Flow Emplacement Mechanisms of a Morphologically Complex Lava Flow

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Fall 2014

Abstract

Geomorphological, geochemical and thin section analysis have been undertaken on the morphologically complex lava flow that crops out along the Northwestern side of Raupo Bay, Banks Peninsula, New Zealand in an attempt to reconstruct its paleoflow pattern. The flow crops out as an anomaly amongst the otherwise flat-lying lava flows that are typical to the area. It has been interpreted as a basaltic andesite pahoehoe flow from the Akaroa vent that underwent an unusual sequence of evolution. This sequence created three very distinct features that can be seen today: a ramping feature, a large radially jointed face and a dissected pahoehoe lobe front. The ramping feature crops out on the western end of the outcrop, where the lava transitions from subhorizontal to vertical over the span of a few meters. It was created by a small lobe off of the main flow pouring over preexisting topography. The columnarly jointed feature is directly adjacent to the ramping feature and was formed when the same lobe flowed into a depression in the landscape and cooled without disruption. The dissected lobe front crops out along the eastern side of the outcrop and is a complex intermingling of pahoehoe tongues and toes with concentric banding of vesicles from shear stress along the front and sides of the feature. Since emplacement, it has undergone extensive erosion that exposed the center of the lobe. The complex geomorphology of the outcrop shows that the flow did not undergo the typical trajectory of a flat lying lava flow evolution, but moved across a complex paleotopography that influenced the emplacement mechanisms of the flow.

1. Introduction

Very little work has been done in the field of reconstructing flow mechanisms through the geomorphology of eroded outcrops. The focus instead has been on the geomorphology of active flow fronts and fields. Even in this field little can be concluded due to the stochastic nature of lava flow patterns. These random factors present fundamental difficulties in predicting flow behavior even with extensive knowledge of parameters such as topography, viscosity, and geochemical composition. Taking into account the indefinite nature of flow behavior, this study uses data from active flow fronts to determine properties of the emplacement of ancient flows.

Reconstructing paleoflow patterns may help to illuminate some of the stochastic influences on lava flow emplacement. Connecting the two areas of study allows for the field of volcanic geomorphology to broaden from areas of current volcanic activity to more accessible areas of past volcanic activity.

In order to accomplish this, this study focuses on a specific flow from Raupo Bay on Banks Peninsula, New Zealand, a region of flat-lying lava flows sourced from the Akaroa vent to the northwest. An exception to this trend is the morphologically complex lava flow that makes up the majority of the northwestern cliff face of the bay. Upon observation, it is obvious that this flow underwent a different evolution than the flows typical to the area. This research aims to understand why through reconstructing the paleoflow pattern of the outcrop in order to develop a model of the evolution of the lava flow and the topography present during extrusion.

The most striking aspect of the flow is its morphology, which is a complex jumble of features. Three features have been well preserved and aid in the reconstruction of the flow: a ramping structure, a radially jointed face, and a dissected pahoehoe lobe front. These features indicate very specific emplacement mechanisms and give insight to the landscape over which the lava was extruded.

2. Geological Setting

Banks Peninsula, shown in Figure 1 of the appendix, extends off the eastern coast of the South Island of New Zealand. The peninsula is roughly 50 kilometers long and reaches a height of 919 meters at its highest point, Herbert Peak. Its irregular topography and high abundance of bays along the periphery of the peninsula denote that it is no ordinary geomorphologic feature. The peninsula is the eroded remnants of two large stratovolcanoes that formed an offshore island through intraplate volcanism during the Miocene. The first of the two volcanoes to form was the Lyttleton Volcano, followed by the Akaroa Volcano. Extrusion of volcanic material occurred between 11-8 Ma. Postdating formation, alluvial fans fed by erosion have connected the originally offshore island to the mainland. The sea has since invaded it, dissecting the volcanic complex and carving out a multitude of bays along its margins.

Raupo Bay, a small bay in the northeast section of the peninsula between Stony Beach and Little Akaloa Bay. It is composed of lava flows from the Akaroa Group, which are dated to 9.6-8.6 Ma. (Dorsey, C.J., 1998) and are the most voluminous of the peninsula.

3. Methodology

A geochemical, thin section analysis and geomorphological approach was taken to reconstruct this flow.

For the geochemical portion of this study, a sample was taken from the ramping structure of the outcrop. It underwent geochemical analysis to identify the major and trace elements present in the rock. The computer program IgPet was then used to determine the lithology of the rock.

Thin section analysis was used to determine the flow type of the lava flow, stages of flow evolution, and the orientation of the ramping feature. To distinguish between pahoehoe and a'a flow the microlite crystal content was analyzed. Crystal density was used to show the evolution of the flow from four samples taken along the length of the flow. An unsuccessful attempt to determine the flow direction of the ramping structure through crystal orientation in thin section was made.

The geomorphological portion of this study was the dominant component. A complete photographic reconstruction of the outcrop was utilized to determine relationships between the geomorphologic features of the flow. Photos were stitched together using the computer program HugIn to create a detailed panoramic representation of the flow. Fifteen field sketches were collected and used to highlight aspects of the flow that were difficult to capture on film such as the concentric banding pattern of the dissected lobe front. The photographs and sketches were analyzed in conjunction with an extensive review of previous studies and literature pertaining to the reconstruction of volcanic outcrops through geomorphologic features.

4. Results and Discussion

4.1 Geochemical Analysis

Geochemical analysis was undertaken to calculate the percentages of major and trace elements present in the outcrop (see Figure 2 in the appendix for a summary). The lithology of the flow was determined as basaltic andesite through use of the computer program IgPet.

4.2 Thin Section Analysis

Four thin sections from samples collected along the length of the flow were analyzed to distinguish between an a'a and pahoehoe flow type. The samples were collected in the direction of movement, thirty meters apart, from both the center and margins of the flow. They indicate an increase in groundmass crystallinity, a characteristic typical to a flow undergoing the transition from an a'a to pahoehoe flow. The transition occurs under a series of textural changes, predominantly the growth of groundmass crystals such as microlite crystals that, when present at high enough levels, prevent the viscous and laminar flow typical to pahoehoe flow fields (Cashman et al., 1999). Figure 3 in the appendix shows the increasing crystallinity of the flow along a span of thirty meters.

4.3 Geomorphological Analysis

4.3.1Ramping Structure

The westernmost geomorphologic feature under study is a six-meter tall ramping structure where the flow changes from subhorizontal to vertical over the span of a few meters (Figure 4 in the appendix). An oriented thin section was collected from this locality and analyzed in an attempt to determine flow direction from the orientation of the groundmass crystals. This thin section can be seen in the bottom left corner of Figure 4. The thin section did not yield any strong conclusions, and the flow direction was instead concluded from geomorphologic evidence. At the base of the ramping structure the feature exhibits a downward, radial pattern, indicative of the flow cascading onto a relatively flat plane and spreading out. It is assumed that a lobe formed off of the front of the flow and cascaded off of the flow plane and into an area of topographic relief. This area of relief was probably a flat area that was out of the flow path of previous flows in the area, or the location of intense erosion. When the lobe cooled the ramping structure was preserved, and the rest of the flow has since been eroded.

4.3.2 Radially Jointed Face

Directly adjacent to the east of the ramping structure is a seven-meter wide and five-meter tall outcrop of large columnar joints formed in a radial pattern. In order to form such well developed columnar joints the lava must have been subject to a long, undisturbed cooling process. Cellular convection of heat during the cooling process allowed for the propagation of cooling joints perpendicular to the cooling surface, as shown in the upper portion of Figure 5 in the appendix. The length of time without disturbance required to form these joints is unique to the rest of the flow. The radial pattern of the joints is indicative of a concave cooling surface such as a depression in the ground where joints would propagate inwards and up. Figure 5 depicts the 'imagined cooling surface' of this feature in the bottom photograph.

The continuity of the radially jointed feature with the ramping structure indicates that after the flow cascaded down from its higher elevation, a small amount of it settled into a depression and became isolated from the rest of the flow. This isolation resulted in the uniform cooling process that formed the large radial joints in Raupo Bay. The presence of this feature indicates that the surface onto which the ramping structure cascaded was not entirely flat, but contained some depressions.

4.3.3 Dissected Pahoehoe Lobe

The easternmost geomorphologic feature under study is a large pahoehoe lobe front that has been dissected by wave erosion. Lobate flow fronts occur commonly in pahoehoe flow fields when rates of crustal deformation are high relative to flow front advance (Cashman et al. 1999). Under specific conditions the crust may rupture and a tongue of lava can protrude from this tear in the lava crust. Pahoehoe tongues may extend for several hundreds of meters and start to develop their own feeding channels before they crust over and extrude small lava toes. Budding tongues may continue to extrude to produce a complex pahoehoe flow front that is gently uplifted by newly arriving lava (Kilburn, 2000). This process is what occurred in Raupo Bay. The large structure that exhibits the concentric banding pattern shown in Figure 5 is an eroded pahoehoe tongue. The smaller, chunky features below and to the west of this structure are the small pahoehoe toes that extruded after the tongue and gently uplifted it. Post-emplacement of the pahoehoe lobe front wave erosion dissected the feature and exposed the cross sectional view that can be seen today.

The cross sectional view exhibits the well-preserved concentric banding pattern present on the interior of the lobe. This pattern is formed by the alignment of vesicles on a minute scale along the direction of flow of the lava that occurs when the lava cools from the outside-in and the solidified crust of the lobe imposes a shear stress on the still molten interior. This process results in a pattern of vesicle alignment reminiscent of the layers of an onion (Calvari and Pinkerton, 1999). The cross sectional view of this alignment and even distribution of vesicle size and shape across the outcrop show that the feature was dissected perpendicular to its flow direction. This provides evidence that the lobe came off of the northeast-trending lava flow front and moved to the southeast.

4.4 Sequence of Flow Evolution

Reconstruction of the flow emplacement mechanisms present in the outcrop shows that Raupo Bay had an uneven preexisting topography that presented obstacles for the pahoehoe flow front as it moved across the landscape. This led to the morphologically interesting features that are seen today. The flow began trending north-northeast as a typical flat lying flow. A lobe protruded from its front and cascaded into an area of topographic relief, cooling to form the ramping structure. A portion of this lobe was then cut off from its source, and settled into a small depression where it cooled under undisturbed conditions. This uniform cooling period formed large cooling joints that crop out in a radial pattern. As the rest of the flow continued trending north-northeast, another lobe protruded, moving to the southeast. As this lava cooled tunnels of pahoehoe tongues and toes extruded underneath its base and gently uplifted the structure. It has since been eroded, revealing a well preserved cross section of a pahoehoe lobe. It is assumed that the flow continued on from this location, though it becomes inaccessible without a boat shortly after the dissected lobe feature.

5. Conclusions

Extensive study has been undertaken in the field of geomorphology of active flow fronts, but little has been done on reconstructing flow patterns from geomorphologic evidence. This study used the field observations and processes observed in active flow fronts to reconstruct a Miocene-aged flow by merging the two fields of study. It is hoped that the techniques outlined by this study will be used in the future in order to better understand the paleotopography of Banks Peninsula as well as globally, where the only evidence of volcanic activity is the geomorphology of ancient lava flows.

The fact remains that lava flows exhibit random and unpredictable behavior during emplacement. There are stochastic as well as topographic controls on flow dynamics, but if we can better understand the results of these stochastic controls then maybe we can begin to understand the causes of these random processes.

Acknowledgments

Thank you to all of the Frontiers Abroad Geology staff for providing me with the opportunity to undertake this research and for making this semester equal parts fun and informative. A special thanks to Dr. Samuel Hampton and Dr. Darren Gravley for their tremendous help both in the field and in the classroom.

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(Appendix on following page)

Appendix

FIGURE 1 Raupo Bay in the context of Banks Peninsula. The outcrop under study is outlined in red on the northwestern cliff face of the bay.

Sample Number	XRF Sample Number	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	Loss of Ignition (%)	Total (%)	Lithology
RBJRA	35823A	45.84	3.55	17.73	16.03	0.17	5.22	6.93	2.91	1.06	0.56	2.92	100.0	Basaltic Andesite

Figure 2 Results from the geochemical analysis of sample RBJRA, sourced from the ramping structure, showing the percentages of major and trace elements present in the flow. This data was corrected for the Loss of Ignition and then run in the program IgPet to determine the lithology of the rock type as basaltic andesite.

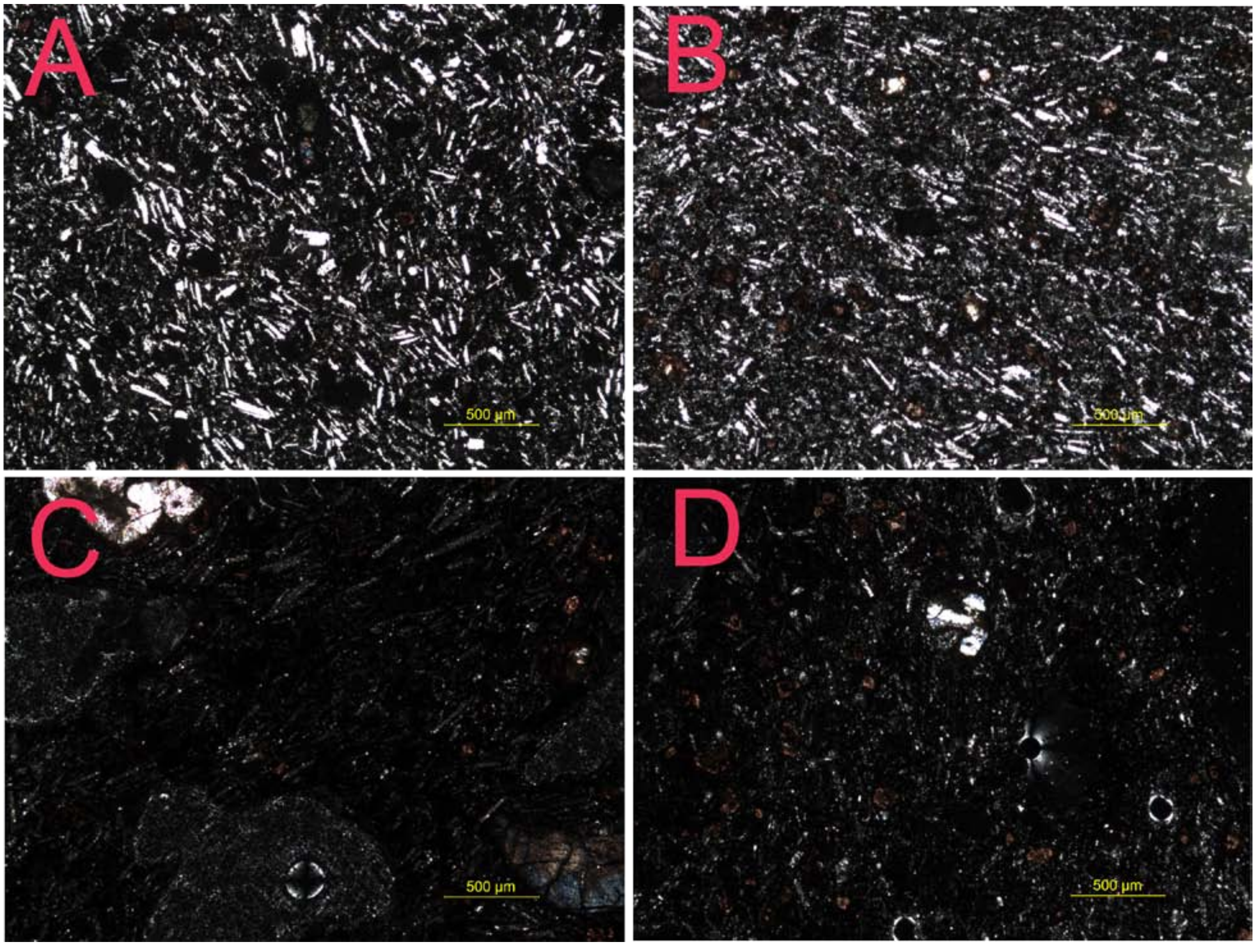

FIGURE 3 Thin sections taken along the length of the flow from both the rubbly and massive portions of the flow showing the increase of groundmass crystallinity. (A) and (B) are from the massive part of the flow, (B) is sourced 30 meters down-flow from (A) and shows an increased crystal density. (D) is sourced 30 meters down-flow from (C) and also shows an increase in crystal density

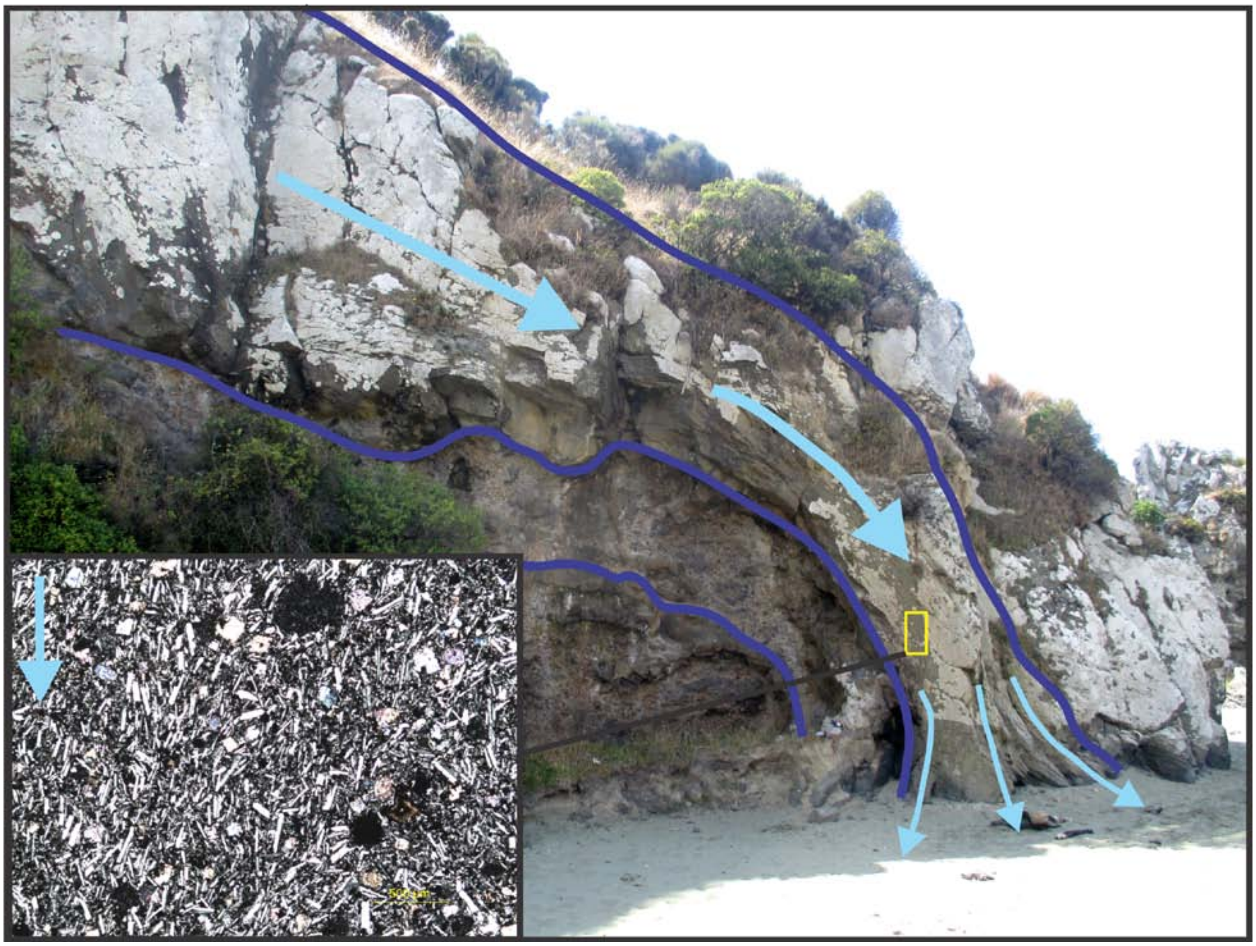

FIGURE 4 The ramping structure on the westernmost section of the outcrop, with flow boundaries marked in dark blue. At this location the flow makes a rapid transition from subhorizontal to vertical as a lobe plunges from the main body of the flow into an area of topographic relief. Bottom left corner: thin section used in an attempt to determine flow direction by crystal orientation.

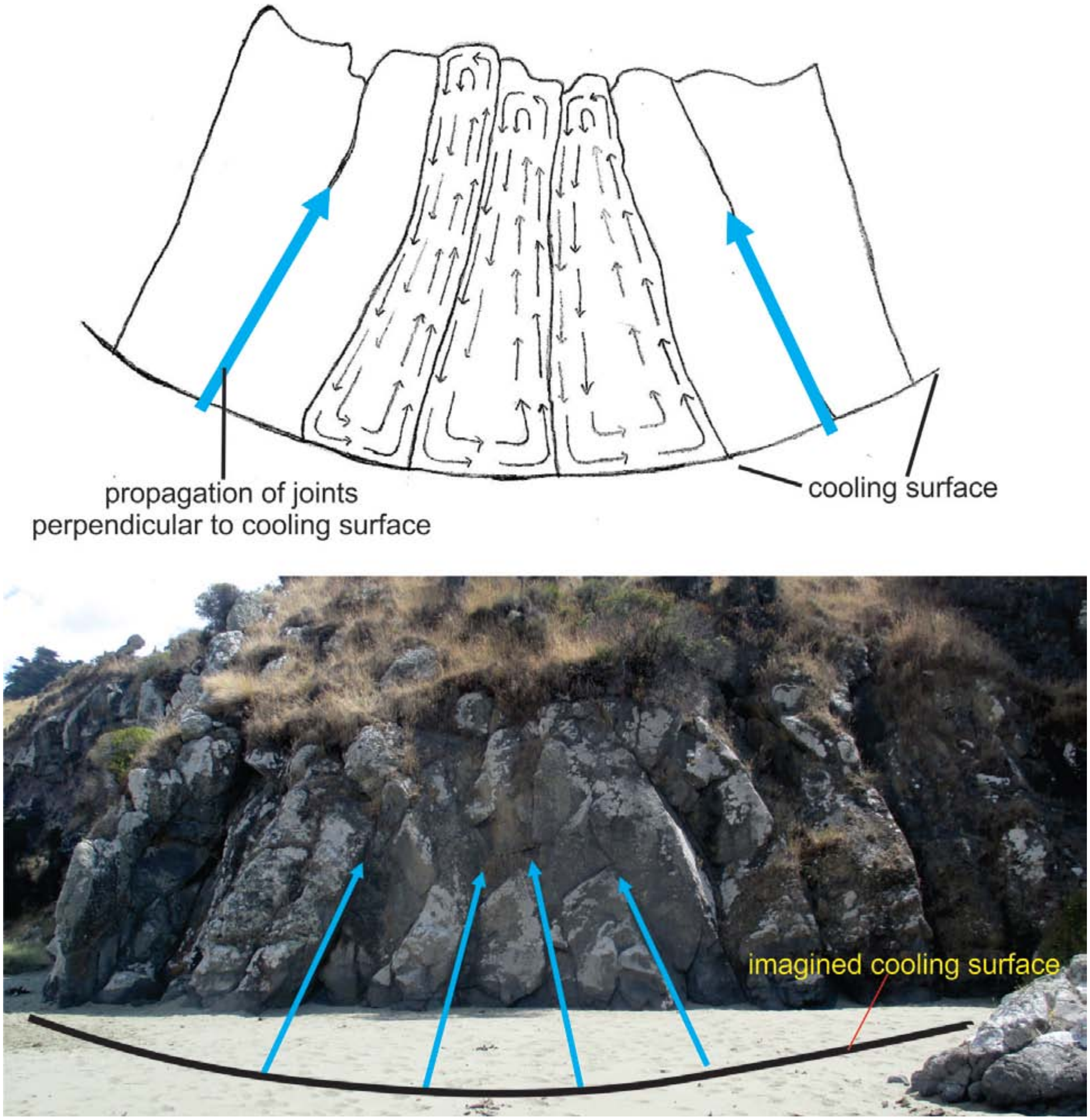

FIGURE 5 Top: schematic of the formation of cooling joints perpendicular to the cooling surface through cellular convection of heat. Bottom: radially jointed face in Raupo Bay, just east of the ramping structure, with the imagined cooling surface outlined in black, and the columnar cooling joints marked in light blue.

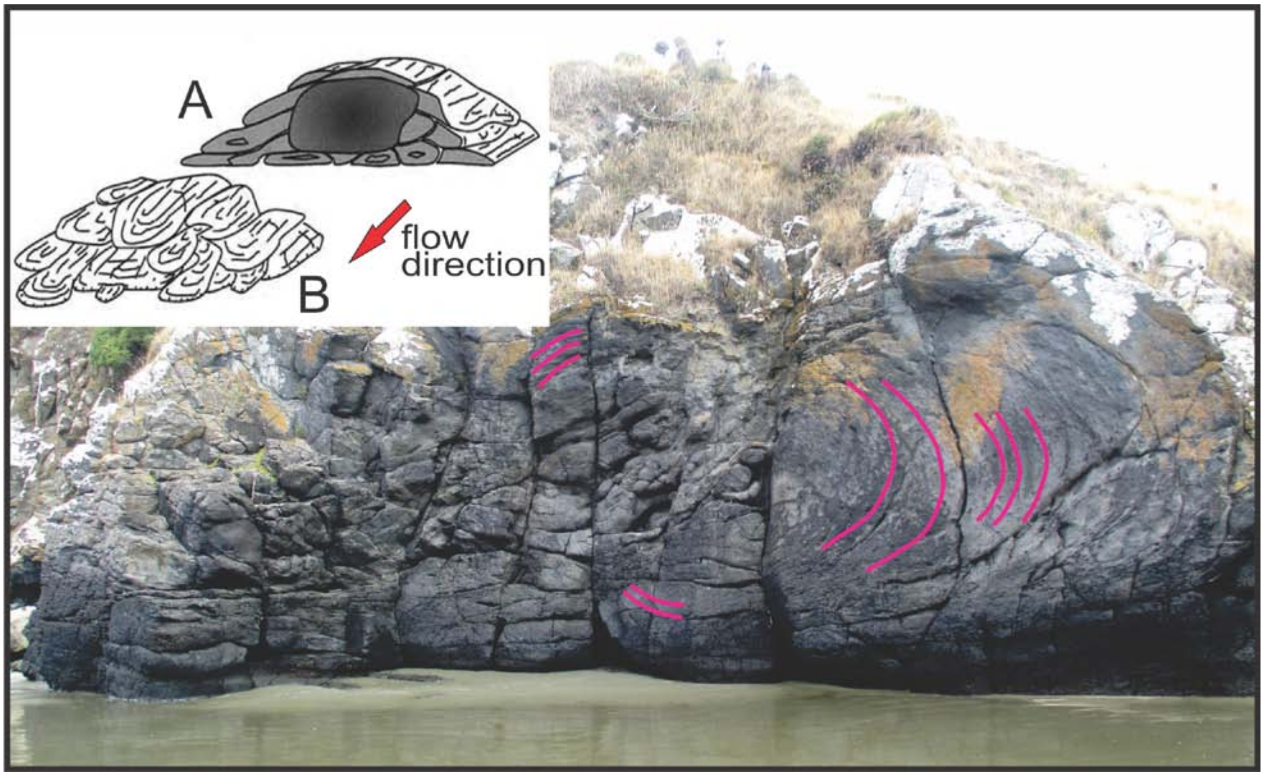

FIGURE 6 Dissected pahoehoe lobe feature and schematic diagram of formation. The pink lines show the concentric banding pattern on the feature. In the schematic diagram, modified from Kilburn (2000), (B) Shows pahoehoe lobe formation prior to erosion, and (A) shows a generalized cross section of a pahoehoe lobe with intermingling tongues and toes.