Ready, Aim, Fire!: Controls on Mount Ngauruhoe's eruption style

Andrew Zuza
The Department of Geological Sciences, University of Canterbury, Christchurch 8442, New Zealand

ABSTRACT

Mount Ngauruhoe, located in the southwest portion of the Taupo Volcanic Zone, has more than 60 diverse lava flows and block-and-ash deposits. The distinctive volcanic deposits of this young andesitic cone record a fluctuation between effusive, strombolian, vulcanian, and sub-plinian eruption styles. While many factors work together to influence eruption style, eruption rates seem to have the greatest influence. It is believed that magma composition and conduit characteristics most affect magma ascension rates, and so they greatly affect eruption style. I examined the volcanic deposits of the Ngauruhoe cone to determine what specific characteristics led to the varied volcanic deposits. Lava flow morphologies and physical characteristics, along with historical data from recent eruptions, were used to infer information regarding the connection between conduit attitude and magma ascension. There is a strong connection between eruption rates and eruption styles for the Ngauruhoe cone. It was determined that mass eruption rates in the order of 10^3 kg/s or lower produce effusive eruptions, eruption rates over 10^5 kg/s generate exclusively explosive eruptions, and eruption rates in between result in a combination of styles. The variation in lava flow lengths may be the product of a lengthening conduit. A longer conduit results in the erupting lava column placing more pressure on the magma chamber, subsequently leading to shorter, less voluminous eruptions. Magma composition played a smaller role in affecting the lava flows since there is little geochemical variation amongst the diverse volcanic deposits. Eruption rates and conduit characteristics are closely related, and they probably have the greatest effect on the varied eruptions at Mount Ngauruhoe.

INTRODUCTION

Mount Ngauruhoe is a stratovalcano located in the Taupo Volcanic Zone (TVZ) on the North Island of New Zealand. It is the youngest active cone of the Tongariro composite volcano complex. The basaltic-andesite volcano has been growing rapidly since about 2.5kya, fluctuating between effusive, strombolian, vulcanian, and sub-plinian eruption styles (Hobden 2002). These different eruption styles have lead to a variety of lava and block-and-ash deposits. Volcanic eruption style is controlled by the complex interactions of a variety of factors, including magma composition, cone orientation, eruption rate, and conduit attitude. In this paper, I examine Ngauhuhoe's past deposits and volcanic history in order to understand the specific volcanic characteristics that affect eruption style and magnitude.

There is good evidence to suggest that magma ascension rates, and subsequent eruption rates, most affect the volcanic eruption style (Hobden 2002, Szramek et al. 2006, & Pioli et al. 2009). Slower eruption rates allow the gas within the magma to leave the melt, whereas faster eruptions do not allow the gas to escape the magma; this built up gas causes explosive eruptions. After an in-depth literature review, it was determined that the physical volcanic characteristics of Ngauruhoe's vent most affect its eruption rates: mainly the conduit and vent characteristics. Magma composition plays a significantly smaller role in affecting the variation amongst these eruptions, mainly because the there is little compositional variation amongst Ngauruhoe's eruptions.

To further understand and substantiate these characteristics, field work was conducted northwest of the Ngauruhoe cone in the Mangatepopo Valley, which has most representative sequence of volcanic flows, ranging from the oldest prehistoric flows (~2.5kya) to the most recent block-and-ash flows of 1975. Comprehensive mapping of the lava flows was conducted in order to determine the relative ages of deposits and to understand the flow morphology. Exact dating of the flows is difficult, but the Mangatawai Tephra fall unit (2.5kya) and the Taupo ignimbrite deposits (1.85kya) provide two absolute time horizons (Hobden 2002). Stratigraphic relationships and morphological features, including flow levees and ogive structure orientations, were utilized to develop the relative ages of the flows. Geochemical work (X-ray fluorescence) was also conducted on representative samples of the deposits to look at evolutionary trends in the lava chemistry and to better understand the associations between different lava flows. Additionally, hand samples were studied to look at the changes in vesicularity of the volcanic deposits through time.

Pioli et al. (2009) loosely determined quantitative eruption rate constraints for eruption style. They found that volcanoes that erupt material at a rate less than 10^3kg/s are typically effusive or strombolian, while eruptions with mass eruption rates greater than 10^5kg/s are usually explosive with no effusive activity. Eruption rates in between, 10^3kg/s to 10^5kg/s, tend to lead to explosive eruptions with lava flows. Using data from Hobden (2002), mass eruption rates were calculated for several of Ngauruhoe's historical eruptions.

Conditions within the volcanic conduit greatly affect magma ascension rates and eruption style. Work done by Stasiuk and Jaupart (1996) has shown how the overburden pressure from the lava column and the general conduit characteristics can affect the nature and morphology of lava flows. They establish that an important control on eruption characteristics is the pressure number, which is the ratio between the weight of the erupting lava column above the vent to the initial overpressure within the magma chamber. A large pressure number means that the initial pressure within the erupting chamber is relatively small compared to the pressure resulting from the erupting lava column. This leads to short-live eruptions, since the pressure of the erupted lava quickly balances initial pressure within the chamber, which ultimately ceases the eruption. A small pressure number signifies that there is initially high overpressure within the magma chamber and so the pressure that erupting lava has on the pressurized chamber is minimal. Stasiuk and Jaupart (1996) found that long and thin lava flows are produced by strongly overpressured chambers with narrow conduits (low pressure number), whereas thicker, shorter flows result from a wider conduit with less initial pressure within the magma chamber (high pressure number). The shape and extent of Nguaruhoe's lava flows were examined considering Stasiuk and Jaupart's (1996) work.

EVOLUTION OF VOLCANIC DEPOSITS

Overall, the observable lava flows become shorter with time, so that the oldest flows form the most distal edges of the lava field, which is consistent with observations at other andesitic lava fields (Linnemann and Borgia 1993). All of the visible pre-historic deposits are lava flows. There are several block-and-ash deposits from historical eruptions, notably eruptions in 1945, 1954, and 1975. There are also many lava flows from historical eruptions. It is difficult to say whether or not this trend represents an increase in explosive eruptions with time, since older explosive eruptions may be masked by more recent lava flows.

Most of the volcanic deposits are geochemically similar. Trace element concentrations between the deposits are almost identical (Figure 1). The major element makeup of the flows shows some variation, but there is no obvious trend for changes with time (Figure 2). A very gradual, and somewhat noisy, increase in silica content through time is evident.

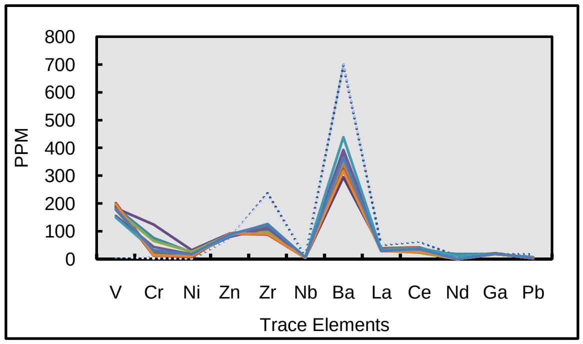

Figure 1: Plot of trace elements for volcanic deposit samples in the Mangatepopo Valley. Solid lines represent Ngauruhoe's volcanic flows and dotted lines represent pumice samples from the Taupo ignimbrite.

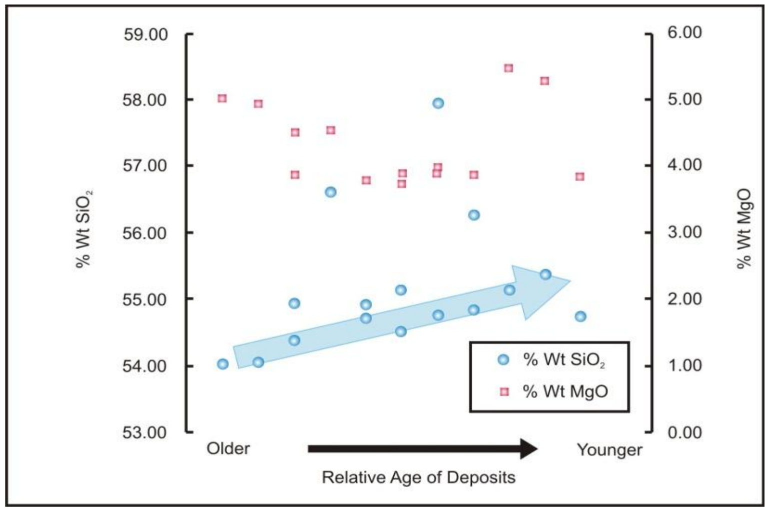

Figure 2: Plot of MgO and SiO_2 weight percentages of lava flows through relative time.

ERUPTION RATES

It is difficult to examine the eruption rates of the prehistoric eruptions. Eruption rate data exists for the observable historical eruptions. There is excellent correlation between eruption styles and eruption rates, where higher eruption rates lead more to vulcanian eruptions, like the 1975 eruption, and lower eruption rates tend to favor strombolian and effusive eruptions, such as the 1954 eruption (Hobden 2002). Using an average density of the basaltic-andesite pyroclastic deposits from the 1975 eruption as reported by Lube (2007) and the average density of basaltic-andesite lava deposits stated by Kilburn (2000), mass eruption rates were calculated (Table 1). There undoubtedly minor density variations amongst the different deposits, but the order of magnitude is most important for the recalculated rates. The eruption rates follow the constraints suggested by Pioli et al. (2009), where eruption rates in the order of 10^3 kg/s or below produce effusive eruptions, eruption rates over 10^5 kg/s generate exclusively explosive eruptions, and eruption rates in between result in a combination of the previous two states. Therefore, it may be inferred that Ngauruhoe's prehistoric deposits, which are all lava flows, were emplaced during eruptions with eruption rates less than 10^5kg/s. No block-and-ash deposits of prehistoric eruptions have been identified, so it is likely that many of the prehistoric eruptions may have had rates less than 10^3kg/s.

Data regarding the vesciularity of the flow deposits is scattered (Figure 3). Through time, vesicle size varies seemingly randomly, with no clear trend. The volume of vesicles in flow deposits follows a very faint, increasing trend with time. Increased vesicularity may represent faster magma ascension rates since the gases in the magma would have less time to escape the melt.

CONDUIT CONDITIONS

The vent of Ngauruhoe has remained in a relatively static position (Hobden 2002), so it is likely that the main vertical conduit has also remained somewhat stationary. Successive eruptions would have led to the evolution of this main conduit. Following Stasiuk and Jaupart's (1996) model, a conduit's condition can be described by its pressure number. The

Eruption Date	Dominant Style	Description	Rate 1 (m^3/s)	Rate 2 (m^3/s)	Recalculated rate (kg/s)
19 February 1975	Vulcanian	Ash fall + block-and-ash flow	280		$6.7x10^5$
27-29 March 1974	Vulcanian	Ash fall	70		1.710^5
13 May - 26 September 1954	Strombolian/ effusive	Lava flows + block-and-ash flows + scoria cone		0.65	$1.6x10^3$
9 - 12 February 1949	Strombolian/ effusive/Vulcanian	Whole eruption		3.6	$9.0x10^3$
		Episode 1 (block-and-ash flow)	9.4		$2.3x10^4$
		Episode 2 (lava flow)	2.7		$6.8x10^3$

Table 1: Adapted from Hobden (2002). Eruption characteristics of selected historical eruptions. Eruption rates calculated from individual eruption pulses (rate 1) or averaged over the whole eruption period (rate 2). Mass eruption rates of block-and-ash deposits use a density of 2400 kg/m^3 as proposed by Lube (2007) and mass eruption rates of lava flows use a density of 2500 kg/m^3 as reported by Kilburn (2000).

actual numerical value of this number is less important than the ratio that it represents: the weight of an erupting lava column compared to the initial pressure within the magma chamber. Eruptions with a low pressure number are not slowed by the weight of the erupting lava column and so they occur as long-lived eruptions that produce voluminous, widespread lava flows. High pressure number eruptions are "plugged up" by the mass of the erupting lava. Consequently, these eruptions are shorter and produce smaller lava flows. Following this concept, the most voluminous flows on Ngauruhoe, the oldest flows, would have been the products of lower pressure number eruptions, whereas the smaller flows resulted from eruptions with a larger pressure number. If this is the case, there has been a shift towards eruptions with larger pressure numbers with time.

DISCUSSION

It is relatively clear that magma ascension rate is a dominant control on eruption style. At least with the historical eruptions on Ngauruhoe, eruptions that occur at rates less than 10^3kg/s seem to produce solely effusive eruptions. This is probably the case for the pre-historic eruptions rates. Magma ascension is such a controlling factor because it influences the decompression and degassing of the rising magma. Work on similar basaltic-andesite volcanoes, such as Arenal in Costa Rica, can provide insight into the magma decompression and ascension rates associated with different eruptions. At Arenal, the cutoff between large, explosive eruptions and smaller explosive/effusive eruptions occurs with a decompression rate of about .0013MPa/s, which corresponds to a magma ascension rate of around .05m/s (Szramek 2006). Faster ascension and decompression rates do not allow the gas to escape the magma, which ultimately leads to more explosive eruptions. The slight trend of increasing vesiculiarty may mean that overall magma ascension rates have been increasing with time. Further work to establish decompression rates at Ngauruhoe would be useful to compare with the published rates at Arenal. It is likely that the eruptions at Ngauruhoe experience similar decompression rates.

The increase in pressure number over time may represent the growth of Mount Ngauruhoe. As Ngauruhoe's cone has grown over the last 2,500 years, the vertical length of the conduit has increased. With this increase in length of the near vertical conduit, the erupting lava is more massive and exerts more pressure on the magma chamber below it. This could potentially result in shorter eruptions because the pressure of the erupting lava would more rapidly balance out the pressure within the magma chamber. The Ngauruhoe cone is approximately one thousand meters tall, so a rough approximation would suggest that the conduit has had a thousand meter increase in length since genesis of the Mount Ngauruhoe. This could have resulted in an additional pressure of 24.5 MPa:

$$1000\ \text{m}\left(\frac{2500\text{kg}}{\text{m}^3}\right)\left(\frac{9.8\ \text{m}}{\text{s}^2}\right) = 24500000\,\frac{\text{kg}}{\text{m s}^2} = 24.5\text{MPa}$$

This means that during recent eruptions, Ngauruhoe's magma chamber may have experienced about 24.5 MPa more pressure from the erupting lava column than it did during its earliest eruptions. At the Arenal volcano, the non-erupting magma chamber is believed to have pressures between 100 and 150 Mpa (Szramek 2006). If Ngauruhoe has a somewhat similar magma chamber, the 24.5 MPa increase in pressure during eruptions is considerable—roughly 16 to 25 percent of the total pressure within the magma

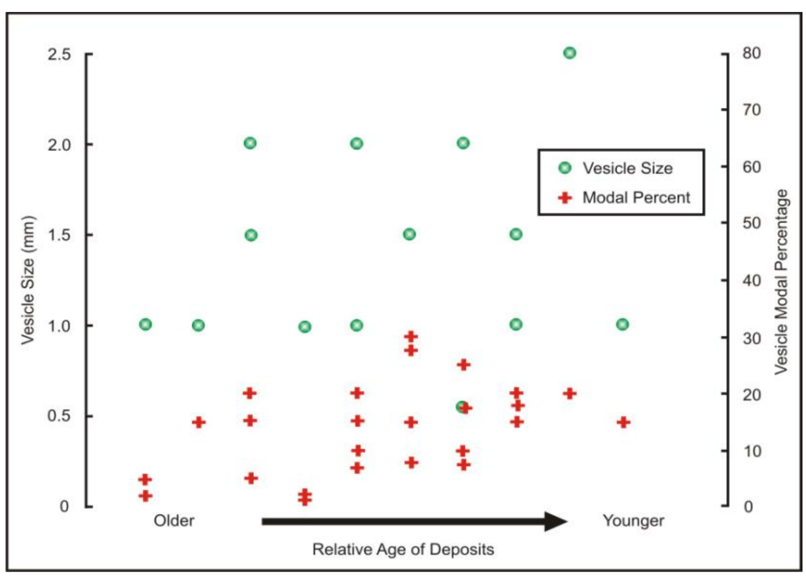

Figure 3: Plot of maximum vesicle sizes and vesicle modal percentages of lava samples through time

chamber. This would lead to shorter, less voluminous eruptions, which explains why the older flows are larger. Additionally, greater pressures would keep more gas bubbles within the erupting lava, which may explain the increase in vesicularity within the lava deposits. Increased pressure may also explain a shift towards more explosive eruptions in recent times.

In general, the oldest, longest flows are less siliceous than the more recent flows. The increased silica content of more recent flows may partly explain why these flows have shorter flow lengths. The increase in silica may also be responsible for trend of mostly explosive, ashy eruptions on historical timescales. The variation in silica content is not great enough to be the main contributor to any of the changes that are seen with Ngauruhoe's eruptions styles. Overall, the geochemical composition of the magmas and lavas seems to be less significant in controlling Ngauruhoe's eruption styles than changes in physical characteristics.

Several significant uncertainties prevent further understanding of the controls of Mount Ngauruhoe's eruption style. It is unclear how many of the past, prehistoric eruptions were explosive in nature. There may have been significantly less in the past, or it is also possible that the explosives eruptions, which produce less voluminous and extensive deposits, are underrepresented in Ngauruhoe's past because they have become covered by more recent flow deposits. Most of the explosive deposits from historic eruptions exist close to the vent, on the steepest slopes of Mount Ngauruhoe. This is where erosion occurs most rapidly. If past explosive eruptions deposited most material proximally, on the steepest slopes, they would have been easily eroded away.

CONCLUSION

It is clear that many factors interact to control eruption style. The fluctuation between effusive, strombolian, vulcanian, and sub-plinian eruption styles for Ngauruhoe's eruptions seems to mostly be due to changes in eruption rates. These rates are controlled by physical characteristics of the cone, rather than geochemical variations within the magma chamber. The minimal geochemical variation amongst different flows does not explain the great diversity of volcanic deposits. A growing conduit may have the largest effect on eruption rates, since a longer erupting column places more pressure on the magma chamber. Further work on the evolution of Ngauruhoe's physical crater would be beneficial to better understand how rising magma is affected as it comes to the surface. Other volcanoes may be affected by other characteristics at differing magnitudes, but it is likely that the eruptions of young, rapidly developing basaltic-andesite volcanoes are most affected by magma ascension rates and physical properties.

ACKNOWLEDGEMENTS

I thank Darren Gravely for helpful discussion and advice. This manuscript benefited from the constructive reviews of the Frontiers Abroad team. I am also grateful to Anekant Wandres, Stephen Brown, and Robert Spiers for their laboratory assistance.

REFERENCES CITED

Allen L.R., 1948, "Activity at Ngauruhoe, April–May 1948", *N Z J Sci Tech* B30:187–193.

Allen L.R., 1949, "The eruption of Ngauruhoe, February–March 1949", *N Z Sci*, *Rev* 7:180–183.

Gregg D.R., 1956, "Eruption of Ngauruhoe 1954–1955", *NZJ SciTech*, B37:675–688.

Hobden, B.J., Houghton, B.F. & Nairn, I.A. 2002, "Growth of a young, frequently active composite cone: Ngauruhoe volcano, New Zealand", *Bulletin of Volcanology,* vol. 64, no. 6, pp. 392-409.

Kilburn, C.R.J 2000 "Lava flows and flow fields", *Encyclopedia of Volcanoes,* Academic Press, Sydney, pp. 291-305.

Linnemann SR, Borgia A., 1993, "The blocky andesitic lava flows of Arenal volcano, Costa Rica." *Active lavas: monitoring and modelling*, UCL Press, London, pp. 25–72.

Lube, G., Cronin, S.J., Platz, T., Freundt, A., Procter, J.N., Henderson, C. & Sheridan, M.F. 2007, "Flow and deposition of pyroclastic granular flows: A type example from the 1975 Ngauruhoe eruption, New Zealand", *Journal of Volcanology and Geothermal Research,* vol. 161, no. 3, pp. 165-186.

Nairn I.A., Self S., 1978, "Explosive eruptions and pyroclastic avalanches from Ngauruhoe in February 1975", *Journal of Volcanology and Geothermal Research*, Res 3:39–60.

Nairn I.A., Hewson C.A.Y., Latter J.H., Wood C.P., 1976 "Pyroclastic eruptions of Ngauruhoe Volcano, central North Island, New Zealand 1974 January and March", *Volcanism in Australasia*, pp 385–405.

Pioli, L., Azzopardi, B.J. & Cashman, K.V. 2009, "Controls on the explosivity of scoria cone eruptions: Magma segregation at conduit junctions", *Journal of Volcanology and Geothermal Research,* vol. 186, no. 3-4, pp. 407-415.

Stasiuk, M.V. & Jaupart, C. 1997, "Lava flow shapes and dimensions as reflections of magma system conditions", *Journal of Volcanology and Geothermal Research,* vol. 78, no. 1-2, pp. 31-50.

Szramek, L., Gardner, J.E. & Larsen, J. 2006, "Degassing and microlite crystallization of basaltic andesite magma erupting at Arenal Volcano, Costa Rica", *Journal of Volcanology and Geothermal Research,* vol. 157, no. 1-3, pp. 182-201.

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D. & Briggs, R.M. 1995, "Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review", *Journal of Volcanology and Geothermal Research,* vol. 68, no. 1-3, pp. 1-28.