Scoria Cone Analysis in Le Bons Bay, Banks Peninsula, New Zealand

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ABSTRACT: Akaroa is a large composite strato-shield volcano comprised of multiple eruptive centers and many parasitic cones that formed as a result of intraplate volcanism during the Miocene. Previously unknown scoria deposits on the flank of Akaroa Volcano on the Banks Peninsula in Le Bons Bay are well exposed at the shore platform, and are useful in understanding volcanic processes in the area. Scoria cones have not been studied in great detail in the Banks Peninsula, but provide valuable insight into the history of Akaroa as they relate to the parent volcano’s magma plumbing system and stress orientations that control the location of vent formation. Stratigraphic columns based on field data and observations were created at three locations along the shore platform of Le Bons Bay in order to understand the formation of the scoria cone and how it relates to Miocene volcanism at Akaroa. The stratigraphic columns suggest a series of very rapid and localized Hawaiian and Strombolian eruptions fed by a feeder dike. Dip angle and direction suggests the vent of the cone is located in the embayment northeast of the study area. The cone’s height is estimated to be in the range of 0.054-0.0972 km. This cone is representative of the range of deposits from Akaroa volcanism, as it is significantly smaller and displays different eruptive sequences than other cones in the area.

INTRODUCTION
Newly discovered scoria deposits on the flank of Akaroa volcano are well preserved on the exposed shore platform in Le Bons Bay, Canterbury, New Zealand (figure 1). Akaroa, the larger of the two composite shield volcanoes on the Banks Peninsula, formed 9.3-8 Ma as a result of intraplate volcanism (Timm et al., 2009). Akaroa, as well as its older counterpart, Lyttelton, have historically been viewed as simplistic volcanoes, and as a result, knowledge regarding the Banks Peninsula’s formation is somewhat limited. Recent studies suggest that Lyttelton, and therefore Akaroa, are volcanic complexes comprised of multiple eruptive centers of significant complexity (Hampton and Cole, 2009). Scoria deposits at Le Bons Bay are useful in understanding scoria
cone formation and volcanic processes in the Banks Peninsula, as they are fed by lateral dike
injections that originate from the parent volcano’s main magmatic chamber (Hampton and Cole,
2009; Shelley, 1988). Therefore, scoria cones reflect major stress fields that control vent
formation and may also be useful in understanding the tectonic controls of volcanism (Ring and
Hampton, 2012). Currently, few studies on scoria cones in the Banks Peninsula have been
conducted.

This study aims to gain a deeper understanding of Akaroa by analyzing one of its parasitic
cones by utilizing field data to create three stratigraphic logs that recreate vertical and lateral
change away from the cone’s vent. These logs are useful in understanding flank explosive
activity on Akaroa. Four volcanic lithofacies are identified based on the variable deposits seen in
the field. The cone’s height is estimated based on the dip angle, and its vent is located by
studying dip direction as well as geomorphological features in the area. This study is significant
to the understanding of Akaroa, as it adds detail to the existing geologic map of the area and the
identified volcanic lithofacies may be useful in identifying other scoria cones.

GEOLOGIC SETTING

Miocene-aged volcanism on the Banks Peninsula primarily resulted in the formation of the
Lyttelton and Akaroa composite volcanoes, but is also responsible for two smaller volcanic
deposits: the Mt. Herbert Volcanic Group and the Diamond Harbor Volcanic Group (Sewell,
1988; Ring and Hampton, 2012). The Lyttelton Volcanic Group was the first to form, and
consists of rocks ejected from 11-9.7 Ma. The Mt. Herbert Volcanic Group, aged 9.7-8.0 Ma,
represents a transitory period between Lyttelton and Akaroa phases of eruption. These deposits
represent late-stage volcanism from the Lyttelton Volcano. The Akaroa Volcanic Group formed
between 9.0 and 8.0 Ma on the southeastern end of the Banks Peninsula. Diamond Harbor
deposits were ejected between 7.0 and 5.8 Ma as a series of monogenetic events in and around
the Lyttelton crater, similar to the volcanic setting in modern-day Auckland, potentially as a
result of slight changes in the region’s stress field (Sewell, 1988, Ring and Hampton, 2012).

The formation of Lyttelton and Akaroa as well as their late-stage counterparts, Mt. Herbert
and Diamond Harbor, is attributed to one two-stage or two smaller separate lithospheric
delamination events that occurred as a result of intraplate volcanism (Timm et. al, 2009). As a
result of previous subduction activity, the lithosphere under which the Banks Peninsula was
formed became enriched in dense crystals and material. This caused the lithosphere to sag into the asthenosphere, allowing molten material to rise to shallower depths, resulting in localized volcanic eruptions (Timm et. al, 2009). Vent locations on Akaroa are primarily controlled by the motion of the Pacific Plate as well as changing fault kinematics associated with the Mid Canterbury Horst and pre-existing fault trends (Ring and Hampton, 2012).

To date, the most comprehensive study of scoria cones in the Banks Peninsula was conducted by Johnston et al. (1997). The authors studied scoria deposits located in Pigeon Bay, located northeast of Le Bons Bay. The authors defined four distinct lithofacies: ash-rich deposits, nonflattened scoria deposits, mixed scoria deposits, and densely welded scoria deposits, which were used as the basis for the volcanic facies proposed in this paper. Pigeon Bay deposits reflect Hawaiian and Strombolian eruptions that grew ashier and less welded away from the eruptive center (Johnston et al., 1997).

METHODS
Data was collected in the field in February, 2014 using the iPad application GeoFieldBook (Malinconico et. al, 2013) in addition to a traditional field notebook. Field methods include:

1. Determining aspect ratios of bombs, lapilli, and ash
2. Measuring the five largest clasts in an approximately 2-meter square
3. Approximating the thickness of each layer
4. Taking strike and dip measurements, where possible
5. Documenting vertical and lateral change through photographs.

Four distinct volcanic lithofacies were identified using the collected field data (figure 2). Three stratigraphic columns were created using CorelDRAW X6 at three distinct locations that were the most representative of both vertical and lateral change along the shore platform.

Measured strikes and dips were plotted on a map in order to observe the trend of the scoria deposits, the diameter of the cone, and to locate the potential position of the vent. The scoria cone’s height can be estimated if the diameter is known using the equation:

\[ H_{co} = 0.18W_{co} \] (Porter, 1972)
Where $H_{co}$ represents the cone’s height and $W_{co}$ represents the cone’s width. The estimate of this cone’s diameter is based on dip angle and direction in the study area, and constrained by scoria deposits capped by a large lava flow across the bay.

**VOLCANIC FACIES**

Volcanic lithofacies of the Le Bons Bay cone are identified using deposit descriptions and modeled, with slight modifications, after those proposed by Johnston et al. (1997). These lithofacies are based on clast size and aspect ratio, and are as follows: (1) nonflattened scoria deposits, (2) mixed scoria deposits, (3) densely welded scoria deposits, and (4) bomb-dominated layers.

**Nonflattened Scoria Deposits** are clast-supported with little to no ash. Clasts are dark grey to black and ash ranges from red-brown to red-orange. These deposits are often massive, but may exhibit coarsening-up sequences. Nonflattened scoria deposits are dominated by lapilli, with bombs comprising of up to 30% of the total composition and averaging 20-60 centimeters in diameter, but reaching up to 1 meter in size. Deposits are predominately not flattened, although a small percentage of clasts may exhibit slight flattening. Deposits exhibit little welding.

**Mixed Scoria Deposits** are categorized of grey and black bombs and lapilli in a matrix of red-orange to yellow ash. These deposits are poorly sorted, as they are composed of clasts that range from fine ash to bombs that range in size up to 1 meter. Lapilli are not flattened, however, both flattened and non-flattened bombs can be present. Bedding is common in these deposits; lapilli banding and grading are frequently observed.

**Welded Scoria Deposits** are comprised of grey, vesicular lapilli and bombs densely welded and heavily eroded. This type of deposit was only observed once in the Le Bons Bay cone, towards the top of the observable deposits on the shore platform, directly below a lava flow. These deposits, therefore, may be the rubbly base of a small lava flow sourced from the cone’s vent.

**Bomb-dominated Scoria Deposits** are not included in Johnston et al.’s (1997) analysis of Pigeon Bay, but are abundant enough in the Le Bons Bay cone to warrant their own category.
These layers are composed of >50% bombs, with the largest generally exceeding 2 meters in diameter. These bombs are grey, vesicular, and rarely flattened. The bombs are preserved in a matrix of lapilli and red-orange ash.

DATA AND INTERPRETATION

Stratigraphy (figure 3)

Six distinct scoria deposits as well as a lava flow and an ash layer were observed on the shore platform. Due to significant lateral change, three stratigraphic columns at distinct locations were created (figure 4).

Column A is the most proximal stratigraphic log, as deposits in this area have the steepest dip angles. Scoria Deposit 1 most closely fits into the nonflattened scoria deposit category, although a few flattened bombs were observed directly below the sharp contact with Deposit 2, which may represent a transitory stage during the eruption. A large wall rock xenolith was found in this deposit, indicating that it is very close to the eruptive source. Deposit 2 is a mixed scoria deposit dominated by ash, with some lapilli and bombs. Bombs increase in size up the section; some display flattening.

Column B records the central stratigraphic log. Four distinct scoria packages are visible. The bottommost layer is Deposit 1, with slightly more bombs and somewhat fewer lapilli than the same deposit recorded in Column A. Deposit 1 is still massive, but does not exhibit any flattening seen in Column A. Scoria Deposit 2 displays distinct lapilli banding (figure 5), indicative of several pulses of eruption. This banding was not seen in Column A, likely because the smaller lapilli were able to travel farther from the eruptive center. There is more lapilli and fewer bombs in Column B than Column A. Scoria deposit 3 is clast supported and contains >70% bombs that are, on average, greater than 2 meters in diameter. The bombs are in a matrix of red-brown ash. This deposit is representative of increasing explosivity from the vent. Scoria deposit 4 is also classified as a bomb-dominated deposit, as it is clast supported and contains roughly 60% bombs greater than 2 meters in diameter in a matrix of red-orange ash. Slight reverse grading was noted.

Column C is the southeastern-most column. The lowest member is Deposit 4, which has significantly more small bombs and lapilli than the same deposit in Column B. This deposit
preserves >80% bombs with a very significant coarsening-up sequence. This deposit is capped by a 10 centimeter thick ash layer that dips 5º N. This ash layer has an undulatory contact with scoria Deposit 5, a mixed scoria deposit with yellow ash, lapilli bands and flattened bombs. Ash decreases and lapilli increases up the section, with few flattened bombs dispersed throughout. Above this layer is a welded scoria deposit capped by a lava flow with bubbles orientated NE-SW (figure 7). This flow is likely sourced from this scoria cone vent. The welded scoria may or may not be the flow’s rubbly base.

Several trends were noted across the shore platform; the following generalizations can be made:

(1) The ash layer between deposits 4 and 5 had a significantly different dip and dip direction from the other deposits. It is inferred that this layer is sourced from another local vent during a pause in eruption in the studied cone.

(2) Bomb size over time suggests that the cone’s most explosive phases were in the middle of its eruptive history. Bombs were largest and most prevalent in Deposits 3 and 4, after which bomb size and percentage decreased rapidly, implying that the vent grew less explosive fairly rapidly.

(3) Ash content generally increases over time. This is common in scoria cones, as most of the magmatic material is ejected in the early eruptive phases.

(4) Bedding is relatively common throughout the entire section, suggesting that there were small pulses of eruption over time with larger ‘hiccup’ resulting in the deposition of larger bombs and massive deposits.

Scoria Cone Vent and Injection Site

Measured dips shallow to the southwest, implying that the vent is northeast of the study area. Dips on the accessible areas of the shore platform range from 17º SW to 10º SW. Based on dip angle and direction, the scoria cone’s vent is approximated to have been in or near the embayment shown in figure 8. To the east of this location, dip angle is roughly northeast, as opposed to southwest. The extent of scoria deposits to the northeast can be constrained by large lava flows seen in figure 8. As these deposits are quite localized, they were likely sourced from a single point rather than a fissure. There are several dikes throughout the field area, however they all crosscut all of the scoria deposits, and were therefore emplaced after the eruptive sequence.
Scoria Cone Size

Accurately estimating the scoria cone’s diameter presents a unique challenge, as it was impossible to walk out the extent of the deposits during field research. Therefore a range of diameters and accompanying heights is presented here:

<table>
<thead>
<tr>
<th>DIAMETER (KM)</th>
<th>HEIGHT (KM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAXIMUM</td>
<td>0.30</td>
</tr>
<tr>
<td>MINIMUM</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Diameter estimates are based on radius measurements from the proposed eruptive center. The minimum radius is the extent from the embayment to the area just past the field area, where dips continued to decrease towards the southwest. The maximum estimate is theoretical, and based off of the hypothesis that vents tend to be located in areas that are more heavily eroded than others, especially embayments. Therefore, this measurement extends to the break in the shore platform before the next embayment (figure 9). The range determined in the above table may be a slight underestimate, as the studied scoria cone is heavily eroded. Despite the erosion, this cone is much more localized than other cones observed in the Le Bons Bay area.

DISCUSSION

Cone Formation

The bottommost layer of this cone records Hawaiian-style eruptions, as it is comprised of vesicular clasts that are reasonably well sorted. Hawaiian eruptions typically feature clasts that are more sorted than Strombolian eruption, as they are less explosive, causing less magma fracturing. Deposits 2 through 6 are moderately to poorly sorted, and likely the product of explosive Strombolian eruptions. Deposits 2 and 5 do, however, have small sections of very well sorted lapilli, which will be discussed further in the next section. The cone underwent several phases of eruption, with the most powerful eruptions represented by deposits 3 and 4, which record the largest bombs and the highest ratio of bombs. Contacts between distinct deposits were sharp (figure 10) with the exception of Deposit 5’s contact with the ash layer and Deposit 6’s contact with the lava flow. The nature of these contacts suggests that the distinct eruptions
occurred rapidly after one another, so there was little time for erosion between eruptions. There is no evidence for unconformities, as there are no changes in dip between deposits, nor are there any visible erosional features at the contacts. Sharp contacts also imply very distinct changes in the eruptive style. The change in style could be accounted for in several ways, although it is most likely a factor of changing volatile content and composition over time.

**Phreatomagmatic Eruptive Activity: An Alternate Hypothesis**

Deposit 5 records yellow ash with distinct lapilli bands, a feature that may be seen in phreatomagmatic eruptions. Houghton and Schmincke (1989) observed ash fall beds with occasional bands of lapilli in the Rothenberg scoria cone, which they classify as phreatomagmatic. However, palagonite ash and phreatomagmatic activity are not mutually exclusive, nor has lapilli banding been established as a distinguishing factor of phreatomagmatic activity. Yellow ash could imply erosion or interaction with water at some stage. Geochemical research is required to determine the eruptive style of this deposit.

**Relationship to Other Cones in the Banks Peninsula**

Although this cone features very similar lithofacies to the cones studied by Johnston et al. (1997), the two areas record significantly different eruptive histories. The scoria cone at Pigeon Bay gets less welded and ashier toward the outer facies of the cone. This cone did not display a particular trend in terms of welding and had some of its most eruptive deposits toward the end of its eruptive sequence. This is likely a product of the volatile condition in the vent.

**Limitations and Future Research**

Due to the cone’s location along the shore platform, it was not possible to get a holistic view of the section from across the bay. A particularly strong swell during field research severely limited the time that it was possible to access the shore platform. With access to a boat, future studies could focus on gathering more detailed data to get a more accurate estimation of the cone’s size and extent. Another useful study would involve studying this cone with aerial photographs, and using its features to attempt to locate other cones in the area. Scoria cones are abundant on the shore platforms of the Banks Peninsula, and mapping them would add a significant amount of detail to
the existing map of the area as well as provide interesting areas to visit if the area were to be classified as a GeoPark.

**CONCLUSION**

The scoria deposits preserved on the shore platform of Le Bons Bay record a series of Hawaiian to Strombolian eruptions, likely formed very rapidly. The cone is quite localized, with a diameter between 0.30 km and 0.54 km and height between 54 and 97 meters. and shows the variability of It records similar deposits as other cones in the area, however, it is unique in that its highest level of explosivity occurred during the middle of its eruptive sequence rather than the beginning. There are sharp contacts throughout the section, implying rapid change in eruptive styles over time.

**ACKNOWLEDGMENTS**

I would like to thank Darren Gravely, Sam Hampton, and James Cowlyn for the input and advice on this project, my field group: Erin Markey, Abra Atwood, and Liz Bertolett for their hard work, support, and positive attitudes during field research week, the Frontiers Abroad program for providing me with this exciting and unique opportunity, and the FA 2014 Family for an unforgettable experience in New Zealand.
REFERENCES


APPENDIX OF FIGURES

**Figure 1:** a) Map of Banks Peninsula, Le Bons Bay marked with yellow dot. b) Detail map of Le Bons Bay. Study area is marked.

**Figure 2:** Table of data with field descriptions from each scoria deposit and its corresponding volcanic lithofacies

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Description</th>
<th>Lithofacies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grey-black bombs and lapilli with little to no ash. Bombs are flattened near the vent. Poorly sorted. Coarsens up Slightly more bombs were observed in medial areas than proximal areas. Medial bombs (40-60 cm diameter) were larger than proximal bombs (20-30 cm diameter), which may be due to slip.</td>
<td>NSD</td>
</tr>
<tr>
<td>2</td>
<td>Grey-black bombs in a matrix of red ash with lapilli banding. Largest bombs range from 30-40 cm, with one 110 cm bomb. Lapilli bands are &gt;10 cm thick and occur very regularly in the upper half of the deposit.</td>
<td>MSD</td>
</tr>
<tr>
<td>3</td>
<td>Approximately 70% bombs. 5 largest bombs are over 2 meters in diameter. Clast dominated, although the deposit contains roughly 25% ash. Massive.</td>
<td>BDD</td>
</tr>
<tr>
<td>4</td>
<td>50-60% grey, vesicular bombs in red-orange ash. 5 largest bombs are over 2 meters in diameter. 30% ash. Clast dominated. Distinctive coarsening up trend; no bedding within the deposit.</td>
<td>BDD</td>
</tr>
<tr>
<td>A</td>
<td>10 cm thick red-orange ash layer that directly overlies deposit 4. Dips 5 N and is inferred to be sourced from another local scoria cone. Pinches out towards the northeast.</td>
<td>Ash Layer</td>
</tr>
<tr>
<td>5</td>
<td>Flattened, vesicular bombs and banded lapilli in a yellow ash matrix. Largest bombs range from 25-90 cm in diameter, with one bomb measuring 120 cm. Matrix supported. Few bombs. Sequence begins with a yellow ash layer, which is topped by bombs and lapilli bands. Fines upward.</td>
<td>MSD</td>
</tr>
<tr>
<td>6</td>
<td>Densely welded scoria or rubbly base to lava flow. Undulatory contact with Deposit 5. Five largest clasts range from 15-40 cm in diameter.</td>
<td>WSD</td>
</tr>
<tr>
<td>B</td>
<td>Small (0.5-1 meter thick) lava flow with aligned vesicles. Vesicles indicate a roughly NE-SW orientation, suggesting that it may be sourced from this scoria cone vent. 15-20% vesicles, 1-2 cm in diameter</td>
<td>Lava Flow</td>
</tr>
</tbody>
</table>
Figure 3: Stratigraphic columns and clast point counts for the three localities depicted in figure 2. NSD - nonflattened scoria deposits. MSD - Mixed scoria deposits. WSD - welded scoria deposits. BDD - bomb dominated deposits. Numbers correlate to stratigraphic deposits detailed in the table below. Scale is approximate and based on rough field measurements.
Figure 4: Fence diagram depicting stratigraphic arrangement of deposits at Le Bons Bay. Different units were observed at each location due to the dip angle of the deposits. Scales are approximate.

Figure 5: Lapilli banding seen in Deposit 2, suggesting several small pulses of eruption over time.
Figure 6: Photos showing the NE-SW lava flow and its undulatory contact with Deposit 6, which may be either welded scoria or the rubbly base to the lava flow.
Figure 7: Geologic Map of study area in Le Bons Bay. Dip angle used to approximate diameter of the cone. Vent is proposed to be in the embayment seen to the east of the study area.
**Figure 8:** Photo of lava flows topping scoria deposits to the east of the study area. This is useful in constraining the extent of scoria deposits from this cone. The bottom photo shows detail of the scoria deposits; most is covered by the lava flow, with the only visible scoria deposits marked by a white line.
Figure 9: Map showing break in the shore platform near study area. Inferred to be the maximum extent of scoria deposits.
Figure 10: Left: contact between deposits 1 and 2, marked by line. Right: Ash layer between deposits 4 and 5.