Parasitic Cones of Western Pa Bay, Banks Peninsula, NZ

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\textbf{ABSTRACT}

Akaroa Volcano is a large extinct strato-shield volcano comprised of one or more central vents, with smaller parasitic vents located around its flanks. Previously undocumented deposits from five parasitic cones have been discovered in Pa Bay. This study focuses on the cones in western Pa Bay. The deposits display a range of small-scale explosive styles, including Hawaiian, Strombolian and phreatomagmatic eruptions, from both point sources and eruptive fissures. These deposits are grouped into four lithofacies to assist in the physical volcanological interpretations: 1) \textit{Varially Welded and Flattened Scoria} 2) \textit{Non-Welded and Non-Flattened Scoria} 3) \textit{Phreatomagmatic} 4) \textit{Intrusives}. In NW Pa Bay, a thin sequence of phreatomagmatic beds dipping SE is the only evidence of an older, eroded cone. This is unconformably overlain by a sequence of variably welded and flattened scoria deposits whose dips radiate away from a point source west of Pa Island. A westward trending dike exposed on Pa Island is proposed as a possible source for this cone. The northwestward dipping, non-radiating deposits in SW Pa Bay imply fissure-fed eruptions from a source in the middle of the bay. Similar textures and a conformable contact between the NW and SW cones implies the two were erupted within a short time period, and from a similar magmatic source. Two other parasitic cones are identified in Pa Bay, one in the SE, and one in the NE. Few flank vents have previously been identified on Akaroa Volcano. This work extends the record of Akaroa flank volcanism, and provides a useful analysis of flank activity that can be applied to modern day hazards from parasitic vents worldwide.
1. INTRODUCTION

Parasitic vents occur when magma is erupted on a volcano’s flanks rather than through a central conduit, and hence represent a surface expression of a diverse internal plumbing network of dykes and sills. Typically, the erupted material is laterally drained magma from the central conduit. However, dykes independent of the central vent can also produce flank eruptions (Acocella & Neri, 2003). The pathways of flank-erupted magma can heavily depend on tectonic control, where dykes follow planes of weakness dictated by tectonic pressure (Acocella & Neri, 2003; Hampton, 2010). Parasitic vents can occur as a point source or fissure, accumulating material around the vent to form a parasitic cone. They erupt proximal pyroclastics and extensive lava flows. Point source eruption typically form scoria or spatter cones. Fissures commonly begin with laterally continuous magma extrusion, but may evolve to concentrate at single points as parts of the fissure are blocked by cooled magma (Bruce & Huppert, 1989).

Several flank eruption deposits have been identified on Akaroa Volcano—namely scoria deposits at Okains Bay and four scoria cones at Pigeon Bay (Johnston et al, 1997; Muller, 2012; Shirley, 2012). These are characteristic of small volume parasitic eruptions from basaltic volcanoes, and include deposits from Hawaiian, Strombolian and phreatomagmatic eruption types:

Hawaiian style eruptions are the least violent eruption style. Low viscosity basaltic magma becomes coupled (rises at the same speed) with exsolved gas, and is extruded at a relatively continuous rate to produce lava fountains and flows (Vergnoille & Mangan 1999). Eruptions can last from minutes to years (Fisher & Schmincke, 1984), and may end with a change to another eruption style (Vespermann & Schmincke 2000). Lava typically lands hot to produce welded spatter, or may completely re-combine to form lava flows. Relict clast textures, fluidal and flattened clasts are common features of these deposits.

Strombolian style eruptions are more violent and characterized by short-lived pulses of eruption (Vergnoille & Mangan 1999). Stagnant or slow-moving
viscous magma is decoupled from faster moving bubbles, which coalesce to form large gas slugs that burst at the surface. With these slug bursts, the magma is fragmented violently and ejected, forming bomb-lapilli sized vesicular pyroclasts. Bombs can be equant to elongate, and display a variety of textures (e.g. cowpat, spindle, cored).

Phreatomagmatic eruptions occur when magma interacts with water. Water flashes to steam due to extreme heating by magma, and the resulting rapid increase in volume causes intense fragmentation of the magma (Morrisey et al 1999). Phreatomagmatic eruptions typically create planar beds of angular lapilli-ash sized fragments.

1.1 Geologic Background

Banks Peninsula is comprised of two main volcanic edifices, formed during the Miocene: Lyttelton Volcano (11-9.7 Ma) and Akaroa Volcano (9.3-8.0 Ma) (Hampton, 2010). These volcanoes intruded into marine sand and mudstones, known as the Torlesse Supergroup. At this time, New Zealand began experiencing the Kaikoura Orogeny, a strike-slip tectonic regime in which faults struck NE-SW (Hampton, 2010; Ring & Hampton, 2012). Along strike, this resulted in localized extensional stresses (Hoernle et al, 2006). This situation is not a normal volcanic setting, and volcanism in this region was most likely due to crustal thinning and athenosphere upwelling, thus causing melting of the lithosphere (Timm et al, 2009). Banks Peninsula volcanism ended when the tectonic forces became predominantly compressional. Initially an island, these volcanoes were later connected to the New Zealand landmass due to the deposition of quaternary sands and gravels sourced from the Southern Alps.

1.2 Methodology

This project was primarily field-based, with fieldwork at Pa Bay, Banks Peninsula. Mapping and pictorial documentation took place, as well as detailed descriptions of each unit, overall stratigraphy and lateral unit correlations. Photographic interpretation allowed for further assessing stratigraphic order and
unit correlation, especially for locations not physically accessible in the field. Adobe
Illustrator was used to process and annotate the field photos. Structural
information (i.e. orientation of bedding, contacts, and orientation of elongate clasts)
was collected in the field and subsequently used to estimate the location of the flank
vents. Samples were collected for further textural analysis. To aid description of
units, Ingram's Bedding Nomenclature (1954) was used.

2. RESULTS

Detailed field observations were made over a 500m stretch of coastline at
western Pa Bay, where deposits from at least three parasitic cones have been
identified. Additional photographic interpretation of inaccessible deposits in
eastern Pa Bay and northwest of Pa Bay allowed further interpretation of these
cones, and also identified deposits from two additional cones at Eastern Pa Bay that
are beyond the scope of this study.

The stratigraphy of six representative locations from the western cones are
presented here. Three additional inaccessible locations (L7-9) are described solely
using photographic interpretation. Structural information for both the six
representative locations, as well as the photographically interpreted locations was
acquired.

All these results are considered in order to interpret the volcanic activity at
Western Pa Bay. Locations are shown in Figure 12.

2.1 Detailed stratigraphy and Photographic Interpretation

Unless otherwise stated, thicknesses are true unit thickness at each location,
measured perpendicular to bedding, or perpendicular to contacts if massive. Many
observed layers contain abundant yet discrete large bombs supported by bedded
lapilli that form the bulk of the units. This creates a pseudo “clast-and-matrix”
texture. To avoid confusion, they are therefore described in terms of discrete
bombs in a lapilli framework.

Accompanying annotated field photographs are presented in Figures 2-11.
**Location 1 (L1)**

This is a 30 x 50 m cliff face directly southwest of Pa Island (Figure 2). This location could not be physically accessed, but was described from direct field observation at 5-30 m distance from outcrops.

A. 6m thick (vertical), thinly bedded deposit with planar beds dipping ~28° SE. Due to the distance from the outcrop, exact grain size could not be determined, but it was evident from the surface texture and absence of discernable clasts that the grain size was significantly smaller than the overlying units, and approximately ash-lapilli size. The upper contact of this unit forms an angular unconformity with Unit J that is hidden by vegetation. This unit is the stratigraphically lowest unit observed, and is texturally different to all other observed units in Western Pa Bay.

B. Massive black lava-like unit with unknown thickness (inaccessible and below wave-base). This unit is laterally extensive and appears to correlate with Unit A in Location 2.

C. 1.5m thick, bedded, orange, clast-supported scoriaceous deposit, containing ~10-30% discrete black bombs distributed irregularly throughout a framework of orangish scoria lapilli.

D. ~7m thick, massive black-grey lava-like unit, thinning from 8m to 5m to the south. This unit can be traced laterally southwards to Unit D, Location 2.

E. 4m thick, orangish, thinly-to-medium bedded scoriaceous unit with bimodal grain size. Bedding is defined by discrete black elongate bombs (<50 cm, 40%), however the bottom meter and top half meter is dominated by scoria lapilli (95%), thus bedding in these locations is indistinct.

F. 1.5m thick, columnar jointed, densely welded, grey lava-like unit. Unit appears to contain relict clast textures (observed from ~3m away) of elongate bombs, with a maximum size of 30 cm.

G. 2m thick, bedded, orange, clast-supported scoriaceous deposit, containing 50-60% bombs (defining beds) including equant and cowpat bombs, in a
scoria lapilli framework. The top 0.3m is almost entirely scoria lapilli with
bombs largely absent.

H. This unit is texturally identical to Unit F. This unit appears to be traceable
laterally to correlate with Unit G, Location 2.

I. 3.5m thick, clast-supported orangish scoriaceous deposit. Bottom 0.5m is
texturally identical to Unit G. The top 3m contain 70% bombs, most of which
are equant, in a scoria lapilli framework.

J. 15m thick sequence of both laterally continuous and pinching layers defined
by differences in color. Due to distance of outcrop, grain size was difficult to
determine, and individual clasts were generally too small to see, suggesting
dominant grain size (~60-90%) to be lapilli or ash. However, some layers
(approximately 3 within the unit) had visible bomb-sized clasts.

K. 1m wide, massive, vertically oriented feature. It crosscuts through Unit I, and
is only visible in the top 3 meters of the outcrop.

**Location 2 (L2)**

This is a 50 x 15 meter outcrop beginning 100m south of L1 and ascending from the
wave base, generally accessible for detailed field observation (Figure 3).

A. Massive black lava-like unit with unknown thickness (inaccessible and below
wave-base). Inferred to correlate to Unit B in Location 1.

B. 1m thick, black-grey, moderately to well sorted, scoriaceous deposit
containing 20% large, equant, sub-round scoria bombs up to 10 cm, in a sub-
angular scoria lapilli framework.

C. 1m thick, medium bedded, moderately to well sorted red scoriaceous deposit
containing ~20 cm thick bomb-rich (bomb:lapilli 45:55) layers interbedded
with layers of bomb-poor (bombs < 5%) clast-supported red scoriaceous
lapilli (lapilli < 1 cm). Bomb-rich layers are bimodal, containing large equant
and elongated sub-angular to sub-round scoria bombs (including cowpat
bombs) up to 30 cm, in a framework of clast-supported, sub-angular scoria
lapilli, identical to that of the bomb-poor scoria lapilli layers.
D. 3m thick, massive grey lava, with a 0.5 m rubbly, vesicular top. Contains
euhedral plagioclase (3-4%, < 1 cm) and euhedral pyroxene (6-7%, < 1.3 cm)
in a microcrystalline groundmass. Massive lava has very elongate, small
vesicles (<1%, < 3mm), rubbly top contains large, round to slightly elongate
vesicles (< 30%, < 2cm). Can be traced laterally to Unit D in Location 1.

E. 1.5m thick, thinly to medium bedded, orangish-red, well-sorted, clast-
supported indurated scoriaceous deposit containing ragged, angular scoria
lapilli (0.5-3 cm). Stratification is weakly marked by bands of larger (<35
cm) discrete black fluidal bombs, including cowpat bombs. Deposit contains
large, euhedral, free pyroxene crystals (7%, < 1cm), and also contains ~10%
void space between scoria clasts. Scoria lapilli contain euhedral pyroxene
(5%, < 0.5 mm), and euhedral plagioclase (5%, <0.5 mm).

Very base of unit E contains coarse scoriaceous bombs with similar
composition and vesicularity to the underlying lava of unit D, thereby giving
the impression of an “apparent” graded contact with the rubbly lava top.
However, these basal bombs are supported in a scoria lapilli framework that
differentiates them from the massive underlying lava.

F. 5m thick, medium bedded, orangish-red, scoriaceous deposit. Bedding is
defined by bands of discrete black bombs (average size ~20 cm), including
cowpat bombs (by far most common, composing 90% of bombs), spindle
bombs, very large denser rounded bombs (up to 1.6 m), and equant scoria
bombs. Bombs have glassy rinds, and are supported by an orangish-red,
moderately sorted, clast-supported scoria lapilli framework (0.5-3 cm).
Deposit also contains large, free pyroxene crystals (%8, <1 cm). Scoria
bombs contain pyroxene (8%, < 1 cm), plagioclase (8%, < 1 cm), and rounded
to slightly elongate vesicles (20%, < 1 cm). Scoria lapilli contain pyroxene
(5%, < 0.5 mm), plagioclase (5%, < 0.5 mm), and rounded to slightly elongate
vesicles (15%, < 1mm).

G. 2.5m thick, massive, columnar jointed, grayish black, lava-like unit,
containing alternating dense and vesicular discontinuous bands, and relict
clast textures. Vesicular patches have 30% vesicles < 1 cm. Unit contains large plagioclase and pyroxene crystals (both 8-10%, < 1.5 cm). Inferred to be Unit H in Location 1.

**Location 3 (L3)**

This is a 20 x 19 meter outcrop 100m southwest of L2, and entirely under the L2 sequence, where the contact between L2 and L3 can be seen in Figure 13.

A. 8m thick, clast-supported, bedded, reverse graded, orangish brown scoriaceous unit. Bedding is indistinct and discontinuous, defined by thin layers of virtually bomb-free angular scoria lapilli, which is clast-supported, and poorly-to-moderately sorted (0.3-5 cm). Dispersed Fluidal bombs present within the scoriaceous lapilli framework are mainly equant, and include cored bombs and occasional cowpat bombs. The unit discontinuously grades in terms of bomb:framework lapilli ratio from 30:70 to 90:10 upsection, where welding intensity also increases from unwelded to completely welded in the upper 2 meters of the unit.

B. 0.5m thick, densely welded, grey lava-like unit. The lower contact with Unit A is distinct, and this unit forms a separate unit to Unit A despite having equivalent welding intensity.

C. 10m thick, bedded, orangish-red, scoriaceous deposit. Bedding grades from thinly to medium bedded, and is defined by bands of discrete black bombs (average size in bottom 5m is 10 cm, average in top 5m is 20 cm), including cowpat bombs, cored bombs (Figure 5), and equant scoria bombs. Bombs are supported by an orangish, moderately sorted, clast-supported scoria lapilli framework (0.5-3 cm), that increases in abundance upsection. Scoria bombs contain pyroxene and plagioclase (both 5%, < 0.5 mm), and rounded to slightly elongate vesicles, were vesicularity increases from 10% on margins, to 30% towards the center.

**Location 4 (L4)**
This is a 8 x 20 meter outcrop, 150m southwest of L3, along the western coast of Pa Bay, shown in Figure 6.

A. 1.5m thick densely welded grey lava-like unit. Top contact is gradational over 0.5m into the unwelded scoria of Unit B. Bottom contact formed a prominent overhang, making underlying unit inaccessible. However, distal observation of the underlying unit appears to show underlying unwelded black scoria, similar to Unit B.

B. 6m thick, black, clast supported, poorly sorted, unit containing scoria bombs and lapilli spanning all sizes from 0.3-30, with bombs (>6.4 cm) accounting for ~40% of the clasts. This unit has a complete range of clast sizes, and does not have the characteristic “bombs in a lapilli framework” seen elsewhere in Western Pa Bay. Bedding is not well defined, however some beds can be traced by semi-continuous lines of flattened cowpat bombs. Scoria bombs are ragged, vesicular (35%, spherical, <0.8 cm), and comprised of a range of equant to elongate bombs including cowpat bombs.

**Location 5 (L5)**

This is a 40 x 20 m outcrop on the east side of the bay (across the bay from L4), seen in Figure 7.

A. 30m thick (horizontal outcrop thickness, no bedding present), massive, jointed, weathered, crystal-rich unit. Euhepial pyroxene crystals (25%, 0.1-2 cm) and euhedral plagioclase crystals (15%, 0.1-1 cm), in a grey, microcrystalline groundmass.

B. Bedded material crosscut by Unit A. Appears to be a red scoriaceous lapilli framework with beds up to 30cm, alternating with ~20cm beds of elongate and equant discrete black bombs (<50cm in size).

**Location 6 (L6)**

This is a 6 x 30 m outcrop approximately 40m NW of L5 (Figure 8). The units at this outcrop can be traced laterally with units in Locations 4 and 5.

A. This unit is a continuation of L4 Unit B. Refer to L4 Unit B for description.
B. This unit appears to correlate laterally with L5 Unit A, and is texturally similar. Refer to L5 Unit A for description.

Locations 7-9 were not accessible during fieldwork, but have been interpreted using distal photographs. They are included due to the presence of additional features that assist in interpreting the physical volcanology of the Western Pa Bay volcanics (e.g. broad structures, macroscale textures, and presence of intrusive units)

**Location 7 (L7)**

Pa Island, E of Location 1, contains a 4m wide, massive, grey, vertically oriented dike (Figure 9). It crosscuts bedded scoria on the north side of Pa Island, and partially creates the south face of the island.

**Location 8 (L8)**

Descriptions were taken looking E along the north-facing coast 300m NW of L1, out of Pa Bay proper. (Figure 10). This far north location contains large sections of bedded, dipping material. Towards the eastern end of the section (near Pa Island), units appear to be variably welded, dipping towards the NE. In the west, unwelded, well bedded, red-orange scoriaceous material dips to the NW (Patel, Personal communication, 2013).

**Location 9 (L9)**

This is a 200 x 50 m outcrop, extending east from L5. It is along the SE coast of the bay (Figure 11). The deposits are orangish-yellow, continuously bedded, clast-supported, and dip NE. They are composed of red scoriaceous ash-lapilli, <1cm black scoriaceous lapilli, large free pyroxene crystals, and <3cm lithics.

### 2.2 Structural Measurements

Strike and dip measurements of bedding contacts and bed stratification were measured directly at regular intervals between locations 2-6, and estimated from
photograph and distal observation elsewhere due to inaccessibility of the outcrops. They are presented in Figure 12.

3. INTERPRETATION

The deposits observed in Western Pa Bay represent a combination of Hawaiian, Strombolian, phreatomagmatic and intrusive activity. The abundant layered scoriaceous deposits, including equant and elongate bombs, and the presence of welding indicate that Western Pa Bay primarily represents proximal volcanic deposits (e.g. Houghton & Gonnermann 2008) from one or more flank vents.

3.1 Lithofacies

In order to assess the spatial distribution of eruptive activity, it is useful to consider the dominant deposit characteristics observed at each location. Therefore, we identify four broad lithofacies based on the observed overall sequences and clast types: (1) Partially Welded and Flattened Scoria (2) Non-Welded and Non-Flattened Scoria (3) Phreatomagmatic (4) Intrusive.

1. Partially Welded and Flattened Scoria – Variations in welded and non-welded deposits, in which at least 80% of bombs are flattened. Clast sizes are typically bimodal, with larger bombs up to 1.6m in an oxidized lapilli framework that ranges in size from 0.5-3cm. Small lava flows are also commonly observed at outcrops associated with this lithofacies.

2. Non-Welded and Non-Flattened Scoria – Predominantly non-flattened (<20% flattened) bomb-rich non-welded deposits. Poorly sorted, with clast sizes spanning a full range of lapilli to bombs (up to 70cm). A small amount of welding may still be observed in areas where this lithofacies is present, but in lower quantities than the previous lithofacies.
3. Phreatomagmatic – Thinly bedded, fine grained yellowish deposits with no apparent bomb-sized clasts.

4. Intrusive – Massive, plutonic units crosscutting other units.

3.2 Interpreted Volcanic History

Detailed interpretation of the eruptive styles associated with each unit described at Locations 1-6 is presented in Table 1. Temporal changes in eruptive activity are recorded by upsection changes at each location. Additionally, each location is classified according to its dominant lithofacies. This, together with structural data, is presented on a map in Figure 12.

3.2.1 Oldest Cone

In the north, an angular unconformity is present between the stratigraphically lowest unit in Location 1 (Unit A) and the overlying units. Unit A is texturally different, with continuous thin laminations and no bomb-sized material. These textures suggest a phreatomagmatic origin for these units (Fisher & Schmincke, 1984). Unit A is therefore proposed to belong to an older, subsequently eroded cone whose activity interacted strongly with water at the time of emplacement.

3.2.2 Northern-Western Cone

Locations 1 and 2 contain a series of Hawaiian and Strombolian deposits that are characterized by the Partially Welded and Flattened Scoria lithofacies. The numerous welded beds, scoriaceous clasts and flattened bombs suggest these represent proximal explosive volcanic material. The deposits show a temporal shift (upsection) from predominantly Hawaiian, to predominantly Strombolian activity. This is concordant with observations by Vergniolle & Mangan 1999 and Houghton & Gornermann 2008, who report that Strombolian activity often follows on from initial Hawaiian-style activity. The fine grain size and pinching beds observed in Unit J initially appear to reflect small-scale phreatomagmatic activity (Clarke et al, 2009).
However, closer field observations suggest the Strombolian-Hawaiian units (to the south) grade laterally northward into Unit J, therefore suggesting the textures observed from a distance are instead due to variable welding within bomb-poor scoria beds. It is difficult to confirm either interpretation of Unit J (phreatomagmatic versus variably welded) due to inaccessibility of the outcrop; however, both interpretations are consistent with proximal explosive volcanism. Note, on the map this unit is ascribed to the *Partially Welded and Flattened Scoria* lithofacies due to its lateral continuity with other Strombolian deposits.

As seen in Figure 12, the deposits in Locations 1 and 2 dip SW, implying a source north of Location 1. Dips shallow southwards, suggesting a shift away from the source and also supporting a vent location north of Location 1. Furthermore, Unit D can be traced laterally between L1 and L2, while several overlying Strombolian beds that are present at Location 1 appear to pinch out or merge southwards before reaching Location 2. This again supports a vent location to the north. Dip directions at Locations 7 and 8 radiate NE to NW, and also away from a region just north of L1, further supporting this region as the source location for the northern Pa Bay pyroclastics. Therefore, all structural and textural evidence point to a source for these northern-western volcanics that is slightly north of Location 1, and is marked on the map in Figure 12. The dike on Pa Island, marked in orange on the map, trends NW and runs through this potential vent location, and is thus proposed as a possible source for this cone.

### 3.2.3 South-Western Cone

A sharp change in dip direction and lithofacies occurs between L2 and L3. Dips at Location 2 trend SW, whereas dips at Location 3 trend N-NW. Lithofacies changes from Type 1 (Partially Welded and Flattened Scoria, shown in red on the map) to Type 2 (Non-Welded and Non-Flattened Scoria, shown in green on the map). South of this point, lithofacies and dip direction remain consistent for approximately 300m. The dips do not radiate, but instead trend parallel to each other and to the NW, approximately perpendicular to the shoreline. These characteristics suggest a linear (i.e. fissure) source to the SE towards the center of
the bay, and represent a separate cone to that described to the north. The distinct
c Change in lithofacies and dip direction between Locations 2 and 3 defines the
contact between this fissure-fed cone and the cone to the north, and is shown in
detail in Figure 13.
The deposits in Location 3 dip under those of Location 2, as shown in Figure
13. Thus, the fissure deposits underlie the scoria cone deposits, suggesting the
fissure eruptions occurred first. However the contact is conformable, with no
evidence of erosive surfaces, suggesting the two cones were emplaced within a short
time period. The *Non-Welded and Non-Flattened Scoria* lithofacies represents most
of the SW cone, and shows that the clasts were sufficiently chilled at the time of
emplacement as to not deform or weld. This may represent: 1) longer flight time
(i.e. higher eruption column or increased distance to vent) 2) cooler initial
maggmatic temperature  3) lower accumulation rate (e.g. Head III & Wilson, 1989).

Near the end of the bay (L6), the dipping scoria beds from the SW cone are
abruptly crosscut by a massive unit. It extends NW-SE, creating a wall-like
appearance at the southern end of the bay. It is interpreted to be a large intrusive
feature, younger than the intersected scoria beds. The interception of these beds
can be seen in at Locations 5 and 6, Figures 7 and 8 respectively. The southwestern
extent of this unit could not be found. Thus, it is unknown how far the SW cone
deposits originally extended prior to their disruption by emplacement of the
intrusive unit.

### 3.2.4 Other Cones

The W dipping scoria beds associated with the SW cone observed in L5
(shown as the *Partially Welded and Flattened Scoria* lithofacies, red on the map) end
in an indistinct contact with a laterally extensive sequence of laminated, NE dipping
beds that are described at L9. These deposits are structurally, texturally, and
compositionally different than all other sections examined above. The beds are
thinly laminated and continuous, with constant thickness. The deposit is composed
of ash to small bomb sized scoriaceous clasts, and also contains lithic fragments (1-3
cm), and highly vesicular black scoria fragments (<1 cm). These characteristics
differentiate the eastern Pa Bay deposits as having a different source that is not consistent with the deposits described for the SW cone. These units therefore appear to represent a fourth cone located in the SE of Pa Bay, however detailed study of this cone is beyond the scope of this study.

There appears to be another undescribed (fifth) cone located to the NE of Pa bay, shown in Figure 12. This region contains texturally different scoriaceous beds dipping away from a prominent dike striking NE-SW (Gravley, Personal Communication, 2013). This dike is striking in a similar direction to the SW cone deposits described in this study. This is consistent with the evidence for a NE-SW trending fissure for the SW cone, since features such as dikes commonly follow preferred orientations in response to broad structural controls (Ring & Hampton, 2012). This NE-SW trend points directly towards the center of Akaroa volcano, as is typical of radial dike networks at volcanic edifices (Acocella).

4. DISCUSSION

Deposits from at least five flank vents have been observed at Pa Bay, and appear to have been sourced from both fissure-style and point source eruptions. The SW cone appears to have been fissure-fed, and is conformably overlain (with no evidence of an erosional time break) by deposits from the NW cone. This cone appears to have originated at a point source. Both cones have similar compositions and textural characteristics, including the presence of distinctive, unusually large (up to 3 cm), free pyroxene crystals. These crystals may have been sourced from a crystal mush deeper in the magmatic system, and entrained by the magma feeding the NW and SW cones. Their presence in deposits from both cones may imply a common source.

Fissure and point source eruptions are not always mutually exclusive, but rather both styles can be present simultaneously, or can evolve from one to the other (Bruce & Huppert, 1989). The 1786 eruption of Laki Volcano in Iceland is an excellent example of this process: it consisted of a 22km fissure with multiple discrete spatter, scoria and tuff cones that erupted from point sources along the
fissure (Thordarson & Self, 1993). Another example is flank eruptions on Mt Etna, Italy, where fissures commonly become blocked by cooled magma, and concentrate activity to 1 or more points (Corazzato & Tibaldi, 2006). A situation such as these may have occurred at Pa Bay, with both the SW and NW cones erupted either simultaneously or in quick succession.

The Akaroa Volcano parasitic cones are excellent examples for studying eruptions from flank vents, as coastal erosion has dissected the cones, allowing for detailed temporal and spatial analysis of the activity that produced these deposits. Flank vents are a commonly overlooked feature in volcanic regions, and human habitation around volcanoes is often located in areas where parasitic cones are present, or may occur in future. Although flank eruptions are generally small-scale, their explosive nature presents a significant hazard. At Mt Etna, over 25 flank eruption events have occurred over the past 100 years, with many settlements less than 20km from the summit (Acocella & Neri, 2003). Therefore, understanding these events is important in terms of volcanic hazards.

5. CONCLUSIONS

Western Pa Bay consists of vent-proximal explosive and effusive volcanic deposits from at least five sources:

- The stratigraphically lowest unit in the area consists of eroded phreatomagmatic deposits from an older cone.
- The SW and NW deposits represent Strombolian and Hawaiian-style eruptions. The SW Pa Bay deposits appear to originate from a fissure-fed eruption, whereas the NW deposits suggest a single source.
- The SW fissure-fed deposits underlie those of the NW cone, however their conformable contact and textural similarities implies simultaneous or near-simultaneous eruption, and their similar compositions suggest they originate from the same parent magma.
- Textural and structural differences in the SE Pa Bay deposits imply these deposits were sourced from a different vent than the NW and SW cones.
• NE Pa Bay contains a further example of a SW-NE trending fissure eruption,
  with scoriaceous beds dipping away from a prominent dike. This supports
  the interpretation of a SW-NE trending fissure source for the SW Pa Bay
  deposits.

  The Pa Bay deposits extend the record of flank volcanism at Akaroa Volcano.
  This is significant for both the volcanic history of Banks Peninsula, and for
  understanding flank eruptions and associated hazards worldwide.

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Appendix of Tables and Figures
**Figure 1:** Location Map of Akaroa Volcano (9.3-8.0 mya) and Lyttelton Volcano (11-9.7 mya), with their contact marked in white. Pa Bay is located on the Northeast coast of Banks Peninsula. Image courtesy of Google Earth.
Figure 2: Location 1 in the NW end of Pa Bay: Units A-K labeled in white. Contacts are solid lines, inferred contacts are dense dashed lines, bedding is thin dashed lines and the unconformity a dashed line. Unit A: Laterally extensive, thinly bedded, with angular unconformity at upper contact. Unit B: Massive black lava. Unit C: Continuous beds of clast-supported scoriaceous lapilli with few bombs. Unit D: Massive black-grey lava, varies in thickness. Unit E: Scoria lapilli with layers containing discrete equant and elongate bombs. Unit F: Densely welded unit with relict clasts. Unit G: Scoria lapilli with layers containing discrete equant and elongate bombs. Unit H: Densely welded unit with relict clasts. Unit I: Beds of discrete mainly equant bombs in a scoria lapilli framework. Unit J: Fine grained (ash-lapilli) with layers containing bomb-sized clasts, with variations in color. Unit K: Massive vertical feature intruding Unit I. Unit A represents phreatomagmatic deposits from an earlier cone. Units B-J represent deposits of the NW scoria cone. Unit K is a younger dike.
**Figure 3:** Location 2, in the NW end of Pa Bay, south of Location 1. Units labeled in white. Contacts are solid lines, inferred contacts are dense dashed lines, and bedding is thin dashed lines. Unit A: Massive black lava. Unit B: Beds of discrete mainly equant bombs in a scoria lapilli framework. Unit C: Scoria lapilli with layers containing discrete equant and elongate bombs. Unit D: Massive, pinching and swelling, black-grey lava with brecciated top. Unit E: Continuous beds of clast-supported scoriaceous lapilli with few bombs, with bomb-rich lower section. Unit F: Bimodal (grainsize) scoriaceous deposit with bedded equant and elongate bombs throughout a framework of scoria lapilli. Unit G: Densely welded unit with relict clasts. This sequence represents part of the NW scoria cone, with units of Strombolian and Hawaiian-style deposits.
Figure 4: Location 3, SW of Location 2, on the west coast of Pa Bay. Units labeled in white. Contacts are solid lines and bedding is thin dashed lines. Unit A: Poorly sorted scoriaceous deposit of mainly scoria lapilli, with varying amounts of equant bombs. Unit B: Densely welded unit. Unit A grades upwards into this unit. Unit C: Bimodal (grainsize) scoriaceous deposit with bedded equant and elongate bombs increasing in size upsection, in a framework of scoria lapilli. This Location represents Strombolian activity from a fissure eruption.
Figure 5: Cored bomb found at Location 3, Unit C.
Figure 6: Location 4, SW of Location 3 on the W coast of Pa Bay. Units labeled in white. Contacts are solid lines, thick dashed line is inferred contact and bedding is thin dashed lines. Unit A: Thin densely welded layered grey unit, grading into nonwelded Unit B. Unit B: Poorly sorted scoriaceous deposit of mainly scoria lapilli, with varying amounts of equant bombs. This Location represents Strombolian activity from a fissure eruption.
Figure 7: Location 5, SE of Location 4, at the back of Pa Bay on the S side. Units labeled in white. Contact between units is thick line, inferred contact is thick dashed lines and bedding is thin dashed lines. Unit A: Crystal-rich massive grey unit that cross-cuts other beds. Unit B: Red scoriaceous lapilli framework with beds of discrete black equant and elongate bombs. Unit B is Strombolian deposits from a fissure eruption, that were later crosscut by an intrusive feature (Unit A). Photograph courtesy of Samuel Hampton.
Figure 8: Location 6, SW of Location 4, at the back of Pa Bay on the N side. Units labeled in white. Contact is solid white line. Unit A: Crystal-rich massive grey unit that cross-cuts other beds. Unit B: Poorly sorted scoriaceous deposit of mainly scoria lapilli, with varying amounts of equant bombs. Unit A is Strombolian deposits from a fissure eruption, that were later crosscut by an intrusive feature (Unit B). Photograph courtesy of Victoria Crystal.
Figure 9: Location 7, Pa Island, NE of Location 1. Contact is solid white line, and bedding is shown with thin dashed lines. A vertically oriented dike, crosscutting scoriaceous beds, is shown trending towards the potential vent location for the NW cone. Photograph courtesy of Samuel Hampton.
Figure 10: Location 8, north-facing coastal location, 300m NW of Location 1, beyond Pa Bay proper. Shows beds of welded (to the east) and scoriaceous (to the west) material, dipping in away from each other. These dips help reconstruct the NW scoria cone location. Photograph courtesy of Lauren Pincus.
Figure 11: Location 9, the SE coast of Pa Bay. Inferred contact shown as dashed white line, and bedding is shown with thin dashed lines. i) Image looking SW along the SE coast, where the extensive laminated unit of Location 9 is located. Inferred contact with the SW cone scoria at Location 5 is shown. ii) Image looking SE towards the SE coast, also showing the extensive laminated units of Location 9. Inferred contact is again shown. iii) Sample of the Location 9 lithic-rich (large triangular granitic fragment) and ash-rich (red matrix) unit. Photographs courtesy of Samuel Hampton.
Figure 12: Map of Pa Bay: shows field locations, lithofacies, strike and dip measurements, inferred vent regions, and cone regions. Image courtesy of Google Earth.
Figure 13: Upper Image: Showing west Pa Bay, looking from east Pa Bay. This image shows the contact between the NW and SW scoria cones, with the NW cone highlighted in red, and the SW cone highlighted in green. From this image, we can see that the SW deposits dip under the NW deposits, implying that the SW cone is “older.” This image also shows the oldest cone in yellow (under the NW cone, separated by an unconformity). Lower Image: A closer image of the NW-SW cone contact, taken from the edge of the SW cone, looking NE. From this image, we can see the deposits are conformable, and may have formed nearly simultaneously.
<table>
<thead>
<tr>
<th>Deposit Summary</th>
<th>Interpretation</th>
<th>Lithofacies (whole outcrop, not layer-specific)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 A Laterally extensive, thinly bedded, with angular unconformity at upper contact</td>
<td>Phreatomagmatic deposit from older cone</td>
<td>Phreatomagmatic</td>
</tr>
<tr>
<td>L1 B Massive black lava</td>
<td>Hawaiian effusive activity</td>
<td></td>
</tr>
<tr>
<td>L1 C Continuous beds of clast-supported scoriaceous lapilli with few bombs</td>
<td>Mild Strombolian activity</td>
<td></td>
</tr>
<tr>
<td>L1 D Massive black-grey lava, varies in thickness</td>
<td>Hawaiian effusive activity</td>
<td></td>
</tr>
<tr>
<td>L1 E Scoria lapilli with layers containing discrete equant and elongate bombs</td>
<td>Mild explosive activity with stronger Strombolian pulses</td>
<td></td>
</tr>
<tr>
<td>L1 F Densely welded unit with relict clasts</td>
<td>Welded spatter. Higher accumulation rate and/or lower eruption column (assuming no change in distance to vent)</td>
<td></td>
</tr>
<tr>
<td>L1 G Scoria lapilli with layers containing discrete equant and elongate bombs</td>
<td>Mild explosive activity with stronger Strombolian pulses</td>
<td>Variably welded and flattened scoria</td>
</tr>
<tr>
<td>L1 H Densely welded unit with relict clasts</td>
<td>Welded spatter. Higher accumulation rate and/or lower fountain height (assuming no change in distance to vent)</td>
<td></td>
</tr>
<tr>
<td>L1 I Beds of discrete mainly equant bombs in a scoria lapilli framework</td>
<td>Pulsating Strombolian activity</td>
<td></td>
</tr>
<tr>
<td>L1 J Fine grained (ash-lapilli) with layers containing bomb-sized clasts, with variations in color</td>
<td>From a distance, this unit looks phreatomagmatic. However, it traces laterally into Strombolian units to the south and may instead reflect thin differentially welded beds.</td>
<td></td>
</tr>
<tr>
<td>L1 K Massive vertical feature intruding Unit I</td>
<td>Dike, younger than all other L1 deposits</td>
<td></td>
</tr>
<tr>
<td>L2 A Massive black lava</td>
<td>Hawaiian effusive activity</td>
<td></td>
</tr>
<tr>
<td>L2 B Beds of discrete mainly equant bombs in a scoria lapilli framework</td>
<td>Pulsating Strombolian activity</td>
<td></td>
</tr>
<tr>
<td>L2 C Scoria lapilli with layers containing discrete equant and elongate bombs</td>
<td>Mild explosive activity with stronger Strombolian pulses</td>
<td>Variably welded and flattened scoria</td>
</tr>
<tr>
<td>L2 D Massive, pinching and swelling, black-grey lava with brecciated top</td>
<td>Hawaiian effusive activity</td>
<td></td>
</tr>
<tr>
<td>L2 E Continuous beds of clast-supported scoriaceous lapilli with few bombs, with bomb-rich lower section</td>
<td>Strong Strombolian onset followed by milder Strombolian activity</td>
<td></td>
</tr>
<tr>
<td>L2 F Bimodal (grainsize) scoria lapilli deposit with bedded equant and elongate bombs throughout a framework of scoria lapilli</td>
<td>Strombolian activity with stronger Strombolian pulses</td>
<td></td>
</tr>
<tr>
<td>L2 G Densely welded unit with relict clasts</td>
<td>Welded spatter. Higher accumulation rate and/or lower eruption column (assuming no change in distance to vent)</td>
<td></td>
</tr>
<tr>
<td>L3 A Poorly sorted scoriaceous deposit of mainly scoria lapilli, with varying amounts of equant bombs</td>
<td>Strombolian activity of varying intensity</td>
<td>Non-welded and nonflattened scoria</td>
</tr>
<tr>
<td>L3 B Densely welded unit. Unit A grades upwards into this unit</td>
<td>Welded spatter. Higher accumulation rate and/or lower eruption column (assuming no change in distance to vent)</td>
<td></td>
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<tr>
<td>L3 C Bimodal (grainsize) scoria lapilli deposit with bedded equant and elongate bombs increasing in size upsection, in a framework of scoria lapilli</td>
<td>Strombolian activity with discrete stronger pulses. Activity strengthens upsection.</td>
<td>Non-welded and nonflattened scoria</td>
</tr>
<tr>
<td>L4 A Thin densely welded layered grey unit, grading into nonwelded Unit B</td>
<td>Welded spatter. Higher accumulation rate and/or lower eruption column assuming no change in distance to vent</td>
<td>Non-welded and nonflattened scoria</td>
</tr>
<tr>
<td>L4 B Poorly sorted scoriaceous deposit of mainly scoria lapilli, with varying amounts of equant bombs</td>
<td>Strombolian activity of varying intensity</td>
<td></td>
</tr>
<tr>
<td>L5 A Crystal-rich massive grey unit that cross-cuts other beds</td>
<td>Intrusive</td>
<td></td>
</tr>
<tr>
<td>L5 B Red scoriaceous lapilli framework with beds of discrete black equant and elongate bombs</td>
<td>Strombolian activity with stronger Strombolian pulses</td>
<td>Variably welded and flattened scoria</td>
</tr>
<tr>
<td>L6 A Crystal-rich massive grey unit that cross-cuts other beds</td>
<td>Intrusive</td>
<td></td>
</tr>
<tr>
<td>L6 B Poorly sorted scoriaceous deposit of mainly scoria lapilli, with varying amounts of equant bombs</td>
<td>Strombolian activity of varying intensity</td>
<td>Non-welded and nonflattened scoria</td>
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