Final Report on EQC Grant for project: Porosity and Permeability variations in volcanic conduits

Paul Ashwell, PhD candidate, University of Canterbury

Collaborators: Dr. Ben Kennedy & Prof. Jim Cole

Abstract

Porosity and permeability variations in high viscosity lava domes are the result of collapse and shear processes during eruption. In depth field mapping of Ngongotaha Dome (Rotorua Caldera) and Ruawahia Dome (Tarawera Volcanic Centre) has produced eruption models that can help explain these variations from styles of eruption of the domes. In addition, high temperature, low stress experiments have been used to quantify the affect of compression on both crystalline and non-crystalline rocks. These experiments have shown that while porosity collapses in a predictable fashion (based upon initial vesicularity and crystal content), permeability will be highly variable during compression as bubbles close (acting to reduce permeability) and cracks open (acting to increase permeability).

Both Ngongotaha and Ruawahia Domes have erupted in a fashion that previous modelling cannot adequately explain. Flow band variations suggest that instead of a simple flow-like eruption, both domes erupted from a series of lobes and sheets that erupted from a fissure-controlled conduit. In particular, Ngongotaha exhibits obsidian sheets bounded by meter scale breccia zones indicating that the sheets moved laterally relative to each other, producing thick breccia zones between them. These breccia zones provided pathways for gas escape, leading to the formation of minerals that have annealed the breccia. The orientation of flow bands in each dome can be linked back to the shape and orientation of the conduit, which in turn is controlled by the regional structure of the host caldera and the overall structure of the rifting of the Taupo Volcanic Zone.

The models produced give new insights into the eruption of lava domes, and the evolution of the porosity and permeability within. Understanding the processes of dome growth, bubble collapse and permeability evolution is key when predicting the behaviour of lava domes, which are one of the common volcanic landforms in the Taupo Volcanic Zone.

Executive Summary

This report will summarise the final findings of the project, list publications and conference abstracts up to this date and further questions of the project. Initial findings were summarised in a report sent to EQC in July 2012, further results and conclusions are summarised here.

Aims of the project

The initial aims of the project were:

1) To map internal structures of the rhyolitic domes of Ngongotaha (Rotorua Caldera) and Ruawahia (Tarawera volcano) to build models as to methods of eruption of both, paying particular attention to areas of high or low porosity.

2) To link the internal structures of the domes to the overall regional structure of the calderas they reside within.

3) To experimentally gauge the mechanism of compression as a way of reducing porosity and altering permeability in large, high viscosity lava domes.

4) To compare our results with other well monitored lava domes, and assess hazard risks from lava dome growth.

Conclusions from project in response to aims

1) Internal structures of Ngongotaha and Ruawahia

The structures of Ngongotaha and Ruawahia were mapped in detail during field work in 2010, 2011 and 2012. Both field sites show a well exposed sequence through the centre of the dome. Structures such as flow banding, lithology variations, fracture patterns and breccia zones help to identify methods of eruption and link the dome into its structural setting.

Ngongotaha Dome is exposed in Henderson's Quarry, which has excavated a section through a lobe of the dome. The lithology variations in the dome can be linked to the style of eruption. At the base of Ngongotaha Dome is a brecciated obsidian that forms the basal breccia, often found at the base of lava flows and domes. This grades into the core of the dome, which is a strongly flow banded microcrystalline rhyolite. This core exhibits the strongest flow banding and fractures in the dome, and represents the centre of an extrusively formed lobe or thick flow. This is also the first eruptive phase of the lobe. At the top, and above the middle, of the dome is a series of obsidian sheets separated by breccia zones. These sheets show a significantly different eruptive style, and a shift from endogenous (lobe-forming) to exogenous (spines or sheets) style of eruption. Surrounding these units is a carapace consisting of breccia of finely pumiceous material which is considered to be the initial vesicularity of the dome eruption. The vesicularity within the domes varies from this due to degassing and bubble collapse.

Flow bands in Ngongotaha Dome are generally radiating from near horizontal near the base, and ramping up to near vertical at the top and centre of the lobe (considered to be above the conduit). Several large ramping structures are seen in the core of the dome, which can be related to lava movement during extrusion. Strike orientations of flow bands are consistent, and match with regional structures mapped across Rotorua Caldera, while dip is variable.

Fractures within Ngongotaha Dome are near vertical, range from a few milimetres to several centimetres in width, and can be traced across several metres of rock face. The fractures are most pervasive in the core of the dome, as the lithology here is more uniform than in the rest of the dome. The orientations of fractures run ENE-WSW; very similar to the orientations of extended faults across Rotorua Caldera. The grouping of the orientations and the similarity to caldera structure suggests that the fractures were made as a result of regional structural processes acting on the cooled lava dome. While these fractures would not have affected the permeability of the erupting lava dome, fractures formed in cooled lava domes may be used as conduits to fluid flow in geothermal environments.

Figure 1 shows a stage in the eruption of Ngongotaha Dome. The eruption started with the extrusion of a lobe of low crystal content lava with vesicularities of approximately 55%. This lobe began to collapse in the centre from compression of overlying material and escape of volatiles to produce low vesicularity (less than 15%) lavas in the core. Shear of the lava during movement created the flow banding, while stalling of the leading edge of the lobe created folding of the flow bands as a result of differences in flow velocity within the lava. The eruption then progressed to the extrusion of less vesicular (possibly due to more efficient degassing in the conduit, or less vesicular material) and higher viscosity sheets of lava that were unable to flow outwards from the conduit due to previosuly erupted material. These sheets collapsed to extremely low vesicularities (less than 5%) and remained in a near horizontal position. Extrusion of a series of these sheets created breccia zones between them, which may have acted as pathways for volatile escape. These breccias are now annealed, so original vesicularity would have been a minimum of 20%, likely much higher. The final eruptive product of Ngongotaha Dome was ‘squeeze ups’ of glassy obsidian material which cross cuts all other units. The exact age relationship of this obsidian is unclear, but it is likely to have happened in the waning phase of eruption before the dome became too cool, as the ‘squeeze ups’ are small intrusions of obsidian that would have become chilled rapidly against colder lavas and not intruded through the dome.

Ruawahia Dome is a crystal rich rhyolite dome erupted at the end of a large Plinian eruption. It erupted onto a series of older domes that make up the Tarawera Volcanic Complex in the southern part of the Okataina Caldera Complex. Internal structures of Ruawahia were exposed during the 1886AD basaltic eruption, which formed a large rift cutting through the centre of the dome. The internal structures are not as well exposed in Ruawahia as Ngongotaha, and so more work is needed to produce a model of similar calibre to that of Ngongotaha. However, there are several meain features that have been identified at Ruawahia.

Variations in internal lithologies are not as extreme at Ruawahia, as the core of the dome is a lower vesicularity equivalent of the carapace. The core does not show extreme flow banding as Ngongotaha, but where present, flow banding is convolute and generally steep close to where conduit is believed to be. Convolute flow banding suggests that the eruption of Ruawahia dome is complex, and involved the extrusion of several sheets or lobes of material. Near vertical flow banding on outcrops at the leading edge of the dome suggest that the eruption produced near vertical flow bands close to the conduit that were then pushed away by the continued extrusion of lava. This movement of material would require a significant amount of shear at the base of the dome, which is not exposed. The flow banding suggests a NE-SW orientated conduit, similar to the 1886AD dyke. Fractures within Ruawahia can be attributed mostly to the eruptive that has exposed the core of the domes rather than to regional structures. Ruawahia dome is also much younger than Ngongotaha, so movement along structures has not been enough to produce a fracture network.

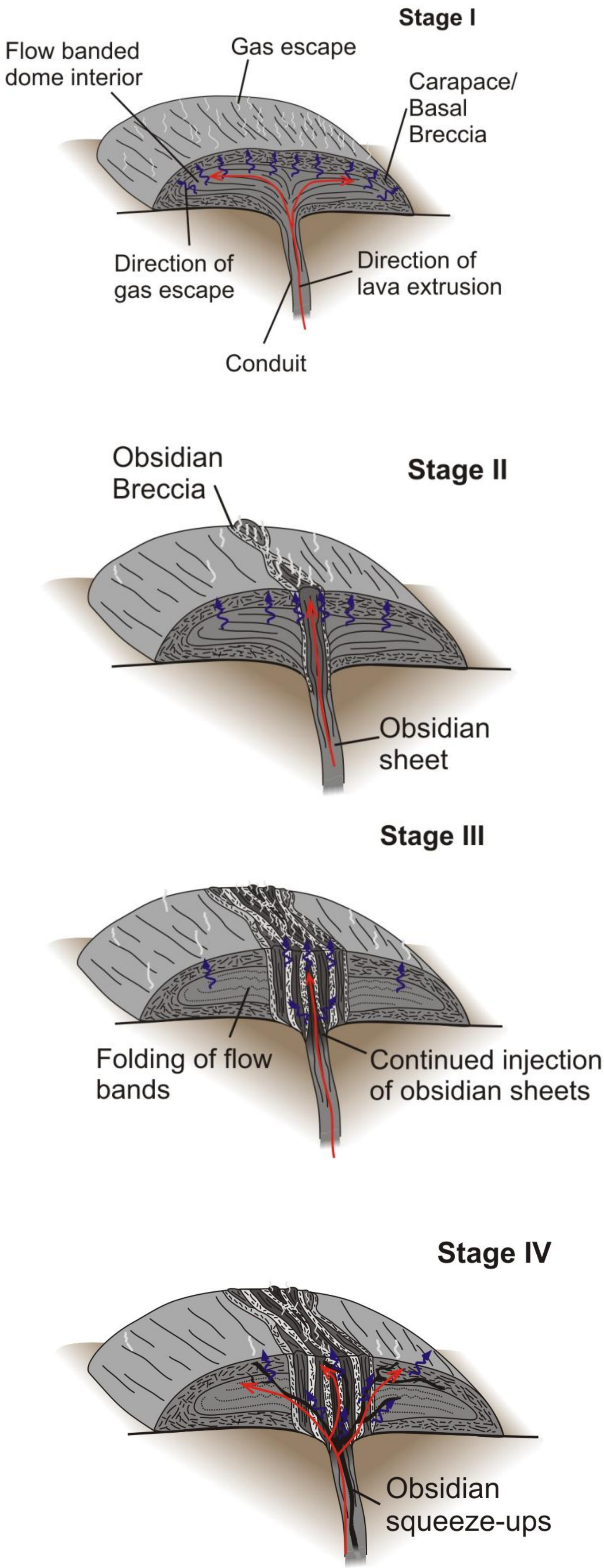

Figure 1: Ngongotaha Dome eruption model

The outer edges of Ruawahia Dome are well exposed, and are far enough away from the 1886AD crater to be unaffected by the eruption of the basalt. Highly vesicular, discontinuous outcrops that show a ropey-skin texture to them occur on the leading edge of the dome. These outcrops may have formed from in situ vesiculation of lava following a dome collapse episode. The ropey-skin texture may be formed from the uneven foaming across flow bands (due to changes in dissolved water across a flow band) after decompression. Sudden decompression would allow bubbles to grow, and if lava was still hot enough then it will foam up with highly spherical bubbles (compared to elongate bubbles from deformation during flow).

2) Linking internal structures to regional structures

The internal structures, as described above, can be linked to the regional structure that the lava dome is part of. Ngongotaha Dome was erupted shortly after the collapse of Rotorua Caldera following the eruption of the Mamaku Ignimbrite; its conduit should therefore be controlled by the same structure that has influenced caldera collapse. The flow banding and lithology variations at Ngongotaha can be attributed to the shape and position of the conduit (in this case, Ngongotaha is dyke fed), which in turn will intrude through weaknesses in the crust where it can be accommodated. Fractures at Ngongotaha can also be linked to the regional structure. Using these structures, as well as positions, geochemistry and relative timing of the eruptions of the other domes at Rotorua Caldera, a caldera structural map has been produced (see figure 2).

The piecemeal collapse of Rotorua Caldera was controlled by two major structural orientations; a NE-SW rift orientation which is mirrored in nearby Okataina Caldera Complex and a NW-SE basement derived structure that has controlled part of the NW caldera margin. The intersection of these structures has formed the overall sub-circular shape of the caldera as well as coinciding with the locations of most of the post caldera collapse lava domes.

At Ruawahia Dome, the suggested conduit orientation for the eruption of the dome is very similar to the 1886AD fissure as well as to the general NE-SW rift orientation across Okataina Caldera. Further investigation into Ruawahia Dome is needed to link these further, and it is unclear at this stage if the basement structure has affected the eruption of Ruawahia Dome at all.

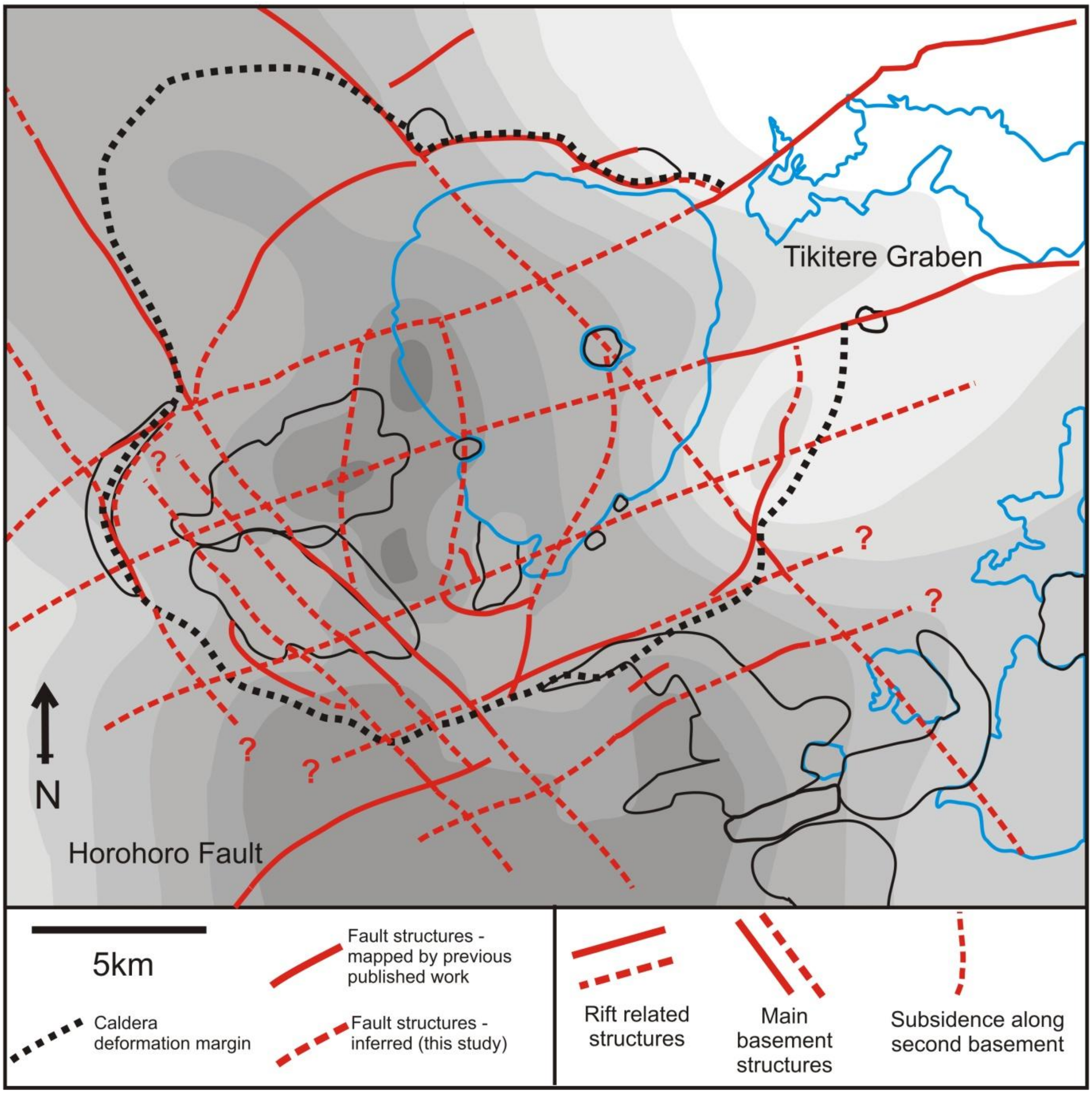

Figure 2: Rotorua Caldera structural map. Black dashed line is caldera margin, thin black lines are locations of lava domes and blue lines are lakes.

3) Compression experiments

The compression experiments aimed to investigate the ability of high viscosity lavas (specifically, Ngongotaha and Ruawahia) to compress. A large dome or thick flow will have a significant burden of overpressure that will affect how quickly or effectively this collapse process occurs, while attributes of the lava such as crystallinity, initial porosity or viscosity may act against the compression and closure of the bubble network. Tomography from compression experiments is shown in figure 3, and changes to porosity and permeability in the experiments is shown in figure 4.

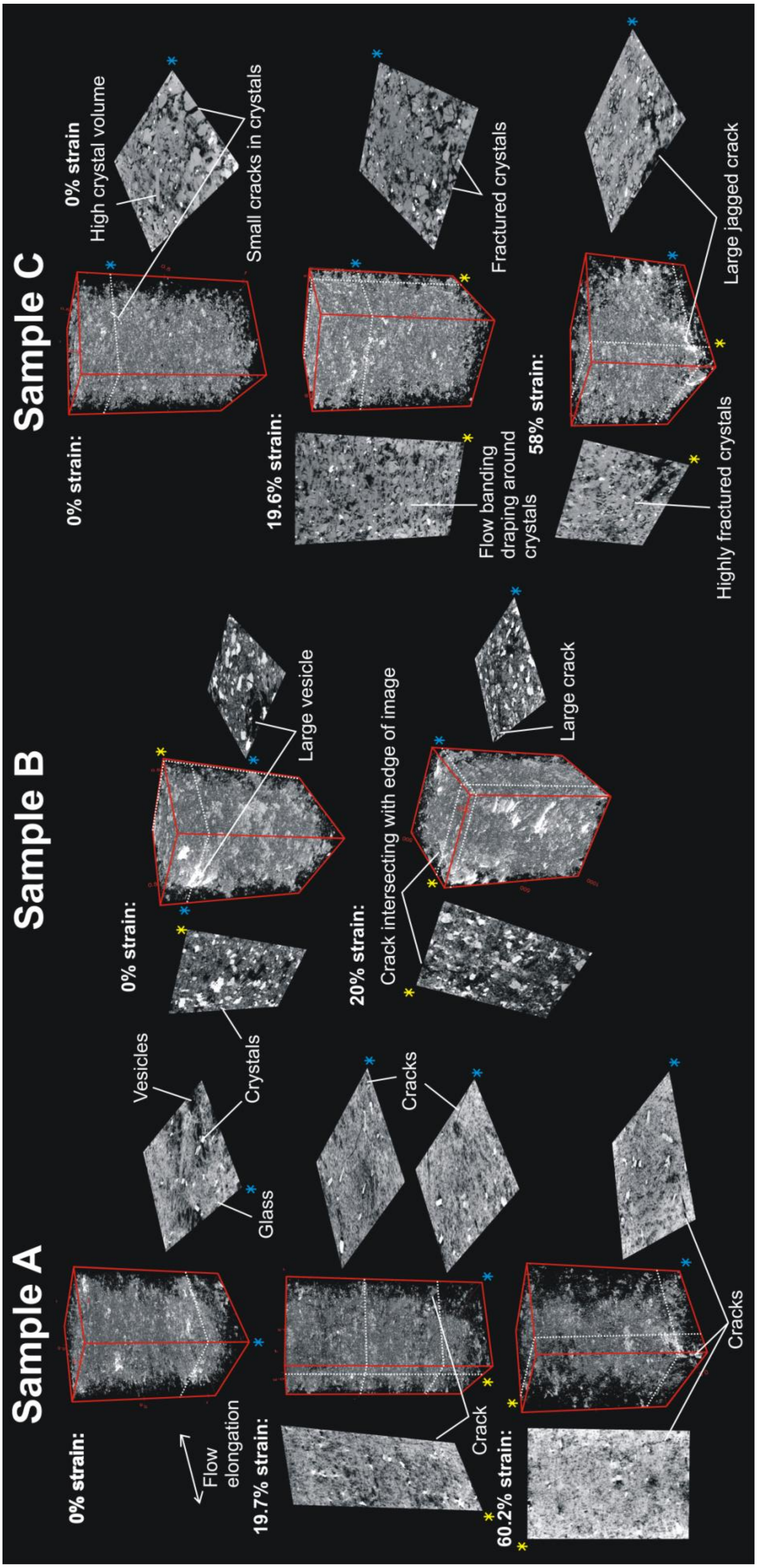
Sample A
0% strain:
Flow elongation
Vesicles
Crystals
Glass
19.7% strain:
Crack
Cracks
60.2% strain:
Cracks
Sample B
0% strain:
Crystals
Large vesicle
20% strain:
Crack intersecting with edge of image
Large crack
Sample C
0% strain:
0% strain
High crystal volume
Small cracks in crystals
19.6% strain:
Flow banding draping around crystals
Fractured crystals
58% strain:
Highly fractured crystals
Large jagged crack

Figure 3 (left): Tomography of cores before compression (top), after ~20% strain (centre) and ~60% strain (bottom). Sample A is Ngongotaha sample, B is high vesicularity Ruawahia sample and C is dense Ruawahia sample (tomography on ~60% vesicular Ruawahia to be completed). Cubes show 3D images of large pores, lighter colours indicate larger vesicles, while 2D images show density of material where lighter colours show iron oxides, grey colours show glass and quartz/ feldspar crystals and black indicates pore space. Blue/ yellow stars give placement indicators for 2D slices within 3D cubes.

The results from high temperature, uniaxial compression experiments (methodology explained in previous report), show that the ability of a lava dome to collapse is controlled by the eruptive vesicularity initially, and by the crystallinity in higher strain environments. The results also suggest that:

- A crystalline lava will form a framework that causes barrelling of the sample to occur at lower strains, and prevents porosity reduction past ~18 – 20%.
- Initially high vesicularity samples will achieve higher strain rates at low strain, creating cracking in glass over crystals.
- Cracking in all samples allowed continued gas movement, even while porosity was reducing.
- Compression alone as a method of foam collapse cannot form dense, obsidian cores recorded in domes and flows.

The results have shown that a dense plug cannot be formed from compression. In crystalline lavas compression forms a crystal framework that preserves porosity below ~18-20%. Cracking in crystals allows permeability to remain within 1 to 2 log units of initial permeability, with only 1 sample (Ngongotaha) showing a couple lack of permeability perpendicular to bubble elongation. The two crystalline lavas from Ruawahia may represent pre-collapse (B) and post-collapse products (C), as the initially vesicular Ruawahia sample is texturally similar at high strains to rocks seen in the core of the dome. However, the pumiceous Ngongotaha sample did not resemble the dense core of the dome after compression. At 60% strain, the Ngongotaha sample did not show a reduction in rate of reduction of porosity as the lack of crystals allowed continued closure of bubbles to ~14% porosity. Extrapolating the trend of porosity reduction suggests that the average porosity of the core lava (~10%) could be attained at 75% strain; strain rates in A were decreasing however, with barrelling occurring at 60% strain. Further collapse beyond 60% in Ngongotaha is therefore unlikely as this suggests a framework consisting of glass may be increasing the strength of the sample. Figure 5 shows how the behaviour of the samples compares to those in a lava dome.

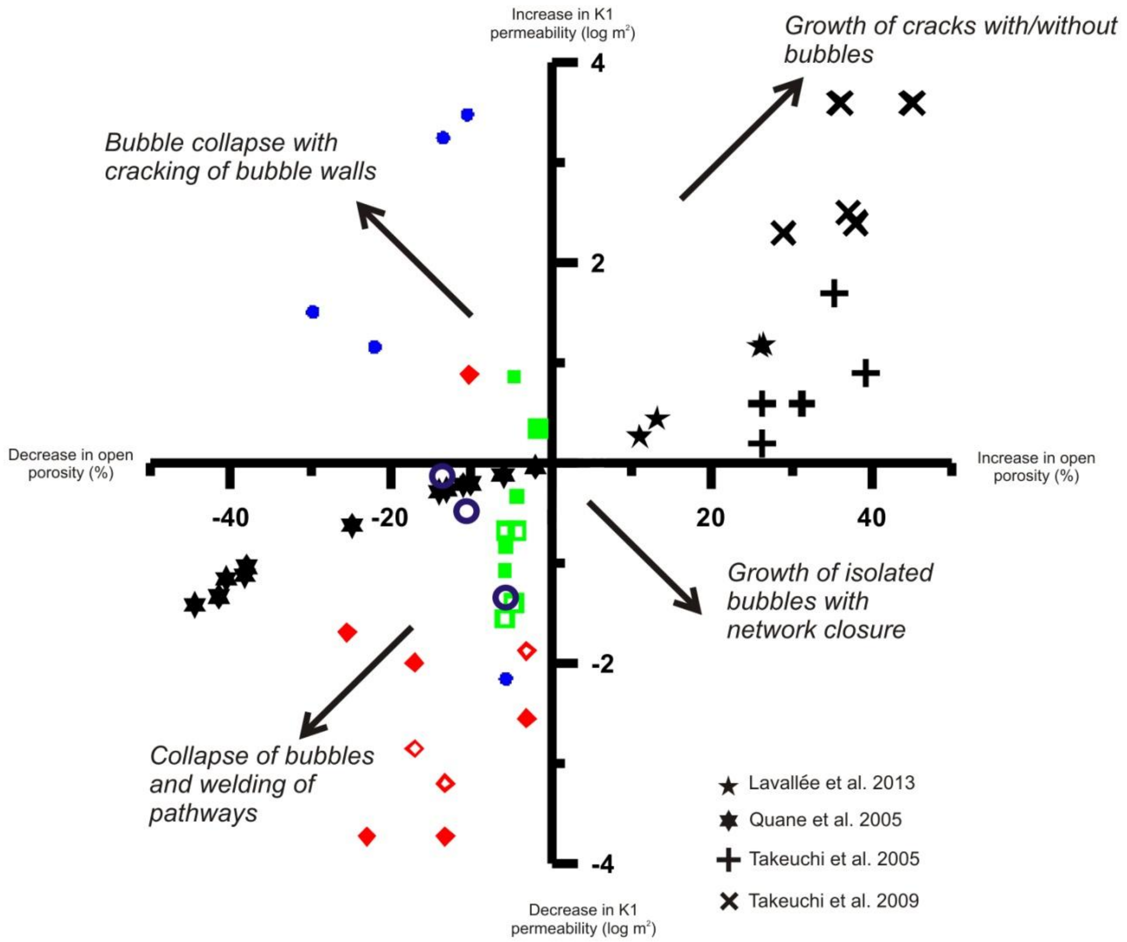

Figure 4: Graph showing porosity (X axis) and permeability (Y axis) changes from compression experiments (blue = Ngongotaha, Red = Ruawahia vesicular, Green = Ruawahaia dense) and other expriments (black shapes)

Compression of a lava dome will manifest as a subsidence in the dome with lateral movement of the edges in a non-confined setting. A dome at Lascar Volcano was observed to subside on a several-year cycle of dome growth, collapse and explosive eruptions. The dome subsidence coincides with a decrease in emissions from the dome, which have been attributed to the permeability of the dome and conduit decreasing as porosity is reduced (Matthews et al. 1997). This reduction in permeability is followed by a build up of volatiles beneath the newly created plug, creating an explosive eruption within a few weeks following the cessation of subsidence of the dome (Matthews et al. 1997).

In this and other cases of dome growth and subsidence, a plug was often formed through the collapse of bubbles. Our experiments suggest that compression could not create a plug through closure of bubbles alone. Cracks forming in glass or crystals produce gas pathways that will help reduce overpressure. Cyclical behaviour of many domes such as Lascar (Matthews et al. 1997), Santiaguito (Johnson et al. 2008) and Soufriere Hills (Loughlin et al. 2010) strongly indicates to a reduction in permeability of the dome or plug. For this reduction in permeability to occur, then any cracks formed during compression must be welded closed by re-melting of the glass or by growth of minerals during volatile escape (as suggested by Matthews et al. 1997). Other processes, such as resorption or shear, may also play a large part in porosity reduction and crack closure in lava domes that leads to violent explosive eruptions.

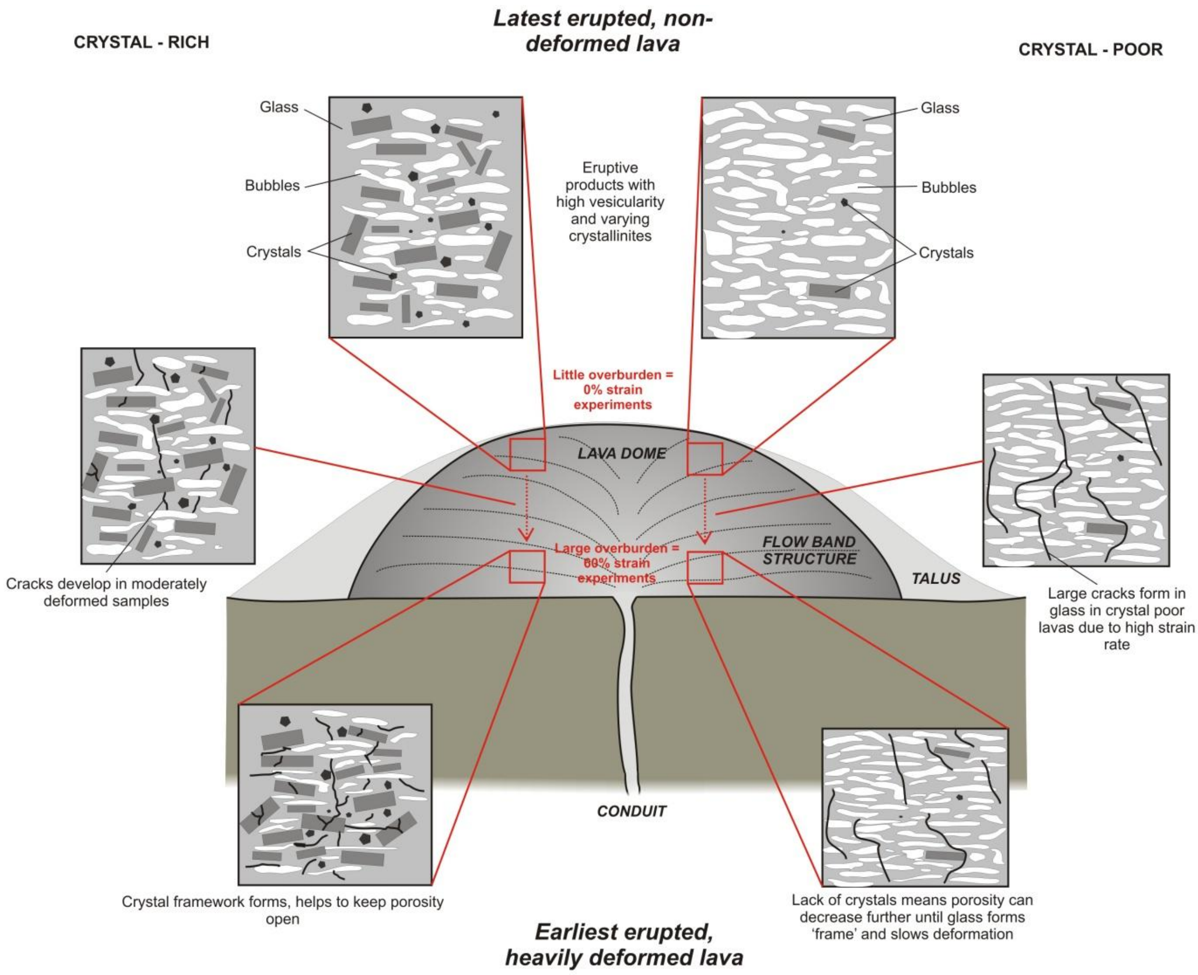

Figure5: Model showing compression in a crystalline (left) and non-crystalline (right) dome

4) Other domes and hazard perspectives

Active domes are the focus of many research projects and hazard initiatives around the world. The eruptions of Mt St Helens, Soufriere Hills and Santiaguito domes have been thoroughly studied and their hazards are well known. However, there has been only a couple of in depth studies of lava domes that have formed following large explosive eruptions. The results gathered from this research will add to the knowledge of the structure of these types of domes and will benefit hazard modelling.

Isolated dome eruptions are common in the Taupo Volcanic Zone (TVZ). The eruption of Ruawahia Dome in 1314AD was the last rhyolitic eruption in the TVZ, and the largest since the 1.8 Ka Taupo eruption. It is likely that the first Maori pioneers witnessed this eruption, as oral histories record a battle between Kupe and a Taniwha who resided in Lake Tarawera. In recent history, there has been only 2 eruptions of rhyolitic lava at Chaiten, Chile and Novarupta, Alaska, with both eruptions forming domes. If a lava dome were to erupt within the TVZ, it would threaten a large population with not only the initial eruption, but also in hazards associated from dome growth which will last far longer than the length of the initial eruption. Dome forming eruptions can last several years to decades.

The results from this project show that the compression of a lava dome will not reduce permeability completely, especially in crystalline lavas. The reduction in permeability (i.e. the formation of a plug) may lead to explosive failure of the dome, leading to dome collapse and pyroclastic flows. This is a common feature in gas rich dome eruptions such as Soufriere Hills. Cyclical activity at volcanoes is associated with plug formation; Santiaguito erupts frequently, a solidified layer acting as a plug and allowing gases to accumulate beneath it until the pressure is enough to move the plug upwards. A crystalline dome will form a framework during compression which will keep permeability open; this is observed in the field from differences in the core of Ruawahia and Ngongotaha domes (crystalline and non-crystalline respectively). However, permeability can still be closed in an actively growing dome by shear, which may destroy this framework or in a stalled dome where hydrothermal minerals may grow in pathways and block them.

Collapse from a oversteepened lava dome is also a common hazard. A dome which grows on a particularly steep slope will often collapse and produce pyroclastic flows, sometimes followed by explosive decompression and the hot, pressurised core is exposed to the atmosphere. The eruption models produced from the fieldwork suggest that a high viscosity dome formed on a flat surface (e.g. intra-caldera) will not produce significant block and ash flows. Ngongotaha has only very minor and proximal block and ash flow development because it erupted on flat ground and, after the switch in eruption style, was no longer able to form an oversteepened leading edge. Ruawahia (and the other domes of Tarawera and Wahanga) have significant block and ash flow development which may be linked to a slightly different eruption style where the first erupted material is pushed out from the centre (leading to the possibility of forming an oversteepened edge), or from the palaeotopography of the dome complex beneath the domes. The change in slope may have been the catalyst that allowed block and ash flow development.

Full list of publications from this research:

P.A. Ashwell, B.M. Kennedy, D.M. Gravley, F.W. von Aulock and J.W. Cole. 2013. Insights into caldera and regional structures and magma body distribution from lava domes at Rotorua Caldera. *Journal of Volcanology and Geothermal Research*. In press. The first page of this paper is included at the end of this report.

P.A. Ashwell, J.E. Kendrick, Y. Lavallee, B.M. Kennedy, F.W. von Aulock, J.W. Cole and D.B. Dingwell. Porosity and permeability evolution in a collapsing lava dome. In preparation for Earth and Planetary Science Letters.

P.A. Ashwell, B.M. Kennedy, F.W. von Aulock and J.W. Cole. Fissure-fed dome eruptions: evidence from internal and external structures. In preparation for Bulletin of Volcanology.

Full list of conference presentations:

B.M. Kennedy, **P.A. Ashwell**, F.W. von Aulock, K. Buchanan, D. Drabble & J.W. Cole. 2009. Playing Vulcan: Re-creating the subterranean conditions that spawn rocks. *GeoNZ 2009, Oamaru*.

P.A. Ashwell, B.M. Kennedy, F.W. von Aulock & J.W. Cole. 2010. Eruption style and emplacement processes of Ngongotaha Dome, Rotorua. *GSNZ 2010, Auckland*.

P.A. Ashwell, B.M. Kennedy, F.W. von Aulock & J.W. Cole. 2011. Linking the internal structures of lava domes to eruption style: An example from Ngongotaha Dome, Taupo Volcanic Zone, New Zealand. *IUGG 2011, Melbourne*.

P.A. Ashwell, J.E. Kendrick, Y. Lavallee, B.M. Kennedy, K.U. Hess, F.W. von Aulock, J.W. Cole & D.B. Dingwell. Experimental Results on the Compaction of Pumiceous Lava Domes. *GSNZ 2011, Nelson*.

P.A. Ashwell, J.E. Kendrick, Y. Lavallee, B.M. Kennedy, K.U. Hess, F.W. von Aulock, J.W. Cole and D.B. Dingwell. 2011. Permeability development during compaction of pumiceous dome lavas: testing the permeable foam collapse model. *AGU 2011*.

P.A. Ashwell, J.E. Kendrick, Y. Lavallee, B.M. Kennedy, K.U. Hess, J.W. Cole and D.B. Dingwell. 2012. Microfracture development and foam collapse during lava dome growth. *AGU 2012.*

P.A. Ashwell, B.M. Kennedy, D.M. Gravley and J.W. Cole. 2013 (Upcoming). Linking lava domes to their structural setting. *IAVCEI General Meeting, Kagoshima*.

P.A. Ashwell, M. Edwards, B.M. Kennedy and F.W. von Aulock. 2013 (Upcoming). Investigating the collapse and inflation of erupting lava domes. *IAVCEI General Meeting, Kagoshima*.

Awards:

2011: Runner up, Best Student Talk at GSNZ 2011 conference, Nelson.

2012: Wellman Research Award from Geological Society of New Zealand to continue research in vesiculation of lava domes following dome collapse and pyroclastic flow production.

References:

Johnson, J.B., Lees, J.M., Gerst, A.G., Sahagian, D. & Varley, N. 2008. Long-period earthquakes and co-eruptive dome inflation seen with particle image velocimetry. *Nature*, 456(7220), pp.377–81.

Loughlin, S.C., Luckett, R., Ryan, G., Christopher, T., Hards, V., De Angelis, S., Jones, L. & Strutt, M. 2010. An overview of lava dome evolution, dome collapse and cyclicity at Soufrière Hills Volcano, Montserrat, 2005–2007. *Geophysical Research Letters*, 37, pp.4–9.

Matthews, S.J., Gardeweg, M.C. & Sparks, R.S.J. 1997. The 1984 to 1996 cyclic activity of Lascar Volcano, northern Chile: cycles of dome growth, dome subsidence, degassing and explosive eruptions. *Bulletin of Volcanology*, 59(1), pp.72–82.

Acknowledgements

This research has generously funded by the Earthquake Commission, to whom I am very grateful both for the funding and the understanding of changing deadlines. GNS, Mighty River Power, the Department of Geological Sciences at the University of Canterbury and the Mason Trust all contributed a small, but vital, amount to the research and I am thankful to them all.

Journal of Volcanology and Geothermal Research xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Insights into caldera and regional structures and magma body distribution from lava domes at Rotorua Caldera, New Zealand

P.A. Ashwell *, B.M. Kennedy, D.M. Gravley, F.W. von Aulock, J.W. Cole

Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

ARTICLE INFO

Article history:
Received 6 August 2012
Accepted 23 April 2013
Available online xxxx

Keywords:
Lava dome
Caldera structure
Rotorua
Flow bands
Geochemistry
Morphology

ABSTRACT

Lava domes emplaced after caldera-forming eruptions are often the only clue to the structure of the caldera and to the regional structure at the time of caldera formation. This is because the deposits from the subsequent eruptions commonly bury subsidence-controlling caldera faults and regional cross faults within calderas. Other calderas and lava domes in the Taupo Volcanic Zone (TVZ), New Zealand, have been previously reported to show strong regional control. At Rotorua Caldera there is a general lack of surface expression of faults, but rhyolite lava domes are well exposed and aligned with regional structures that have been mapped outside of the caldera. Our summary of published data and new observations allows these lava domes to be subdivided into three groups based upon their petrology, geochemistry, relative age and spatial distribution: (1) the Kaikaitāhuna Group of pre-collapse (451 ka), crystal-rich domes at the caldera boundary, (2) the Utuhina Group of crystal-poor, high alkali, post-collapse domes (c. 200 ka) surrounding the locus of collapse and directly related to the earlier (240 ka) Mamaku ignimbrite eruption, and (3) The Ruamata Group of crystal-rich, more calcic, less devitrified post-collapse (60–36 ka) domes further out from the collapse locus. Mapping of the morphology and internal structures of the Utuhina Group domes shows an ENE–WSW elongation direction and vent alignment, which is parallel to and down strike of (a) the extensional rift orientation independently mapped either side of the caldera, (b) the local caldera morphology and (c) structures mapped at nearby Okataina Caldera Complex. A second NW–SE trending orientation in the caldera morphology is parallel to a pre-collapse basement fabric, and has partially controlled the locations of the domes. A third orientation is hinted at through consistent N–S striking flow bands within Ngongotaha Dome, which are parallel with a gravity anomaly. We suggest that this orientation is a N–S section of a caldera ring fault that links regional structures and was utilised during caldera collapse. A subsequent dike intrusion also used this structure, erupting a fissure-style dome that contains radiating flow bands which mimic the orientation of the feeder dike. However, the structure, morphology and location of post-collapse lava domes generally echo the unburied regional structures outside the caldera indicating that dike intrusion also occurred along regional structures. We suggest that the regional structures at Rotorua Caldera, which are similar to those at Okataina Caldera Complex, show that the kink in the orientation of the rift across the TVZ to the SE of Rotorua was active to at least 240 ka, and possibly earlier. This kink is significant due to its proximity and influence on both Rotorua and Okataina caldera systems and their associated geothermal fields. We conclude that internal structures, such as flow bands and morphology of lava domes are direct consequences of the shape and location of the feeder dike, which in turn is controlled by the structure of the caldera and region. We also suggest that lava dome eruptions at Rotorua were from a series of small, related nestled magma bodies. A key outcome of this study is the reconstruction of the wider structure of the caldera and surrounding structure based upon the localised internal features, distribution, and morphology of related lava domes.

1. Introduction

The structure, location, morphology, and chemistry of lava domes are important in understanding the interplay between caldera-forming eruptions and tectonics. The association of lava domes and large plinian or caldera-forming eruptions has been well documented in the Taupo Volcanic Zone (TVZ), and other volcanic systems (Cole, 1970; Irving et al., 1980; Wilson et al., 1984; Nakada et al., 1995; Wilson et al., 1995; Fink and Anderson, 2000; Platz et al., 2012).

The calderas of TVZ show a strong regional structural control on their morphologies and eruptive histories (Cole, 1990; Wilson et al., 1995; Spinks et al., 2005), and pre-existing fault structures have acted as pathways for eruption of ignimbrites and lava domes (Walker, 1984; Cole and Spinks, 2009). Caldera collapse structure controls the location of domes at Valles Caldera (Smith and Bailey, 1968; Heiken et al., 1990; Kennedy et al., 2012) and at the Ubinas–Huaynaputina–Ticsani Volcanic Group, Peru (Lavallée et al., 2009), while the domes of the Inyo Crater

* Corresponding author. Tel.: +64 3 364 2987x7697.
E-mail address: paul.ashwell@pg.canterbury.ac.nz (P.A. Ashwell).

0377-0273/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jvolgeores.2013.04.014