Modeling lava dome collapse using correlation between porosity and unconfined compressive strength

Martin Keenan[1], Paul Ashwell[2]

[1]Department of Geosciences, Williams College, Williamstown, MA, [2]Department of Geology, University of Canterbury, Christchurch, NZ

I. Abstract

Unconfined compressive strength (UCS) is a strong control on lava dome stability and can be used to model domes and study the possibility of collapse. Connected porosity measurements were taken on rhyolite cores from the Tarawera and Ngongotaha lava domes and subsequent strength tests determined the UCS of each core. The data were then analyzed to produce a negative exponential function relating UCS to connected porosity. This function, along with data on the porosity, thickness and density of the Cordón Caulle obsidian flow and Unzen lava dome, was used to generate models for lava dome collapse. These models compare estimated UCS of the rock to the load of the lava dome and predict the risk of collapse. Despite the exclusion of other relevant factors, e.g. tensile strength and seismicity, it is concluded that porosity, via UCS, is a significant to provoking collapse.

II. Introduction

A complete understanding of compressive strength requires a comprehensive analysis of rock microstructures. Variables such as porosity, mineralogy, crystal content and glass content will undoubtedly play a role in the determination of strength as they are part of the fundamental framework that constitutes a rock (Sammis & Ashby 1986; Chang et al. 2006). When hardened rock is subjected to pressure and approaches failure, the points at which cracks nucleate and grow depends on the relative size and placement of microstructures within the rock (Sammis & Ashby 1986; Isida & Nemat-Nasser 1987). In the case of volcanic rocks, these variables are partly dependent on the rate of magma cooling and the rate of magma ascension (Heap et al. 2014b). Ascending magma experiences drops in pressure as it travels upward. Lower pressure causes gasses in the magma to exsolve, forming bubbles. The growth of and movement of these gas bubbles is controlled by the melt viscosity and the diffusion of volatiles (Gardner et al. 1999). When the magma cools, the bubbles are frozen in place as pore space. Porosity has been proven to be one of the most important factors affecting rock strength (Sammis & Ashby 1986; Wimmer & Karr 1996).

When porous rocks are compressed, cracks originate at the pores and begin to grow in the general direction of the compressional axis. The amount of pressure and size of the pores decides how far these cracks travel. With closely packed pores, cracks will often connect, creating a growing chain of cracks which ultimately leads to rock failure (Sammis & Ashby 1986; Baud et al. 2014). If a relationship between porosity and rock strength can be established, it will be possible to incorporate the two variables into models that test the stability of rock structures. This paper will attempt to specifically model lava domes.

To observe how porosity influences rock strength, we have performed uniaxial compressive strength testing on a set of rock cores taken from the Tarawera Volcanic Complex and the Ngongotaha lava dome. The Tarawera complex, one of the youngest sections of the Taupo Volcanic Zone (TVZ), was built by five distinct eruptions from ~22 ka to 1314 AD and consists of a series of overlying domes with accompanying lava dome collapse episodes forming block and ash flows (Ashwell 2014). The Ngongotaha dome is a lava dome in Rotorua Caldera, and is ~200 ka (Ashwell 2014). The cores were selected from different areas in each dome. Through compressive strength testing, we are able to see relationship between measured porosity and strength.

The majority of research on the role of porosity on compressive strength thus far has been on concretes, sedimentary and non-volcanic igneous rocks, with not as much attention given specifically to volcanic rocks. Some studies have examined the effect of porosity on basalt strength (Al-Harthi et al. 1999) as well as a combination of porosity and vesicle size on basalt strength (Heap et al. 2014b). Determination of strength in volcanic rocks is particularly important to estimating the stability of volcanic edifices. Collapses often occur in the weakest areas of the edifice and can be triggered by eruptions or seismicity (Vallance et al. 1995; Heap et al. 2014a). Events like these are hazardous to humans in the surrounding area and a sound understanding of the potential for collapse is crucial to assessing the risk and deciding the proper safety precautions (Voight 2000). Establishing the control porosity has on lava strength would greatly increase the accuracy of collapse predictions.

III. Methods

i. Porosity Measurements

As porosity has already been shown to be relevant to rock strength (Sammis & Ashby 1986; Wimmer & Karr 1996), tests for porosity were performed on each rock sample. Connected porosity measurements were obtained via gas pycnometer at Massey University using an ultrapycnometer 1000 with nitrogen gas.

ii. UCS Testing

Tests for the uniaxial compressive strengths (UCS) of the rocks were performed using the standard method for UCS testing outlined by the American Society for Testing and Materials (ASTM 1984). In preparation for testing, the rock samples were cored to a diameter of 23 to 25 mm and a height of 55 mm. The equipment used was a Clifford Tecnotest L1-112-EQ08 machine. The Clifford has a self-contained loading apparatus that holds the core and applies and increasing load along the vertical axis of the core until failure occurs. Tecnotest data acquisition software was used to continuously collect data on the load, stress and strain of the cores throughout the testing.

iii. Modeling

The data on porosity and the data from the strength testing were collated in the statistical software R. A nonlinear function was then fit to the data in order to interpret UCS as a function of connected porosity. This function was then applied to two existing lava domes: Cordón Caulle in Chile and Unzen in Japan. The Cordón Caulle obsidian flow is a laterally-extensive, compound lava flow (Schipper et al. 2015). Unzen is a volcano composed primarily of lava domes and their collapsed debris. Dome-forming eruptions have occurred every 4,000 to 5,000 years for the past 500 ka (Nakada et al. 1999). Cordón Caulle and Unzen were chosen because they represent two end members of the types of lava dome/flow eruptions, i.e., thin, expansive flows to thick, top-heavy dome structures. Porosity measurements were gathered from previous studies on these domes and used to predict their UCS. This calculation used the nonlinear function generated from the core testing. Data on the domes' thicknesses and densities were collated and used to predict the load of the overlying dome on its base rock. If this load were to exceed the predicted UCS, we would conclude that it is in danger of collapsing and if it were under the UCS, we would conclude that it is stable.

IV. Results

i. UCS and Connected Porosity Function

A negative, nonlinear relationship has been shown to exist between the connected porosity and the uniaxial compressive strength of the rhyolite cores. The function generated to describe this relationship, shown graphically in Figure 1, is

Eq.1
$$s = -7.797 + 53.721e^{-0.032p},$$

where *s* is the unconfined compressive strength and *p* is the connected porosity. Prior research has shown that strength as a function of porosity tends to follow a negative exponential form (Chang et al. 2006). The lowest porosity rocks have the highest UCS, with UCS decreasing rapidly and then gradually slower as porosity increases. At mid to high levels of connected porosity, about 20% and upwards, the functions change in UCS becomes significantly smaller.

ii. Cordón Caulle Model

The values for the thickness and porosity of the Cordón Caulle obsidian flow were taken from Tuffen et al. (2013) and Schipper et al. (2015) . These values are averages of the estimated range of thicknesses and porosities in the flow. The thickness is estimated at 35 meters and the porosity at 26.5 percent. With a density of 2.5 g/cm^3, and using the acceleration of gravity at g=9.81 m/s^2, the load of the flow would be 0.63 N/mm^2. The estimated UCS from Eq.1 is 15.3 N/mm^2. Since the UCS is higher than the load, this flow is classified as stable. Cordón Caulle has experienced no large collapse events in its history. This model is shown in Figure 2.

iii. Unzen Model

The values for the thickness and porosity of the Unzen lava dome were taken from Yamamoto et al. (1993) and Scheu et al. (2006) . The model was set up in the same way as the Cordón Caulle model and the values used for thickness and porosity are again averages of the range of thicknesses and porosities in the dome. The estimated thickness is 450 meters and the estimated porosity is 29 percent. Using a density of 2.5 g/cm^3, the load of the dome is 7.83 N/mm^2. The UCS function calculates UCS as 13.5 N/mm^2. The values for the load and strength are closer than those in the Cordón Caulle model, however the strength is still greater than the load and the dome is considered stable. This is contradictory to the multiple collapses of the Unzen lava dome in its 1991 eruption; however this contradiction is addressed in the discussion section. This model is shown in Figure 3.

V. Discussion

These models only looked at the effect of the load of lava domes and their UCS, and therefore they are very simple models. Lava dome collapses can be caused by a large number or combination of factors. These include water saturation, topography, tensile strength, seismicity, erosion and dome shape. More realistic models would incorporate these variables, however in this case where we were only interested in the role of UCS in the dome, these variables were not necessary.

The other factors determining lava dome collapse are worth discussing in depth. Rainfall is one factor shown to have a strong relationship with collapses. A seven month period of dome growth and little rain over the Soufriere Hills dome in Montserrat was followed by a short period of extreme rainfall in 2001 (Matthews et al. 2002). A few hours after the rainfall began, dome collapse events occurred along with pyroclastic flows. Matthews et al. (2002) have shown that rainfall is indeed a factor that can contribute to collapse. While direct observations were not possible, it is thought that rain seeps into cracks in the hot dome and vaporizes into high-pressure steam which destabilizes the dome. The limitation to this is that rainfall must be high enough that there is enough rain available to enter the dome without vaporizing at the surface. In this case hazards are somewhat preventable, as meteorologists can easily predict storms of the magnitude necessary to produce collapses and send out warnings beforehand.

Topography of the land beneath the dome could possibly affect collapse as well. Our models assume the land beneath the dome is flat. However in reality it is more likely to have some slope. If the dome is built on ground that is sloping downwards, gravity would contribute a greater force to pulling it down. It could also increase the tensile strain on the rock which could create fractures. Dome shape could also play a role. Changes in shape could lead to varying thicknesses and varying loads throughout the dome. Low tensile strengths in lavas have been shown to produce wider, flatter domes (Iverson 1990). It is possible that in a situation where a dome is thin enough and on a slope that the effect of tensile strain could be greater than the compressive strain of the overlying weight.

Some limitations existed in the data used in the models. The connected porosities in Cordón Caulle and Unzen were both taken from the carapace. However the model assumes that the rock that is failing is at the bottom of the dome. This rock would very likely have a different porosity than the rock at the carapace. A greater knowledge of how porosity varies within domes would greatly increase the accuracy of the model.

The role that temperature plays should also be brought into question. The UCS measurements taken with the strength testing apparatus were performed at room temperature. The Cordón Caulle obsidian flow only just erupted in 2012. The flow is likely still very hot, especially on the inside. This could change the dynamics of the compressive strength. Because of the lack of a temperature variable, our model works best with flows that have cooled sufficiently to the point where heat is no longer a factor.

One more assumption the models make is that collapse is a result of the failure of the rock at the bottom of the flow. The exact mechanics within flows are not completely known and it is possible that failure could have many causes. Perhaps failure begins in the middle or outside of the dome and not at the bottom. In this case the model would be very similar to the models in this study, however the weight of the overlying rock would be less if the failure zone were higher up in the dome.

Despite their limitations, the models did yield some interesting results. The difference between estimated load and UCS of Unzen (5.7 N/mm^2) was considerably smaller than that of Cordón Caulle (14.7 N/mm^2). Unzen could be interpreted as having a higher risk of collapse in this case. The other factors previously discussed could add to the probability of the dome collapsing. In the case of Unzen's 1991 collapse, it was triggered during a violent eruption where there was considerable shaking (Yamamoto et al. 1993). The added effect of the eruption to the effect of the UCS and any other variables most likely created the failure necessary to induce collapse.

VI. Conclusions

Porosity is shown to have a direct, negative exponential relationship with lava unconfined compressive strength. UCS is an important factor in the cause of lava dome collapses and therefore porosity is a control on dome collapse. The function relating porosity and UCS produced from strength testing allows the modeling of lava dome stability using real world data on thickness and porosity of domes. There are limitations to these models including the reliability of porosity data and the exclusion of other variables contributing to dome collapse.

An improved model would incorporate a better understanding of mechanics within lava domes as well as other factors in dome collapse besides UCS. Knowledge of dome mechanics would allow us to accurately portray how failure inside a dome begins. Other factors such as rainfall, seismicity and tensile strength would make a more accurate and comprehensive model.

VII. Acknowledgements

We would like to thank Frontiers Abroad and the University of Canterbury Geology Department for making this research possible. We also greatly appreciate the help from Sarah Pope, Marlene Villeneuve and the technical staff at the UC Geology labs, who with their combined efforts made this project possible.

VIII. References

Al-Harthi A, Al-Amri R, Shehata W 1999. The porosity and engineering properties of vesicular basalt in Saudi Arabia. Engineering Geology 54(3): 313-320.

Ashwell P 2014. Controls on rhyolite lava dome eruptions in the Taupo Volcanic Zone.

ASTM 1984. Standard test method for unconfined compressive strength of intact rock core specimens. Soil and Rock, Building Stones: Annual Book of ASTM Standards 4.08.

Baud P, Wong T-f, Zhu W 2014. Effects of porosity and crack density on the compressive strength of rocks. International Journal of Rock Mechanics and Mining Sciences 67: 202-211.

Chang C, Zoback MD, Khaksar A 2006. Empirical relations between rock strength and physical properties in sedimentary rocks. Journal of Petroleum Science and Engineering 51(3): 223-237.

Gardner JE, Hilton M, Carroll MR 1999. Experimental constraints on degassing of magma: isothermal bubble growth during continuous decompression from high pressure. Earth and Planetary Science Letters 168(1): 201-218.

Heap M, Lavallée Y, Petrakova L, Baud P, Reuschle T, Varley N, Dingwell DB 2014a. Microstructural controls on the physical and mechanical properties of edifice-forming andesites at Volcán de Colima, Mexico. Journal of Geophysical Research: Solid Earth 119(4): 2925-2963.

Heap MJ, Xu T, Chen C-f 2014b. The influence of porosity and vesicle size on the brittle strength of volcanic rocks and magma. Bulletin of Volcanology 76(9): 1-15.

Isida M, Nemat-Nasser S 1987. On mechanics of crack growth and its effects on the overall response of brittle porous solids. Acta metallurgica 35(12): 2887-2898.

Iverson R 1990. Lava domes modeled as brittle shells that enclose pressurized magma, with application to Mount St. Helens. Lava Flows and Domes, Springer Berlin Heidelberg. Pp. 47-69.

Matthews AJ, Barclay J, Carn S, Thompson G, Alexander J, Herd R, Williams C 2002. Rainfall-induced volcanic activity on Montserrat. Geophysical Research Letters 29(13).

Nakada S, Shimizu H, Ohta K 1999. Overview of the 1990–1995 eruption at Unzen Volcano. Journal of Volcanology and Geothermal Research 89(1): 1-22.

Sammis CG, Ashby MF 1986. The failure of brittle porous solids under compressive stress states. Acta Metallurgica 34(3): 511-526.

Scheu B, Kern H, Spieler O, Dingwell D 2006. Temperature dependence of elastic P-and S-wave velocities in porous Mt. Unzen dacite. Journal of volcanology and geothermal research 153(1): 136-147.

Schipper CI, Castro JM, Tuffen H, Wadsworth FB, Chappell D, Pantoja AE, Simpson MP, Le Ru EC 2015. Cristobalite in the 2011–2012 Cordón Caulle eruption (Chile). Bulletin of Volcanology 77(5): 1-19.

Tuffen H, James MR, Castro JM, Schipper CI 2013. Exceptional mobility of an advancing rhyolitic obsidian flow at Cordón Caulle volcano in Chile. Nature communications 4.

Vallance JW, Siebert L, Rose WI, Girón JR, Banks NG 1995. Edifice collapse and related hazards in Guatemala. Journal of Volcanology and Geothermal Research 66(1): 337-355.

Voight B 2000. Structural stability of andesite volcanoes and lava domes. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 358(1770): 1663-1703.

Wimmer SA, Karr DG 1996. Compressive failure of microcracked porous brittle solids. Mechanics of materials 22(4): 265-277.

Yamamoto T, Takarada S, Suto S 1993. Pyroclastic flows from the 1991 eruption of Unzen volcano, Japan. Bulletin of Volcanology 55(3): 166-175.

IX. Figures

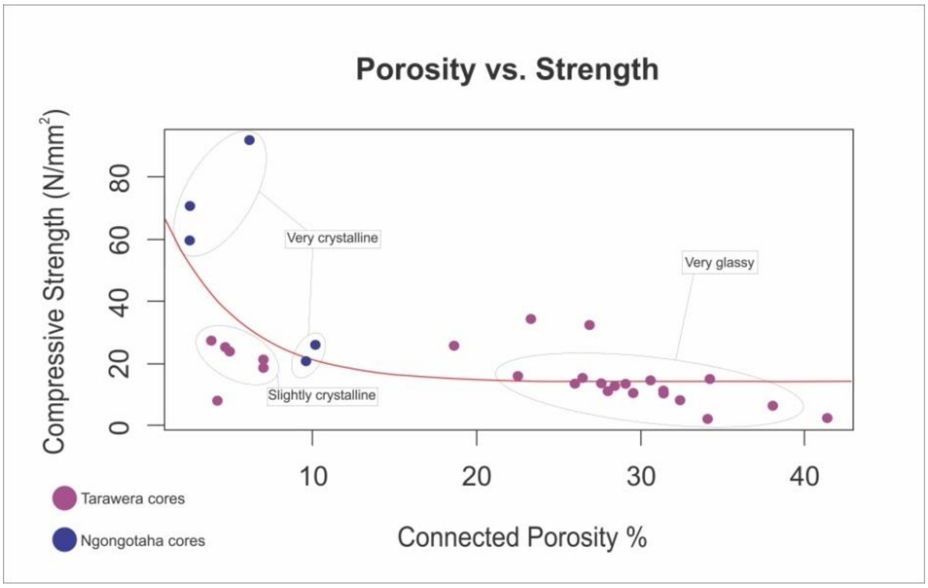

Figure 1. Scatterplot and function relating connected porosity to UCS. Some data points are grouped together based on relative crystallinity/glassiness determined through visual analysis.

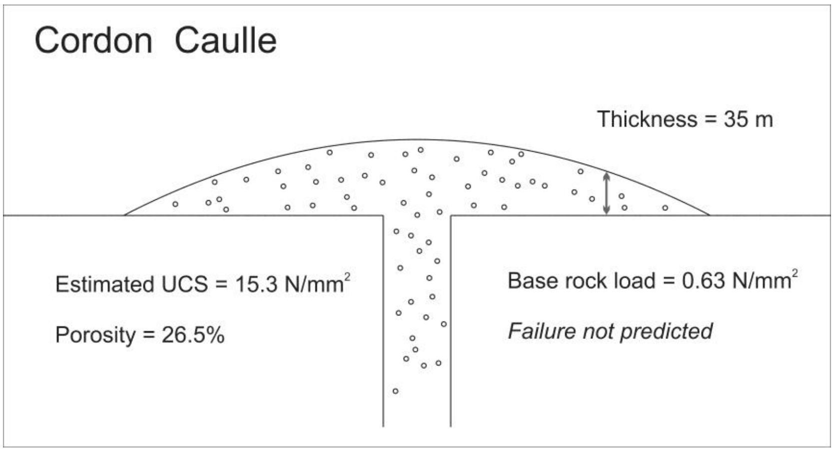

Figure 2. Cordón Caulle model showing connected porosity and flow thickness.

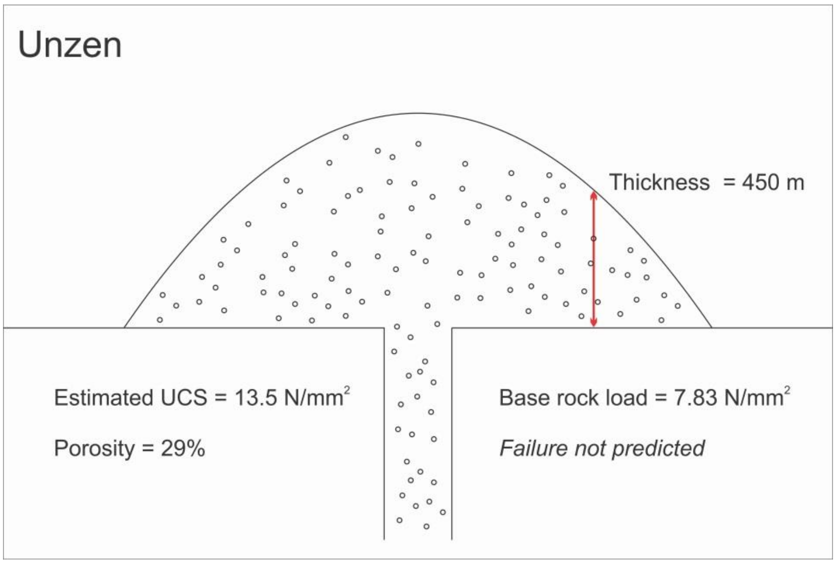

Figure 3. Unzen model showing connected porosity and dome thickness.

For submission to *The Journal of Volcanology and Geothermal Research*

Keywords: *volcano, stability, Cordón Caulle, Unzen, failure*