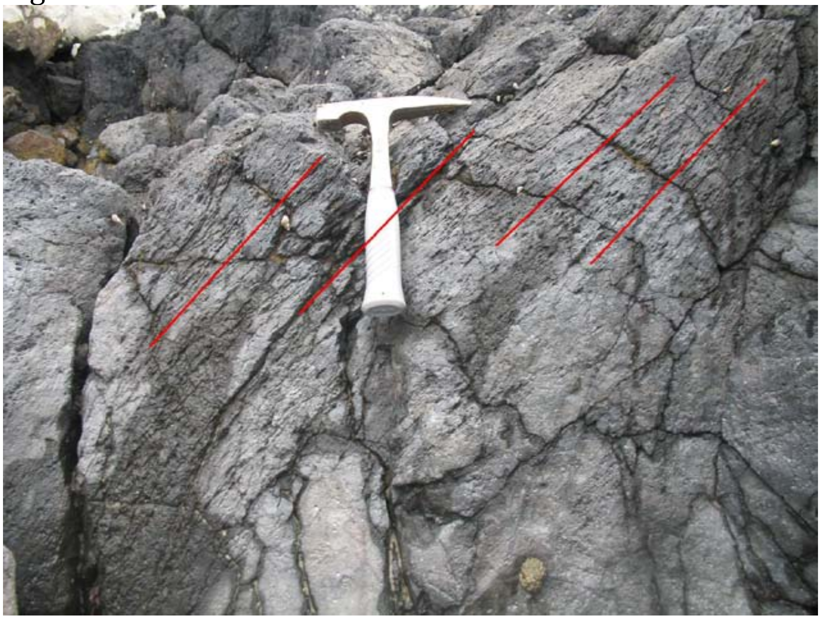

Figure 8.

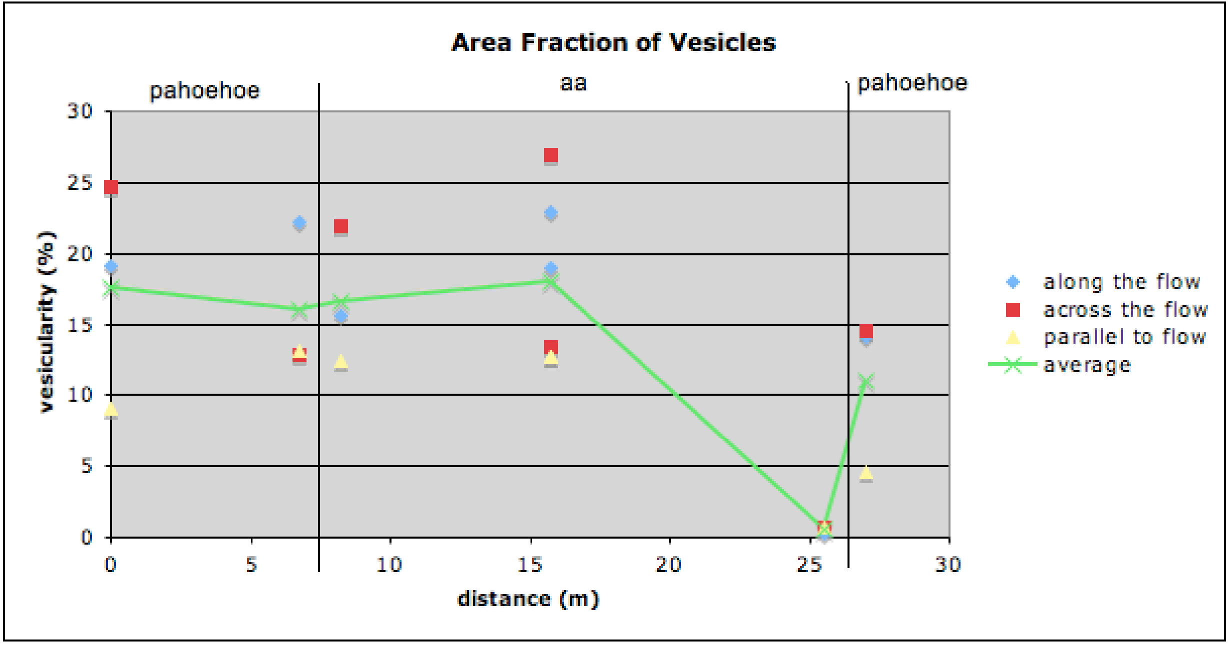

Figure 9.

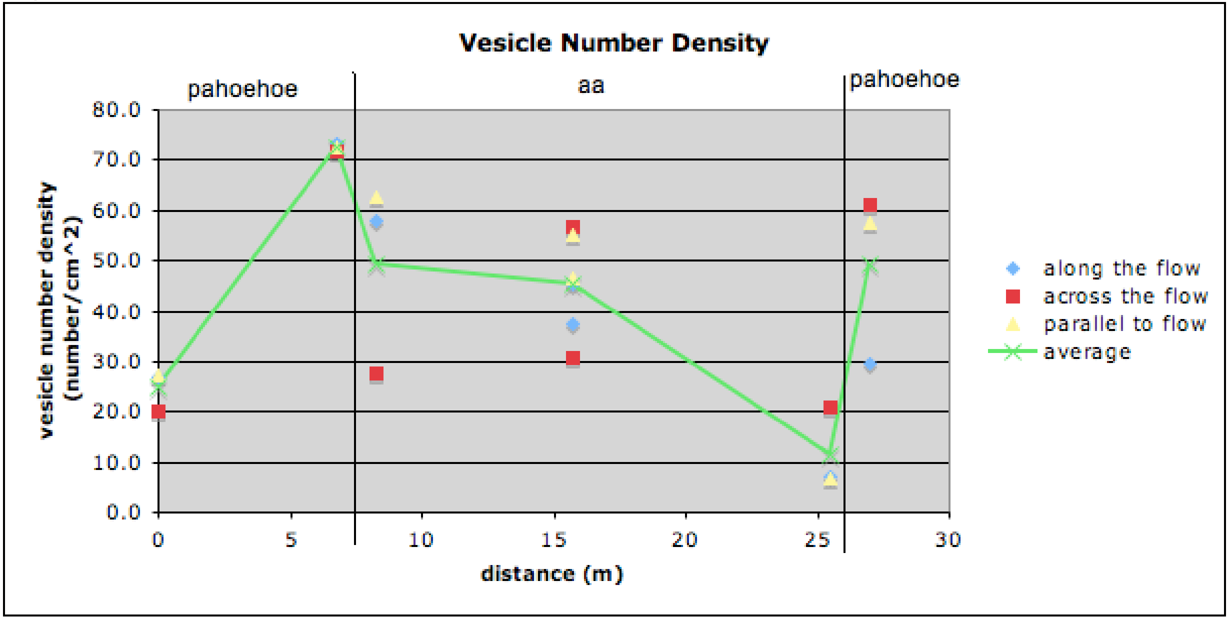

FIGURE CAPTIONS

Fig. 1. Geological sketch map of Banks Peninsula (Price and Taylor, 1980).

Fig. 2. Schematic diagrams (not to scale) of four basaltic lava flows: a) pahoehoe, with differential flow and rapid healing of crust, b) toothpaste, with differential flow of rigid crust and shearing (S) at margins, c) proximal-type aa, with differential flow causing tearing and rotation of skin and movement toward the levees (L), and d) distal-type aa, a plug flow with loose rubble on the surface and rotated rubble and

shearing in marginal zones. The velocity profiles are shown, with the arrow length proportional to flow velocity. (Rowland and Walker, 1987).

Fig. 3. Idealized vertical section of a pahoehoe flow, divided into vesicular upper and lower zones with a nonvesicular core in between. The upper and middle zones make up roughly 50% and 40%, respectively, of the total section height. The lower zone generally makes up 30-40 cm, regardless of section height (Polacci, et al., 1998). Vesicle size increases from crust to core (Self, et al., 1998).

Fig. 4. Transitional zones between pahoehoe and aa based on the relationship between viscosity (η) and shear strain rate (ε) during different flow histories: A) pahoehoe lobe on flat ground, B) pahoehoe flow over steep slope, C) transition from pahoehoe to aa flow over steep slope, D) transition from pahoehoe to aa flow over constant slope, E) transition from pahoehoe to aa as crust gets chilled, and F) transition from pahoehoe to aa due to remobilization. Point E represents the start of eruption and point S represents solidified lava at rest at the end of the flow path (Peterson and Tilling, 1980).

Fig. 5. From left to right, the lava flow transitions from pahoehoe to aa through a squeeze-up and breaks out of the aa channel into pahoehoe again. Blue backpack for scale.

Fig. 6. A close up of the aa squeeze-up from the pahoehoe as the flow moves upwards. Note the arrows indicating flow direction and the black outlines of breccia and changed flow direction. Rock hammer for scale.

Fig. 7. Example of shear lines (indicated by red lines) found in pahoehoe. Rock hammer for scale.

Fig. 8. Changes in vesicularity as pahoehoe transitioned into aa and broke out of aa. The left black line denotes the squeeze-out and the right black line denotes the pahoehoe break out of aa.

Fig. 9. Changes in vesicle number density as pahoehoe transitioned into aa and broke out of aa. The left black line denotes the squeeze-out and the right black line denotes the pahoehoe break out of aa.

TABLES

Table 1.

	Pahoehoe	Transitional (i.e., toothpaste)	Aa
Surface Features	-smooth, billowy, or ropy[1]	-spinose[2]	-fragmental and spinose[1]
Structure	-vesicular upper and lower zones and a nonvesicular middle zone[3]	-unbroken, rigid crust of squeeze-ups[2]	-brecciated upper and lower zones and a massive central zone[4]
Distinguishing Features	-presence of lava tubes[5] -presence of many small flow units[5]	-flow units significantly thicker than those in pahoehoe[4]	-levee channels[1]
Vesicle Shape	-spheroidal[1]	-elongate	-irregular[1]
Vesicularity and Vesicle Number Density	-higher[3]	-intermediate[3]	-lower[3]
Microlite Crystallinity and Crystal Number Density	-lower[3]	-intermediate[3]	-higher[3]

TABLE CAPTIONS

Table 1. Summary table of pahoehoe-aa spectrum. [1]Macdonald, 1953; [2]Rowland and Walker, 1987; [3]Polacci, et al., 1998; [4]Walker, 1971; [5]Nichols, 1936; Walker, 1971

APPENDIX

Pahoehoe A

Height	Vesicularity	Size	Shape	Notes
30 cm	30%	5 mm	spherical	
12 cm	0%	-	-	
15 cm	5%	1 mm	spherical	slaty
30 cm	30%	3 mm	spherical	
20 cm	20%	5 mm	spherical and elongate	
30 cm	40%	3 mm	elongate	
30 cm	0%	-	-	

Aa Squeeze-up

Height	Vesicularity	Size	Shape
1 m	5-30%	<1-5 mm	spherical and elongate

Pahoehoe B (Break-out)

Height	Vesicularity	Size	Shape
50 cm	7%	5 mm	spherical
50 cm	50%	1-7 mm	elongate

Pahoehoe C

Height	Average Flow Unit Height	Vesicularity	Size	Shape
100 cm	5 cm	15%	<1-2 mm	spherical
50 cm	9 cm	20-25%	<1-2 mm	spherical

Pahoehoe D

Height	Vesicularity	Size	Shape
1 m	25%	3 mm	irregular but rounded
1 m	15-20%	<1-2 mm	spherical and elongate

Pahoehoe E

Height	Vesicularity	Size	Shape	Notes
10 cm	30%	4 mm	spherical	
20 cm	15%	1 mm	spherical	
10 cm	30%	<1 mm	elongate	slaty
20 cm	10%	6 mm	elongate	slaty
50 cm	45%	3 mm	spherical	
20 cm	40%	1 mm	spherical	

Pahoehoe F

Height	Vesicularity	Size	Shape
100 cm	25-30%	8 mm (max 8 cm)	elongate
120 cm	10%	1 cm	elongate
40 cm	25%	5 mm	elongate

Hand Samples Data

Sample No.	Number of Vesicles	Vesicle Area (cm^2)	Total Area (cm^2)	Area Fraction (%)	Vesicle Density (number/cm^2)	Distance From Sample 1 (m)
1D	1028	7.365	38.422	19	26.8	-
1F	550	6.756	27.341	25	20.1	-
1P	827	2.742	30.336	9	27.3	-
2D	3671	11.085	49.983	22	73.4	6.75
2F	1499	2.679	20.942	13	71.6	6.75
2P	1035	1.868	14.305	13	72.4	6.75
3D	1202	3.247	20.807	16	57.8	8.25
3F	443	3.517	16.031	22	27.6	8.25
3P	878	1.745	13.994	12	62.7	8.25

4aD	445	2.256	9.85	23	45.2	15.75
4aF	479	2.273	8.434	27	56.8	15.75
4aP	653	1.511	11.836	13	55.2	15.75
4bD	909	4.586	24.196	19	37.6	15.75
4bF	763	3.345	24.947	13	30.6	15.75
4bP	735	1.99	15.749	13	46.7	15.75
5D	208	0.085	28.585	0	7.3	25.5
5F	215	0.078	10.24	1	21.0	25.5
5P	103	0.111	15.626	1	6.6	25.5
6D	434	2.057	14.612	14	29.7	27
6F	986	2.339	16.144	14	61.1	27
6P	557	0.446	9.696	5	57.4	27