Basaltic Lava Flow vs. Welded Basaltic Ignimbrite:
Determining the Depositional Nature of Volcanic Flows

Emily Sexton\textsuperscript{1,2}, Sam Hampton\textsuperscript{2}
\textsuperscript{1}Washington University in St. Louis, \textsuperscript{2}University of Canterbury

Abstract

Welded basaltic ignimbrites are one of the rarest forms of ignimbrites found in the field. However, a specific flow found in Raupo Bay on Banks Peninsula was determined to be one of these anomalous pyroclastic density current deposits. The goal of this study was to evaluate the differences between lava flows and ignimbrites while using structural, geochemical, and thin section analysis to determine the depositional nature of this flow, referred to as Layer A. Distinguishing characteristics of ignimbrites are that they rarely contain a basal breccia, they thicken in valleys but also cover higher elevations, thinning to a few meters in distal regions, the welded zone makes up most of the unit with a gradation in density, and then contain deformed fiamme and aligned glass shards (see Table 1). Although rare, basaltic ignimbrites are emplaced by similar processes to intermediate and felsic ignimbrites (Watkins et. al., 2002). Layer A thickens into a valley and thins along higher topography, with a zone of intense welding extending all the way to its base, forming a sharp basal contact, while becoming less welded towards the top. It also has a significantly different composition than the underlying stratigraphic units, and contains flattened, sheared scoria clasts, aligned bubbles and lava lithics. Thin sections show flattened rock boundaries and microlites rimming around phenocrysts. It is thus concluded that Layer A is a rare welded basaltic ignimbrite, emplaced at temperatures well above the minimum welding temperature transported in a Northwest-Southeast orientation.

1. Introduction

Densely welded ignimbrites can often exhibit characteristics that are similar to those of lava flows. This case study evaluates what an ignimbrite is and how lava-like ignimbrites differ from lava flows through the use of field photos, geochemistry, and thin section analysis. In particular, welded basaltic ignimbrites are rarely found in the field and underrepresented in literature. Most studies of ignimbrite focus on those of intermediate to felsic composition (Watkins et. al., 2002).
Ignimbrites are pyroclastic density currents that are rich in ash and pumiceous material. They are represented by lapilli made of pumice and scoria, ash made of glass shards, and some foreign lithic fragments. Ignimbrites can vary from nonwelded to welded (Freundt et. al., 2000). Table 1 outlines the differences in characteristics of lava flows and ignimbrites. Ignimbrites can be distinguished based on the character of a basal breccia, the nature of the distal parts of their flow, their relationship to pre-existing topography, variations in welding, the presence of deformed fiamme and aligned glass shards, and sometimes from the type of source.

The focus of this research is to determine if a basaltic volcanic flow in Raupo Bay is a lava flow or a densely welded ignimbrite. This study will provide a basis for which lava flows can differ from lava-like ignimbrites, in particular welded basaltic ignimbrites, which are some of the rarest pyroclastic currents. Additionally, most of Banks Peninsula has never been geologically mapped, leaving many gaps in the geologic record. By determining the paleotopography in which the volcanic flow was deposited, the flow direction, and the depositional nature of the flow, this study can help piece together the geologic record of Raupo Bay as well as Banks Peninsula.

2. Geologic Setting

Banks Peninsula was formed by intraplate volcanism during the late Miocene and the Pliocene. It consists of two volcanoes, Lyttelton and Akaroa. Lyttelton was active between 10 and 12 m.y. and Akaroa was active between 8 and 9 m.y. (Stipp and McDougall, 1968). The volcanism made up Banks Peninsula of basaltic and andesitic lava flows. Since the active volcanism on the peninsula, significant erosion has taken place, leaving cliff faces with cross sections of lava flows (Stipp and McDougall, 1968). Raupo Bay, shown in Figure 1, is on the Northeast coast of Banks Peninsula and was formed by lava flows from the Akaroa volcanic complex. This study focuses on the upper most volcanic flow found in the central cliffs of Raupo Bay, referred to as Layer A. The nature of the formation of Layer A differs greatly from that of the lava flows and scoria cones beneath it. Determining the depositional nature of Layer A will create a more complete geologic history of the flow as well as the underlying layers.
3. Methodology

Geologic field mapping of Raupo Bay was completed in February, 2014. GPS coordinates were taken for locations of Layer A and variations in height of the unit were recorded. Rock samples of A were collected and brought back to the Department of Geological Sciences at the University of Canterbury. The rocks were cut, exposing fresh surfaces, thin sections were prepared and geochemical analysis of the major elements was competed. The geochemical information was useful in determining that Layer A is basaltic and seeing how the silica content varied from layer to layer in Raupo Bay. The thin section information was vital in observing the presence of fiamme, deformed air bubbles, and squished clasts within the samples. Additionally, pictures of cliff faces were utilized to show the paleotopography in which Layer A was deposited, as well as its relationship to this topography and its upper and lower boundaries to help determine if the layer is an ignimbrite of a lava flow.

4. Results

4.1 Paleotopography and Relationship of Layer A to the Prior Topography

4.1.1 Stratigraphic Units

In the central region of Raupo Bay, there are 4 separate units. The oldest and second oldest layers (L1 and L2, respectively), are both lava flows. L1 is rubbly with a dark gray/black colour and platy joints. It is crystal poor with large phenocrysts. L2 is blocky with irregular columnar jointing and brecciated regions within the flow. It is porphyritic and has a dark gray colour. L3 creates a wedge shape, thickening along the headland and thinning inland. It is deposited on a relatively flat surface but the upper boundary slopes away from the ocean. It is massive in the middle and becomes brecciated at the top and bottom of the flow, with red-yellow colour. It contains pebble to boulder sized clasts in a fine grained matrix, and looks to contain scoriaceous material. Above L3, there is a thin layer of bright red ash that acts as a marker layer. Layer A, the youngest unit, is gray-dark gray in colour with a purple tint. It has massive columnar jointing and varies from thicknesses of 3-16 m. It is crystal medium to poor.

4.1.2 Southeastern Side of Layer A

Figure 2(A) shows the Southeastern side of the peninsula containing Layer A. With an exception of some slight height variations, the thickness of A is relatively uniform on this side (around 3-4 m thick), as shown in the diagram below the photograph in Figure 2(A). The layer contains massive
columnar joints, and in some locations, clusters of radial jointing. It is overlain by a thick layer of Loess.

4.1.3 Cross-section View of Layer A on the NE Eroded Cliffs

A section of the headland has been eroded away, exposing a cross-section view of L2, L3, and A. Figure 3 shows A thickening into an inland valley, and thinning over the wedge-shaped L3 deposit on the headland. In the thick, ponding region, the upper surface is relatively flat, but in the mantling part of the flow, the upper surface is slanted, parallel to the paleotopography. The flow climbs over L3, while the cooling joints remain perpendicular to the underlying ash layer.

4.1.4 Northern Side of Layer A

Figure 4 shows a view of the Northern side of the central peninsula. It shows Layer A thickening into topographic lows and thinning over higher topography. A mantles L3, thinning along the headland, but as L3 pinches out inland, Layer A mantles L2 along the western region, maintaining a relatively uniform thickness of about 6 m.

4.2 Columnar Jointing and Upper and Lower Contacts

Layer A is composed of massive columnar joints, which make up the vast majority of the unit. These cooling joints are 0.5-1 m wide and are perpendicular to the underlying surface. They extend all the way to the base of the flow, where there is a sharp contact with the red ash deposit. The cooling joints are broken and sheared towards the bottom, creating a couple separate layers of short, thin joints before reaching the base, but there is no basal breccia. There is a gradation in welding intensity, from densely welded at the bottom of the flow to less welded at the top of the flow, where the massive joints transition into a less welded, ashy deposit. Figure 3 shows the massive columnar jointing in Layer A with the sharp basal contact and welding gradient. Along the SE and NW sides, there are radial jointing patterns, shown in Figure 4, where the joints come together near the base of the flow but spread out in the upper region, mantling the underlying topography.

4.3 Geochemical Analysis

Geochemical results conclude that although the youngest layer in the stratigraphic sequence, L1, is a picrite basalt and the next youngest layer, L2, is a Hawaite, the two are very similar in composition. L3, which has a much higher silica content, is a Benmorite and Layer A was determined to be a picrite basalt. The geochemical distribution for all 4 layers is shown on a Cox-Bell-Plankhurst (1979) diagram in Figure 5. Within the three youngest layers, there is an increase in SiO$_2$ content and Na$_2$O
+ K₂O content. However, Layer A, which overlays an ash deposit above L3, has an anomalously low silica and Na₂O + K₂O content compared to the rest of the stratigraphic units.

4.4 Rock Sample Analysis

Samples of Layer A were taken from two locations, shown in Figure 1. Sample WP52A was taken from the bottom of a 3 m high mantling section, while samples WP58A and WP58B were taken from the bottom of a 13 m high pooling section. WP52A is not oriented but WP58B was cut looking at a cross section view of the rock, while WP58A was cut looking down the sample. Pictures of these samples are shown in Figure 6. WP52A contains pumiceous scoria clasts and lava lithics 2-5 mm wide. The WP58B sample also shows scoria fragments, with their long axes oriented horizontally and their short axes vertically. There are air bubbles that have been vertically flattened and aligned with a NW orientation. The WP58A sample has scoria clasts 2-10 mm wide that do not appear to be flattened when looking down the rock. However, the side of the sample shows a flattened scoria clast that appears to be sheared horizontally.

4.5 Thin Section Analysis

Thin section analysis determined that the samples of Layer A contain plagioclase microlites (30-40%) in a gray, possibly magnetite matrix (40-50%) with olivine, clinopyroxene, and plagioclase phenocrysts (~20%). Thin section trends show crystal rimming and squished rock pieces. Photomicrographs for samples WP52A, WP58A, and WP58B are shown in Figure 7. The WP52A sample shows rock fragments with identifiable boundaries squished around phenocrysts. Rimming of groundmass plagioclase crystals around larger phenocrysts is noticeable. The WP58A sample also shows microlite rimming around phenocrysts and squished rock fragments. Air bubbles in pumice fragments are visible. The WP58B sample shows groundmass crystals rimming around phenocrysts, and in one occasion, rimming around a rock boundary that has a phenocryst within it.

5. Discussion

5.1 Paleotopography

Layer A’s underlying layer, L3, exhibits scoria cone characteristics. Scoria cone deposits consist of bombs, scoriaceous lapilli, and minor ash. Elongate and rubbly particles agglutinate together in scoria deposits, causing the outer walls of scoria cones to be welded together but the individual clasts are still distinguishable (Vespermann and Schmincke, 2000). L3’s transition from a massive interior to red-yellow breccia inland indicates that the wedge-like shape is not a product of
weathering, but rather a result of the depositional nature of the layer. The vent location could have been underwater, where the bay is now located. Massive scoria breccias are commonly formed by volcanic eruptions in shallow water (Vespermann and Schmincke, 2000). The distal region of the scoria cone deposit in Raupo Bay created a valley while the slope of the scoria cone created the walls of the valley. After the deposit of the scoria cone, there was a layer of bright red ash deposited on top of L3, which acts as a marker horizon. Layer A then filled in the valley on top of the ash horizon.

5.2 Topography of Layer A

Layer A pools to thicknesses of 13-16 m in paleotopographic valleys and mantles higher topography, thinning to a relatively uniform thickness of 3-4 m. This behaviour is characteristic of ignimbrites, which can climb over topographic barriers (Henry and Wolff, 1992). In doing so, they maintain upper surfaces that are parallel to the paleotopography. They have a tendency to pool into valleys, with a horizontally flat upper surface (Walker et. al., 1980). Contrastingly, lava flows are stopped by topographic barriers and cannot climb to higher regions like an ignimbrite can (Henry and Wolff, 1992).

5.3 Columnar Jointing and Contacts

In many densely welded ignimbrites, particles in the flow have such high temperatures and low viscosity that they will agglutinate upon contact with the ground before basal cooling can affect the welding, causing the zone of intense welding to extend all the way to the basal contact (Freundt, 1998). In the Gran Canaria welded basaltic ignimbrite, the welded region makes up about 95 vol.% (Freundt and Schmincke, 1995). This differs from a lava flow, which has a solid interior with brecciated crusts on the top and bottom of the flow (Kilburn, 2000). Additionally, welded ignimbrites have a gradation in density, with density decreasing upward due to a decrease in load stress (Branney et. al., 1992). The physical properties of Layer A resemble those of a welded ignimbrite because it has a sharp basal contact with the underlying ash layer, does not have a basal breccia, and it exhibits a gradation in welding from densely welded towards the bottom to less welded at the top, with an ashy upper region. It also has a variation in columnar jointing near its base, exhibiting shearing and detachment from the jointing in the centre of the flow. This is particularly noticeable at the base of the radial joints. This can occur in ignimbrites when the base of the flow agglutinates to the ground, but the central region remains mobile. The particulate and non-particulate flows have different rheologies and travel at different velocities, causing the flow to become detached (Branney and Kokelaar, 1992). This could be the cause of the detachment and shearing of the columnar joints at the base of Layer A.
5.4 Geochemistry

Geochemical analysis shows that Layer A is anomalously low in SiO$_2$ content compared to the underlying lava flows and scoria cone. The Gran Canaria densely welded basaltic ignimbrite was deposited at a high temperature with low viscosity and 48 wt. % SiO$_2$ (Freundt and Schmincke, 1995). The Villa Senni Eruption Unit (VSEU) basaltic ignimbrite also had less than 50% SiO$_2$ (Watkins et. al., 2002). Therefore, it could be possible that Layer A, with a picrite basaltic composition and 45.5% SiO$_2$, could be an ignimbrite with low viscosity, similar to the Gran Canaria and VSEU basaltic ignimbrites. Although it is not a distinguishing characteristics, the anomalously low silica content indicates the possibility of a different eruptive nature than the underlying layers.

5.5 Rock Samples and Thin Section

Layer A contains pieces of flattened fiamme and deformed rock fragments. Mundula et.al. (2009) say that the presence of flattened fiamme is an indicator of compaction during welding in an ignimbrite. This is reasonable because samples WP58A and WP58B were taken from the bottom of a thick section of the unit while sample WP52A was taken from the bottom of a thinner section. The pumice is more flattened in the WP58 samples due to the greater overlying load stress. The rock samples contain scoria clasts and lava lithics within the ground mass, which is typical of an ignimbrite (Watkins et. al., 2002). Thin section analysis shows rock deformation, with squished clasts and ground mass crystals rimming around phenocrysts. Additionally, gradation in density and welding in ignimbrites causes a horizontal shear component that is large enough to align clasts within the flow (Watkins et. al., 2002). In sample WP58B, there are aligned bubbles that could have been caused by this horizontal shear component.

The alignment of the bubbles in the WP58B sample indicates the horizontal shear stress was acting along a NW-SE orientation, which corresponds to a NW-SE flow direction. This is consistent with the alignment of the radial columnar joints in the unit. There are radial patterns along the SE and NW sides of the rock unit, meaning the flow would have travelled along that orientation, filling in paleochannels as it went, forming radial columnar jointing patterns.

5.6 Emplacement of Welded Basaltic Ignimbrites

High-grade ignimbrites are formed when pyroclastic flows remain at a temperature well above minimum welding temperature during transport and deposition. High temperatures correspond to low magma viscosities, enabling particle coalescence and deformation to form a deposit that appears lava-like (Freundt and Schmincke, 1995). Mafic ignimbrites in particular are rare and are commonly unwelded with small volumes. There are only two documented cases of mafic pyroclastic...
flows that reached farther than 7 km downslope (Freundt and Schmincke, 1995). However, the Villa
Senni Eruption Unit (VSEU) ignimbrite has a morphology and internal structure similar to those in
more silicic ignimbrites, and thus Watkins et. al. (2002) suggests that ignimbrites from the entire
compositional spectrum are emplaced by similar processes. In the basaltic Gran Canaria welded
ignimbrite, the eruption was driven by buoyancy of the basaltic magma and degassing of felsic
magma (Freundt and Schmincke, 1995). The flow was density stratified and highly turbulent, which
prevented the collapse of the flow, making it look lava-like (Freundt and Schmincke, 1995).
Therefore, density stratified and highly turbulent pyroclastic density currents of basaltic composition
traveling with high temperatures and low viscosities will emplace welded basaltic ignimbrites in a
similar way that welded intermediate and felsic ignimbrites are deposited.

6 Conclusion

Layer A in Raupo Bay exhibits ignimbrite characteristics in that it pools in topographic lows and
mantles topographic highs, it has a sharp basal contact with broken columnar joints and it has a
gradation in welding from densely welded at the bottom to ashy at the top. Layer A also has a
significantly different composition than the underlying layers, and it contains flattened pumice and
rock fragments, aligned bubbles, and microlite rimming. It can therefore be concluded that Layer A is
a welded basaltic ignimbrite that was emplaced at a high temperature and low viscosity with a NW-
SE flow direction.

7 Future Work

Most reported mafic ignimbrites are small in volume (< 20 km³) with a small area extent (Watkins et.
al., 2002). There are only two documented cases of mafic ignimbrites traveling over 7 km from the
vent (Freundt and Schmincke, 1995). Therefore, future work for this project should include
continued field mapping of Layer A to determine the volume and areal extent of the flow to
determine if it is anomalous among welded basaltic ignimbrites.
8 Acknowledgements

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9 References

Banks Peninsula basemap from KiwiImage, taken by DigitalGlobe using the Quickbird II satellite.


## Appendix of Tables

| Character of Basal Breccia | Ignimbrites | Lava Flows |  |
|---------------------------|-------------|------------|  |
| Welding and Gradation | Zone of intense welding makes up most of unit. Gradation in density, with densest at bottom and ash at top (Freundt and Schmincke, 1999). | Solidified interiors with solid breaking crust on top and bottom of flow (Kilburn, 2000). |  |
| Relationship of Unit to Pre-Existing Topography | Thicken in valleys but also covers higher elevations (Freundt and Schmincke, 1995). | Restricted by topographic barriers (Henry and Wolff, 1992). |  |
| Nature of Distal Parts of the Flow | Thin to a few meters in distal regions (Henry and Wolff, 1992). | Thick to their margins with steep, abrupt flow fronts (Henry and Wolff, 1992). |  |
| Fiamme and Glass Shards | Presence of deformed/flattened fiamme and aligned glass shards in ignimbrites (Mundula et. al., 2009). |  |  |
| Columnar Jointing | Usually associated with lava flows, but sometimes a characteristic of ignimbrites (Temel et. al., 1998). |  |  |
| Flow Banding | Occurs in both lava flows and strongly rheomorphic ignimbrites (Henry and Wolff, 1992). |  |  |
| Pyroclastic Material | Can be present at the base of both a lava flow and an ignimbrite (Henry and Wolff, 1992). |  |  |

Table 1: Criteria that distinguish a lava flow from a welded ignimbrite and characteristics that cannot be used to distinguish between the two.
Appendix of Figures

Figure 1: (A) A map of Banks Peninsula showing the location of the study site, Raupo Bay, along the NE coast and (B) A map of Raupo Bay including the locations that rock samples were taken from.

Figure 2: (A) Southeast side of Layer A where the unit maintains a relatively uniform height of 3-4.5 m.
(B) Cross-section view of Layer A on the NE eroded cliffs where A thickens into a paleotopographic valley and mantles higher topography
(C) Northern side of Layer A where it mantles higher topography and things to 4-6 m over L2 and L3
Figure 3: (A) The zone of intense welding with columnar joints makes up most of the flow. (B) Layer A has a sharp basal contact, with broken, sheared columnar joints. (C) There is a density gradient from densely welded at the base to less welded at the top.

Figure 4: Radial jointing in Layer A formed in paleochannels, draping the pre-existing topography
Figure 5: Geochemical components of L1, L2, L3, and A plotted on a Cox-Bell-Plankhurst (1979) diagram show that Layer A is a picrite basalt with a significantly different composition than the underlying layers.

Figure 6: WP52A sample shows pieces of lava lithics (LL) as well as pumiceous scoria pieces (Sc). WP58B sample also shows pieces of pumiceous scoria as well as aligned flattened bubbles. WP58A sample shows scoria pieces, one of which has been flattened under load stress.
Figure 7: Photomicrographs showing ground mass crystal rimming around phenocrysts, air bubbles from scoria fragments, and flattened rock fragments.