Volcanic Geology of Le Bons Bay Peak, Banks Peninsula, New Zealand

Tyler Stetson Brown
University of Canterbury

Bank's Peninsula not only has an intimate relationship with Christchurch, it has a fascinating and not well understood history. Starting life as a volcanic island, it was connected to the mainland through outpouring rivers laden with sediment from the eroding alps. Traditionally, Bank's Peninsula has been thought of as two large cones that form current day Lyttelton bay and Akaroa bay. However, recent research has suggested that Lyttelton bay is a sum of smaller volcanoes that form a larger ring. This is telling of a larger lack of depth to the known story of Banks Peninsula. Of particular interest is Le Bons Bay Peak, labeled as part of the Diamond Harbour Formation. Strangely, it is the only part of the eastern side of Banks Peninsula that is not classified as part of the Akaroa Volcanic Group. This study attempts to verify Le Bons Bay Peak's classification, and explain its origins.

Background

Geology of **Banks Peninsula**

Banks Peninsula is a topographic oddity along the eastern coast of New Zealand. It is a mountainous region with peaks reaching 919 m (Mt. Herbert) amid a flat plain that extends for about 200km along the coast. It's out of place nature is revealing of it's geological history. Volcanism in Banks Peninsula began approximately 12 millions years ago and ceased around 5.8 million years ago with the majority of the large scale action happening between 11-8 million years ago (Hampton et al, 2009). This period of volcanism built an island to the east of the South Island. Following the islands creation, alluvial fans fed by erosion of the South Island's alps extended the coast out eastwards to touch the western edge of Bank's Peninsula, thus linking it to the mainland.

As table 1 illustrates there are 5 groups of formations in Banks Peninsula; Lyttelton Group, Mt. Herbert Group, Akaroa Volcanic Group, "Church Type" Lavas, and the Diamond Harbour Volcanic Group (Sewell, 1988). Lyttelton is the oldest group of the five, occupying a time period from around 11 to 9.7 Ma. In this period, a large cone shape was created that encompasses the NW part of Bank's Peninsula. Although the Lyttelton volcanics appear to be from one large vent, research by S.J. Hampton and J.W. Cole suggests otherwise.

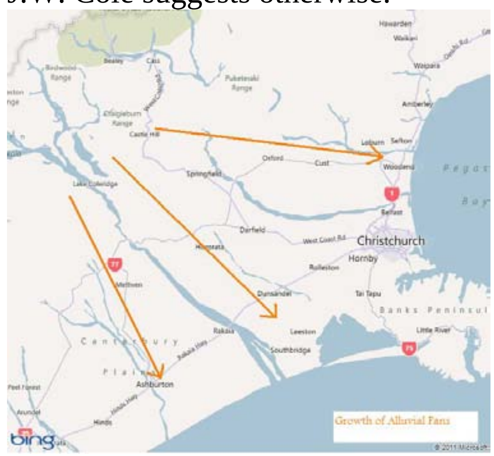

Figure 1: rivers deposited sediment, growing the coast out towards Banks Peninsula

Combined data sets of convergent dyke orientations, valleys and ridges, among other evidence suggests there are as many as 15 vent locations that form a roughly crescent shape (Sewell, 1988). The Lyttelton "cone" can be thought of as almost synonymous with the Lyttelton Volcanic Group as the vast majority of material within it is the Lyttelton Volcanic Group. However, the Mt. Herbert Volcanic Group resides partially within the Lyttelton cone and the "Church Type" Lavas and the Diamond Harbour Volcanic Groups reside almost exclusively within the Lyttelton cone region. In general the Lyttelton Volcanic Group has a higher silica content then the Akaroa Volcanic Group with >~48% SiO2 wt % (Timm et al, 2009). The cause of the extrusion of Lyttelton Volcanic Group material is thought to be a delamination of the lithosphere under Lyttelton due to a buoyancy imbalance created by subduction. The subducting plate to the west may have fed a movement of material that enriched the eastern plate's lithosphere, increasing it's density (Timm et al, 2009). Eventually the density may have reached a threshold where a sufficient bouyancy imbalance was present to cause a gravitationally induced delamination of the lithosphere around Lyttelton. Asthenospheric material then moved into fill the gap left by the delaminated lithosphere and melted from decompression (Timm et al, 2009). This is the proposed source of material for the Lyttelton Volcanic Group.

The Mt. Herbert Group occupies a transitional period from 9.7 to 8.0 Ma ago that lies at the end of volcanic activity in the Lyttelton region (Lyttelton Volcanic Group) and continues to the end of volcanic activity in Akaroa region (Akaroa Volcanic Group). The Mt. Herbert Group is the smallest of the three voluminous groups and deposited between the Lyttelton "cone" and the Akaroa cone (Sewell, 1988).

The Akaroa Group was extruded from 9.6 to 8.6 Ma (9.0 Ma to 8.0 Ma pre Timm et al, 2009). It is the most voluminous Group on Banks Peninsula and makes up the near complete volume of the eastern side of Banks Peninsula. The Akaroa Group is generally less silica rich then the Lyttelton Group , with <~48% SiO2 wt % (Timm et al, 2009). The cause of the extrusion of the Akaroa Group may have either been a second pulse in the delamination associated with the Lyttelton Volcanic Group, or it may be representative of a second delamination event entirely. It is not known whether the Akaroa cone is representative of a single large vent or a ringed conglomeration of vents as is the case with Lyttelton. Lyttelton's complex nature and linked history to Akaroa casts doubt on the single vent explanation of Akaroa however.

The "Church Type" Lavas formed from 8.1 Ma to 7.3 Ma ago and are volumetrically small relative to the previous three Groups. The "Church Type" Lavas encompass both flows and intrusives and overlap chronologically with the youngest Akaroa and Mt. Herbert lavas but have distinct geochemical and mineralogical attributes (Sewell, 1988). This Group is found on Quail Island (at the center of the Lyttelton "cone"), on the mid-southern edge of Lyttelton Harbour and on the southwest side of the Lyttelton "cone" (Sewell, 1988).

The Diamond Harbour Group is the youngest Group on Banks Peninsula, occupying a time period between 8.4 Ma to 7 Ma (7 Ma to 5.8 Ma pre Timm et al, 2009) (Sewell, 1988). While the Diamond Harbour Group has a greater volume than the "Church Type" Lavas, it is still much less voluminous than the Lyttelton Volcanic Group, the Mt. Herbert Group and Akaroa Group. The Diamond Harbour Group mainly formed monogenetic vents within and on the sides of the Lyttelton "cone".

It is worth noting that the dates stated here for the volcanic groups are based off of R.J. Sewell, 1988. More recently, Christian Timm, et al. 2009, revises these dates. However, as only 14 samples were dated over the entirety of the peninsula these dates can only be used in a complementary fashion (figure 3).

Le Bons Bay Peak

Le Bons Bay Peak is a hill on the eastern side of Banks Peninsula about 1.5 km west of Le Bons Bay (6a, see figure 1). Le Bons Bay Peak is composed of variably oriented columnar to tabular jointed basanite and is surrounded by Akaroa Volcanics

(Sewell et al, 1993). The Le Bons Bay Peak is labeled on Sewell's geologic map as part of the Diamond Harbour Group, and asserted by R.J. Sewell and S.D. Weaver (Sewell et al, 1993) to be part of the Diamond Harbour Group. However, the paper that Sewell proves this in is not available at this time. More recently a sample analyzed from Le Brons Peak was dated to 8.42 Ma +/- 0.16 Ma (Timm et al, 2009) suggesting the Le Bons Peak is either a Diamond Harbour Volcanic, Mt. Herbert Volcanic or a Akaroa Volcanic. Research has been done on xenoliths taken from Le Bons Peak, but nothing has been published on the structure or history of Le Bons Peak (Sewell et al, 1993).

The local topography Le Bons Bay Peak formed on is assumed to be a roughly planar surface that gently slopes away from the inner extent of Akaroa bay. This can be seen from the orientation of lava flows below Le Bons Bay Peak and across the valley to the north of it.

GROUP	ESTIMATED VOLUME	FORMATION	K/Ar AGE RANGE (Ma)	Revised dates (2009)	LITHOLOGY
DIAMOND HARBOUR VOLCANIC GROUP	20 km^3	STODDART BASALT	7·0 - 5·8		Fresh, columnar-jointed, olivine ± clinopyroxene phyric basanites, olivine-basalts and olivine-hawaiites – rare olivine-basalt dikes
		KAIORURU HAWAIITE	6·9 - 6·8		Commonly weathered, vesicular, pale pink, olivine + clinopyroxene-phyric and aphyric olivine-hawaiites
"CHURCH TYPE" LAVAS	5 km^3	CHURCH BASALT	8·0 - 7·3	8.4 – 7/6	Fresh, columnar-jointed, olivine ± clinopyroxene ± plagioclase - phyric olivine-basalts
		CHATEAU INTRUSIVES	8·0		Grey, columnar to knobbly-jointed aphyric hawaiites
		DARRA BASANITOID	8·1 - 7·7		Fresh, columnar-jointed olivine ± clinopyroxene-phyric basanitoids -rare basanitoid dikes
AKAROA VOLCANIC GROUP	1200 km^3		9·0 - 8·0	9.6–8.6	Fresh, medium to fine-grained, olivine-clinopyroxene-plagioclase-phyric and grey, aphyric hawaiites - rare trachyte domes and dikes
MT HERBERT VOLCANIC GROUP	100 km^3	HERBERT PEAK HAWAIITE	8·5 - 8·0		Grey, columnar-jointed, aphyric and rarely olivine-phyric olivine-hawaiites
		PORT LEVY FORMATION	8·9 - 8·5		Grey-black, columnar-jointed, aphyric hawaiites - rare porphyritic basalts and mugearites
		ORTON BRADLEY FORMATION	9·5 - 8·6		Black, fresh aphyric, olivine-hawaiites & olivine + clinopyroxene + plagioclase-phyric olivine-basalts
		KAITUNA VALLEY HAWAIITE	9·7 - 9·5		Columnar-jointed, dark grey-black, fresh, olivine + clinopyroxene-phyric olivine-hawaiites
LYTTELTON VOLCANIC GROUP	350 km^3		11 - 9·7	12.5 – 10.5	Moderately weathered, plagioclase ± olivine ± clinopyroxene - phyric hawaiites - trachyte lava flows and domes - numerous trachytic and basaltic dikes

Table 1: Geological Groups of Bank's Peninsula (R.J. Sewell, 1988)

Background

Lava Dome Morphology

Lava domes grow in either of two ways. The first method is endogenous growth, where the dome inflates like a balloon. The second is exogenous growth, where material breaches the surface of the dome and cools as a lobe atop it. The key difference between the two is that in endogenous growth, the shape of the dome remains constant (in a general sense) and the dome expands uniformly from within. Exogenous dome growth is not as simple. As each new lobe or spine is created in exogenous growth it pushes its way out, modifying the shape of the surrounding older lobes and spines. Often this creates a complex conglomeration of lobes.

The factors that contribute to a dome’s shape are diverse. Roughly, they are the nature of the magma, the speed at which the magma effuses at, the speed at which the extruded magma cools at, and the pull of gravity. Fluctuations of any of the first three factors can further complicate the shape of a dome (Fink & Griffiths, 1998). One might be tempted to say that the viscosity of the magma is almost synonymous with the silica content of the magma, however this not entirely true as vesicularity and water content are known to influence viscosity *(Lyman et al, 2002)*. Further, the chemical makeup of the magma is not in many cases the most important variable. Viscosity can be more largely dependent on magma effusion rate, as effusion rate determines the time magma has to cool before emplacement. It can be seen from this that a mafic magma extruding at a low rate may be more viscous than a silicic magma extruding at a higher rate. Indeed it is the combined aspects of a magma's chemical susceptibility to crystallinity and the time allowed for the magma to crystallize that determines its viscosity.

Fundamentally, the most important aspect that determines the shape of a dome is the relationship between the speed at which magma effuses to the speed at which it cools (Fink & Griffiths, 1998). A paper published by Fink & Griffiths in 1998 found a dimensionless number composed of the time it takes for a magma exposed at the surface to solidify divided by the time it takes for a flow to advance a distance equal to its thickness. This allowed four categories inhabiting different ranges of this number to be created (Fink & Griffiths, 1998). This study is one of the more successful categorizations of dome morphologies.

Spiny domes inhabit the lowest ranges of the dimensionless number, and are described as “tall and very steep sided, with relatively smooth upper surfaces covered by small blocks and ash. Their tops are commonly punctured by one or more subvertical spines with smooth, curving sides.”(Fink & Griffiths, 1998). They are roughly circular in shape (surrounding surface geometry permitting). Spiny domes are the extreme representation of exogenous growth, featuring tabular spines that rise almost directly from the source conduit to breach the surface. Emplacement of lobes in a spiny dome is a not a fluid like process and is akin to pushing a book into a narrow space on a bookshelf.

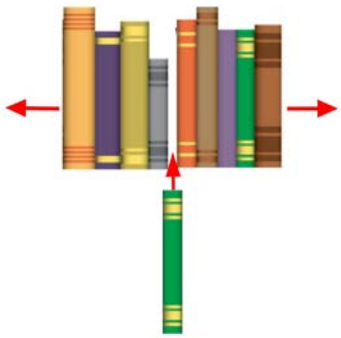

Figure 2 represents a new spine of lava rising. The book or spine in the process of being emplaced displaces older ones horizontally.

Lobate domes inhabit the next higher range of the dimensionless number. Rounded lobes successively protrude from the core of the dome, pushing their way out between previous lobes. Different from spiny domes, lobate domes are what their name says, and feature lobate shapes as opposed to spiny tabular shapes. Also, the interactions between lobes in a lobate dome are much more fluid than in a spiny dome. Often successive lobes will extrude in alternating directions, and result in an interfingered, stacked shape (Zavada et al, 2008).

Platy domes inhabit a higher range of the dimensionless number then lobate domes. They are similar in shape to lobate domes, save they are less eccentric and tend to be closer to the shape of an ideal dome. Lobes are less defined aswell, and may merge with one another near the conduit (Fink & Griffiths, 1998). Ridges are found in perpendicular and parallel orientations to the flow direction.

Axisymmetric domes inhabit the highest range of the dimensionless number. They are closest to the idealized, uniform shape of a dome. They have the lowest relief, and feature “laterally extensive, transverse folds with relatively short wavelengths (1-5m) [that] may parallel their entire margins” (Fink & Griffiths, 1998). These domes may also be referred to as coulees (Fink & Griffiths, 1998). These categories are compartmentalizations of a continuum. Thus, the boundaries that differentiate the four categories are arbitrarily placed. This continuous nature allows an interesting transitional area from fluid like platy and axisymmetric domes to more solid like movement of tabular extrusions in spiny type domes. This has been studied in Alina J. Hale et al, 2007. A particularly good illustration of how extrusive growth begins is found in this study. As stated before, the method of effusion is determined by the comparison between the magma's effusion rate and cooling rate. Once a sufficiently slow effusion rate occurs, or at least the magma is able to cool sufficiently, the magma crystallizes past a threshold and shear banding begins to occur. The increased crystallinity causes shear as the magma begins to behave plastically. The shear band forms at the conduit lip where magma moves at the highest rate and thus has the highest shear. This shear band adopts the geometry of the conduit lip's cross section and propagates upwards. If this process continues a spine will eventually breach the surface. Essentially, the conduit walls themselves temporarily extend upwards to the surface as the effusing magma loses its fluid coupling to the surrounding magma.

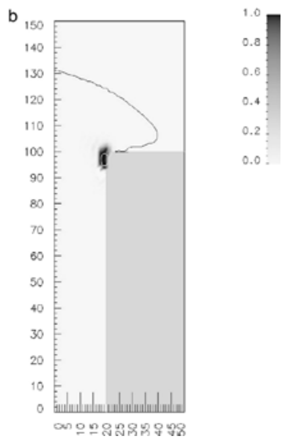

Figure 4. The dark area represents the region in which plastic behavior, or non-fluid like behavior begins to occur on a theoretical dome. Courtesy of Hale & Wadge, 2007.

These four morphological categories of domes all form under constant conditions on a flat surface from a cylindrical conduit. This means of course, that domes that look like any of these four categories are rare. The flat surface aspect of many dome models is an especially unusual condition, as domes often form amid other volcanic processes such as volcanoes. Further, the complicated shape of a dome is often masked by curtains of talus from destroyed older dome activity. This can be caused either by background erosion, or by explosive dome failures. All these factors together make it difficult to observe, nonetheless understand the shape of a dome in the first place.

Methods

Samples taken from Le Bons Bay Peak, nearby Akaroa Volcanics (Panama Rock), and from Diamond Harbour Volcanics were chemically analyzed via XRF. As there are Diamond Harbour Volcanics that are chemically very similar to Akaroa Volcanics it may be difficult to distinguish Le Bons Bay Peak's origin through chemical analysis. Thus, the structure of Le Bons Bay Peak will be mapped. Strike and dip orientations of fractures throughout the structure will be determined and mapped. Insights from structural analysis and numerous samples will be combined to form a bigger picture of Le Bons Bay Peak.

Results

Geochemical

Geochemical analysis found the dike to the west of Le Bons Bay Peak (L17D1) to be very similar in composition to the Peak itself (based off of sample taken at L1, on the northeast side of the dome). This strongly suggests that they are genetically linked. However, the size of the dome is quite small and is on the order of a meter or so wide. It is doubtful that a feeder dike of this size could be considered a major source of the material at Le Bons Bay Peak.

The chemistry of Le Bons Bay Peak does appear to similar to the chemistry of the Diamond Harbour sample CD77, save for a small difference in the Silica Dioxide percent weight. There does appear to be a significant difference in Mg0 % and TiO2% between the Akaroa group and Le Bons Bay Peak samples. However, observed geochemistry of the Akaroa group only represents a small subset of locations among a large area. As a result, these samples may not actually be representative of the range of chemistries in the Akaroa Volcanic Group.

Sample	L1	L17 D1	L4	L17F	LBP-Timm et al	DH - Timm et al	DH - Timm et al2	Akaroa - Timm et al	Akaroa - Timm et al3
UC Field	BP-34	BP-37	BP-35	BP-36	MSI20E	CD112	CD77	N36C3602	MSI 144
SiO2%	42.9	42.86	49.55	48.45	42.29	45.53	48.06	44.52	44.93
TiO2%	2.87	2.82	2.52	2.3	2.85	3.22	1.94	4.11	3.69
Al2O3%	12.37	12.19	16.9	18.16	12.26	15.81	13.82	15.27	16.01
Fe2O3T%	14.53	14.48	12.5	12.97					
MnO%	0.19	0.19	0.2	0.17	0.18	0.18	0.15	0.16	0.18
MgO%	11.25	11.82	3.99	1.77	11.51	6.32	9.24	5.02	4.94
CaO%	10.64	10.52	7.01	5.43	10.74	9.5	9.24	11.62	8.71
Na2O%	3.68	3.87	4.62	4.56	3.77	3.53	2.95	2.66	3.34
K2O%	1.02	1.14	1.8	2.06	1.13	1.27	1.03	0.36	1.27
P2O5%	0.72	0.7	0.92	1.2	0.71	0.6	0.39	0.23	0.61
LOI%	-1.01	-1	-1.03	2.87					
Total%	99.15	99.59	98.97	99.91					

Table 1. Geochemical analysis of samples from Bank's Peninsula. L1, L17 D1, L4 and L17F are from Le Bons Bay Peak. Samples designated DH are from Diamond Harbour

Results

Structure

Le Bons Peak is fairly regular in its composition. Local variances in texture and facies is minimal along the extent of the dome. Further, save for the lava flows found on the western side of Le Bons Dome, all other exposed rock feature well defined tabular joints that range in thickness from 5 cm to 50 cm. Jointing along the majority of the peak tends to dip at a sub vertical angle. In some places this jointing is exceptionally regular in geometry. In IMG_7362, a photo of an exposure on the southern edge of Le Bons Bay Peak, this is particularly evident. It is unlikely that effusion and subsequent onion skin cooling would create such regular geometry. Near brittle deformation under high shear strains is more likely. This is because it is much more likely that a mechanical large scale process rather than cooling would result in such regular shape.

The larger scale trends of the sub-vertical jointing throughout Le Bons Bay Peak suggest the jointing is not of onion-skin origin as well (see Figure 5). It can be seen in DIAGRAM1 that the jointing appears to form a semicircle along the perimeter of the dome from the north eastern side to the north western side. If this dome was an idealistic dome shape, one would expect a radial behaviour reflected along the southern exposure. Additionally, one would expect radial fractures that tended towards more horizontal slopes if the majority of the original structure was represented (Fink et al, 1998). As can be seen in Image 1, this is not apparent. There is a possible point of divergence in jointing along the exposure, but it was not able to be examined closely due to excessive vegetation. In either case, the jointing is still largely uniformly oriented along the southern exposure of Le Bons Bay Peak. This makes it difficult to determine the size and original geometry of Le Bons Bay Peak as the shape can not be determined by simply extrapolating a radial trend.

Figure 5. Strikes and dips of jointing found on Le Bons Bay Peak. Unmarked strike and dips represent information inferred from images and thus are not accurate enough to justify quantification. Unmarked dips are all sub-vertical.

Image 1. Exceptionally regular tabular jointing found on south eastern side of Le Bons Bay Peak.

Conclusions

Geochemical analysis of Le Bons Bay Peak found it to be of similar makeup to the Diamond Harbour Group. Therefore, this designation seems correct.

The overall trends of the subvertical jointing and the regularity of the jointing itself leaves two possible scenarios for the formation of Le Bons Bay Peak. First, what's left of the dome at Le Bons Bay Peak may be too small of a piece to show a radial trend. Secondly, Le Bons Bay Peak formed as something other than a typical dome. The designation as an upheaved plug given by Sewell et al, 1993 may be an accurate one here then. In this case, the tabular jointing could have formed from intense shear experienced during the ascent of the plug. Further research into vent plugs may shed more light into the history of Banks Peninsula.

References

Brugger, C. R., Johnston, A. D., & Cashman, K. V. (2003). Phase relations in silicic systems at one-atmosphere pressure. *Contributions to Mineralogy and Petrology, 146*(3), 356-369. Retrieved from www.scopus.com

Fink, J. H., & Griffiths, R. W. (1998). Morphology, eruption rates, and rheology of lava domes: Insights from laboratory models. *Journal of Geophysical Research B: Solid Earth, 103*(1), 527-545. Retrieved from www.scopus.com

Hale, A. J., & Wadge, G. (2008). The transition from endogenous to exogenous growth of lava domes with the development of shear bands. *Journal of Volcanology and Geothermal Research, 171*(3-4), 237-257. Retrieved from www.scopus.com

Hampton, S. J., & Cole, J. W. (2009). Lyttelton volcano, banks peninsula, new zealand: Primary volcanic landforms and eruptive centre identification. *Geomorphology, 104*(3-4), 284-298. Retrieved from www.scopus.com

Price, R. C., & Taylor, S. R. (1980). Petrology and geochemistry of the banks peninsula volcanoes, south island, new zealand. *Contributions to Mineralogy and Petrology, 72*(1), 1-18. Retrieved from www.scopus.com

Lyman, A. W., Koenig, E., & Fink, J. H. (2004). Predicting yield strengths and effusion rates of lava domes from morphology and underlying topography. *Journal of Volcanology and Geothermal Research, 129*(1-3), 125-138. Retrieved from www.scopus.com

Sewell, R. J. (1988). Late miocene volcanic stratigraphy of central banks peninsula, canterbury, new zealand. *New Zealand Journal of Geology & Geophysics, 31*(1), 41-64. Retrieved from www.scopus.com

Sewell, R. J., Hobden, B. J., & Weaver, S. D. (1993). Mafic and ultramafic mantle and deep crustal xenoliths from banks peninsula, south island, new zealand. *New Zealand Journal of Geology & Geophysics, 36*(2), 223-231. Retrieved from www.scopus.com

Timm, C., Hoernle, K., van den Bogaard, P., Bindeman, I., & Weaver, S. (2009). Geochemical evolution of intraplate volcanism at banks peninsula, new zealand: Interaction between asthenospheric and lithospheric melts. *Journal of Petrology, 50*(6), 989-1023. Retrieved from www.scopus.com

Závada, P., Kratinová, Z., Kusbach, V., & Schulmann, K. (2009). Internal fabric development in complex lava domes. *Tectonophysics, 466*(1-2), 101-113. Retrieved from www.scopus.com