EXPERIMENTAL CALIBRATION OF PHREATIC AND HYDROTHERMAL EXPLOSIONS: A CASE STUDY ON LAKE OKARO, NEW ZEALAND

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ABSTRACT

Phreatic and hydrothermal explosions often occur with little or no warning and represent a significant hazard in geothermal areas. They occur at a range of temperatures and pressures within varying rock types and can lead to increased local permeability and the development of shallow hydrothermal resources. A range of mechanisms including heating or decompression allows hydrothermal/supercritical fluid to rapidly flash to steam, triggering an eruption.

Previous studies have focused exclusively on either physical characteristics of explosions or experimental modelling of trigger processes. Here, a new experimental procedure has been developed to model phreatic fragmentation based on shock tube experiments for magmatic fragmentation by Alidibirov & Dingwell (1996). Water saturated samples are fragmented from a combination of argon gas overpressure and steam flashing within vesicles. By integrating physical characteristics of porosity, permeability and mineralogy with analysis of these experimental results, a model of phreatic fragmentation is proposed to aid future hazard modelling in geothermal areas.

The explosion forming Lake Okaro, Taupo Volcanic Zone, was used as a case study. The Rangitaiki ignimbrite represents the stratigraphically lowest unit seen within the breccia deposits. Therefore we suggest the explosion was generated within this rock type and have used this as the experimental sample material. To evaluate alteration effects, both the original material and hydrothermally altered samples were analysed. Experiments were performed at room temperature and 300°C with pressures from 4 to 15 MPa, to reflect the conditions at the study location, while also assessing the effect of water saturation on fragmentation. First analyses of grain sizes reveal a clear shift to smaller grain sizes with water saturated samples (independent of pressure or sample type) possibly reflecting improved efficiency in the conversion of energy, most likely in combination with strength reduction due to water weakening effects. We provide herewith a first parameterisation of conditions for phreatic and hydrothermal eruptions and offer an explanation for the reduction in grain size associated with phreatic eruptions.

1. INTRODUCTION

Phreatic and hydrothermal explosions are the most common form of volcanism on Earth, often occurring suddenly and without warning. Although common, these systems remain poorly understood. Knowledge in this area is critical for improved hazard and risk assessment, particularly for the geothermal industry which invests millions of dollars in the most susceptible areas. Previous studies (Browne & Lawless, 2001; Germanovich & Lowell, 1995; Hedenquist & Henley, 1985) investigate either the physical characteristics of eruptive sites or modelling the processes that trigger these explosions, without linking the two.

The unpredictable nature of these explosions results from the wide ranging pressure and temperature conditions over which they occur, as well as the many trigger mechanisms. Such mechanisms range from surface processes including landslides, dome collapse or crater-lake break-out, through to magmatic processes including rapid magma ascent or intrusion, ultimately leading to either heating or decompression driven degassing of H_2O and or CO_2 (Nairn et al., 2005). Anthropogenic activity during geothermal exploration and production can also cause significant decompression therefore triggering these explosions (Hedenquist & Henley, 1985). Whatever the source mechanism, the explosions are triggered when water or supercritical fluid flashes to steam through either rapid decompression or heating, producing over-pressure and fragmentation.

Fragmentation occurs when the strength of the magma or rock is overcome, for instance due to a pressure differential across a rapidly decompressing sample. The minimum pressure change required to produce full fragmentation of a sample is defined as fragmentation threshold (Spieler et al., 2004). Connected porosity has a significant influence, controlling the amount of gas available for decompression and therefore the energy produced during fragmentation (Spieler et al., 2004; Alatorre-Ibargüengoitia et al., 2010). Previous studies have shown an inversely proportional relationship between these two characteristics (Spieler et al., 2004).

Here we used an experimental set-up based on Alidibirov and Dingwell's (1996) shock tube experiments for magmatic fragmentation. Fragmentation of water saturated samples occurs as a result of argon gas overpressure and steam flashing within the vesicles, occurring after rapid decompression. With this set-up a wide range of volcanic conditions can be modelled, including temperature and decompression amount. This enables direct measurement of fragmentation characteristics including grain size, fragmentation and particle velocity. All are essential parameters for understanding the processes causing phreatic and hydrothermal fragmentation. To constrain how these explosions occur, we have modelled a 700 year old explosion crater, Lake Okaro (Hardy, 2005). Samples from the crater have been characterised to determine physical properties such as porosity and mineralogy along with experimentally derived parameters to better understand how this eruption occurred. In the future this can be applied to other geothermal settings to improve hazard modelling and reduce the risk associated with these explosions.

2. GEOLOGICAL SETTING AND MODEL OF LAKE OKARO

Lake Okaro is located within the central Taupo Volcanic Zone, forming part of the Waiotapu geothermal system. Its location and formation, along with many other explosion craters within this area, is strongly linked to the Ngapouri fault (Hedenquist & Henley, 1985). Ngapouri is a NE-SW striking normal fault, outcropping 500 m southeast of the lake (Nairn et al., 2005). It is thought that the system was primed by the intrusion and degassing of a dyke associated with the Kaharoa phase from Mt Tarawera. The dyke may have caused initial faulting but most importantly provided gasses and heat to prepare the geothermal system. With the system primed, only a small trigger was required to produce the explosion (Browne & Lawless, 2001).

Although crater wall slumping has left a lake only 18 m deep (Irwin, 1974), maximum crater depths have been estimated based on volume of breccia erupted. Hedenquist and Henley (1985) calculated a depth of 100 m from a breccia volume of 3.7×10^6 m^3 (Cross, 1963), density of 2.0 g/cm^3 and crater shape part way between an inverted cone and cylinder. Two major stratigraphic units occur within this depth range (Figure 1): the shallower Earthquake Flat Pyroclastics and the deeper Rangitaiki Ignimbrite along with several minor units (Nairn, 1984; Hedenquist & Henley, 1985; Hardy, 2005; Molloy et al., 2008).

Laterally significant variations occur within the Rangitaiki Ignimbrite. This includes variation in welding, allowing some regions to act as aquifers while others act as aquitards (Lonker et al., 1990). Relatively high porosity values within our sample material indicate that within the hydrothermally altered zone the Rangitaiki forms an aquifer, while above it forms an aquitard. Rising gas increases the pressure within the hydrothermal system, priming it for explosion. The 100 m depth estimate proposed by Hedenquist and Henley (1985) confirms this model by placing the initiation point in the lower portion of the Rangitaiki Ignimbrite.

3. SAMPLE MATERIAL

To perform these experiments, Rangitaiki ignimbrite samples were collected from both the Okaro Breccia and nearby in-situ locations allowing comparisons between the hydrothermally altered material and the equivalent material in its unaltered form. Altered samples were collected from the breccia at various locations within 500 m of the lake, while the unaltered samples were collected from an outcrop of the Okataina Caldera boundary wall, just off Brett Road. Alteration is primarily illite-smectite with 30% illite, most likely indicating that alteration occurred in a liquid saturated hydrothermal system. From this material, cylindrical cores were drilled (25 mm in diameter and 40 mm in length). All cores were measured for density and porosity with helium pycnometry (Micromeritics Accupyc 1330) prior to any experiments. Altered and unaltered samples have average open porosities of 40% and 24% respectively. The samples were then saturated by submerging in water then placing under a vacuum for several minutes before releasing the vacuum, causing the pore spaces to fill with water.

4. EXPERIMENTAL METHOD

Several studies have been completed using the fragmentation device of Alidibirov and Dingwell (1996) to investigate magmatic fragmentation, with only preliminary experiments investigating phreatic fragmentation (Serr, 2010; Scheu et al., 2011). The fragmentation "bomb" is a shock tube apparatus made up of three main components (Figure 2). Firstly a high pressure autoclave containing the sample is used to represent the conduit. Above this is a large tank (3 m high and 0.4 m in diameter) at atmospheric pressure where the fragmented material is caught. These two components are separated a set of scored diaphragms, allowing opening of the pressurised autoclave at precisely calibrated pressures (e.g. Alidibirov & Dingwell, 1996; Spieler et al 2004; Alatorre- Ibargüengoitia et al. 2010). Using saturated samples, this set-up can be used to investigate phreatic fragmentation.

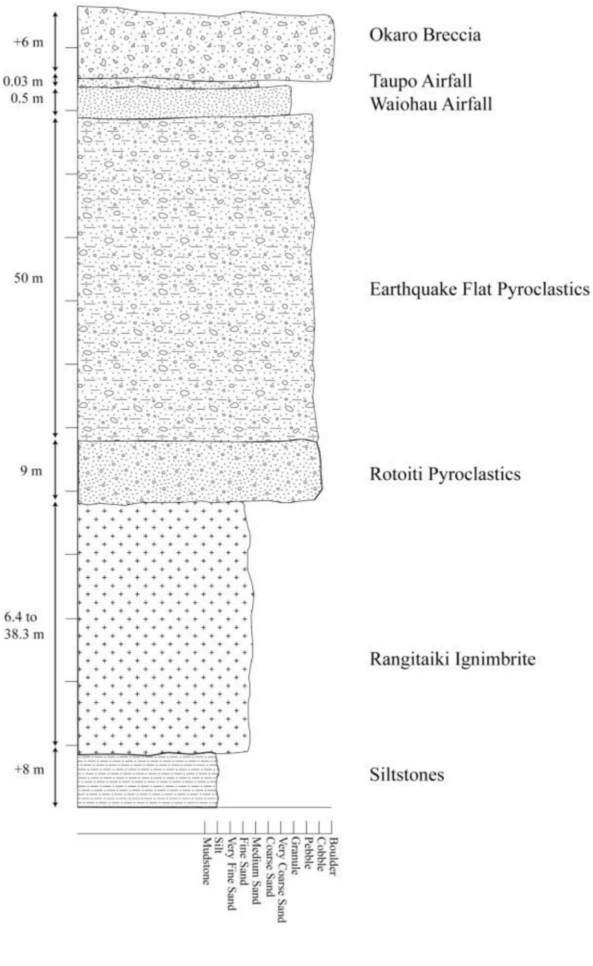

Figure 1: Composite stratigraphic log of units at Lake Okaro developed from various sources including bore logs and airfall thickness maps (Nairn, 1984; Hedenquist & Henley, 1985; Wilson & Walker, 1985; Hardy, 2005; Speed et al., 2002; Molloy et al., 2008).

Saturated samples are placed within the autoclave, then heated and pressurised with argon gas. Decompression is triggered by opening a pressure-release valve, which causes failure of the uppermost diaphragm and almost simultaneous rupture of the lower diaphragm. If the pressure differential is great enough fragmentation will begin, if not, the gas will simply filter through the sample (Spieler et al., 2004; Mueller et al., 2008). This rapid decompression produces a shock wave travelling through the air and a rarefaction wave propagating through the sample, ultimately producing layer by layer fragmentation (Spieler et al., 2004; Koyaguchi et al., 2008).

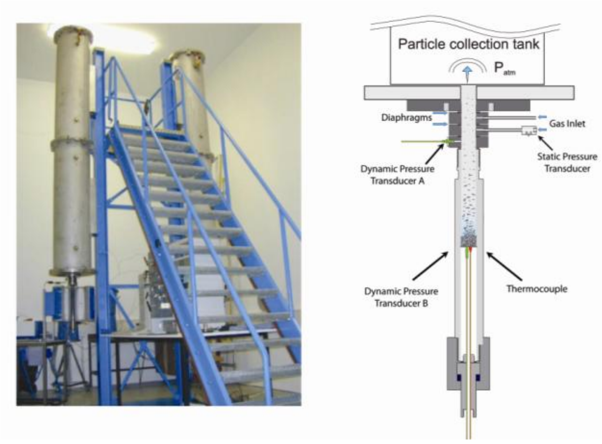

Figure 2: Experimental set-up of the fragmentation bomb (left) and details of the phreatic autoclave (right). The photo shows two fragmentation bombs with large tanks where particles are collected sitting above the furnace and autoclave. The schematic autoclave shows the sample location in respect to the pressure transducers, thermocouple and diaphragms.

Fragments are collected in the large tank. Rinsing this tank with pressurised (8.5MPa) desalinated water, enables recovery of more than 99% of particles (Kueppers et al., 2006). The particles are washed from the tank through a 125 µm sieve, separating out a coarse and fine fraction. The coarse fraction is dry sieved at half-Φ intervals down to 3.5 Φ, while the fines are analysed using a Beckman-Coulter LS230 for laser refraction.

Fragmentation velocities are obtained by measuring the time the fragmentation front needs to travels through the sample. Dynamic pressure sensors placed above and below the sample record when the pressure drops thereby indicating the start and end of the sample's fragmentation (Scheu et al., 2006). Together with the sample length, fragmentation velocity can easily be calculated.

A variety of fragmentation experiments were performed to investigate the effects of saturation, alteration and temperature (Figure 3). To obtain initial baseline data, we performed dry experiments on both altered and unaltered ignimbrite, then as a comparison we completed the same experiments with fully saturated samples. Both dry and saturated experiments were run at a variety of pressures (ranging from 4 MPa through to 15 MPa) and two temperature conditions (room temperature and 300°C).

5. RESULTS

Initial experiments were completed to obtain dry fragmentation thresholds for both altered and unaltered material. Although results within each sample type and temperature range show variation (Figure 4), they fit well with the inversely proportional threshold trends obtained in previous studies (Spieler et al., 2004; Kennedy et al., 2005; Scheu et al., 2006; Mueller et al., 2008). This suggests that sample material has little influence. All previous experiments have been performed on igneous rocks and we see little difference between them and the ignimbrites (of a sedimentary nature with variation in welding and structure) used in this study.

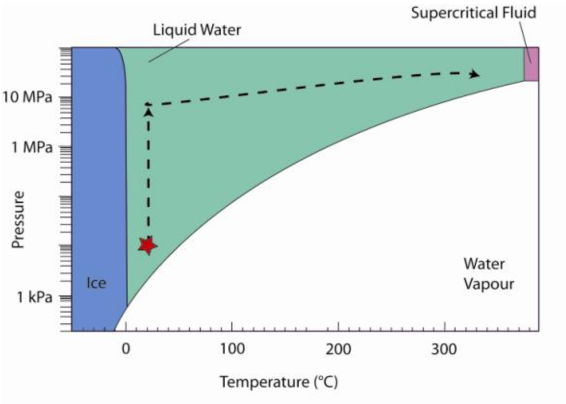

Figure 3: Pressure and temperature path shown for saturated experiments run at 300°C and 10 MPa. To ensure water stays in the liquid phase, samples were initially heated to 5 MPa before combined heating and pressurisation. Dry experiments were initially pressurised (1 MPa) to check for leaks, before heating then final pressurisation.

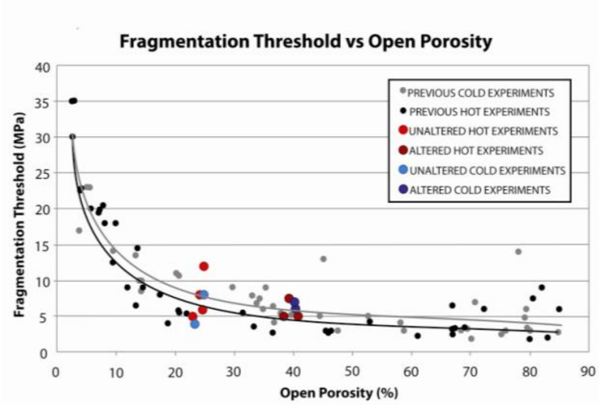

Figure 4: New fragmentation thresholds for ignimbrites plotted against data from previous experiments on volcanic samples. There is a clear correlation, indicating that the inversely proportional relationship between threshold and porosity holds.

After fragmentation thresholds had been established, experiments were performed just above the threshold at 8 and 10MPa, then significantly above the threshold at 15MPa. These pressures ensured full fragmentation every time, as well as accurate pressure recordings for speed analysis. Speeds obtained range from 14 to 42 m/s, with no significant differences observed between level of saturation, sample type or applied pressure.

Experiments were repeated to determine the accuracy of grain size distributions, with results showing almost identical weight fractions at each size interval, confirming reproducibility. A clear reduction in grain size occurs with saturation independent of applied pressure or sample type (Figure 5). With saturation there is also a greater distribution of sizes in comparison to the sharp peak of predominant grain sizes from dry experiments. Alteration appears to influence the grain size distribution, with higher applied pressure resulting in smaller fragments (Figure 6). This may occur as a result of clay strength and the threshold at which failure occurs. There is no change within the unaltered samples.

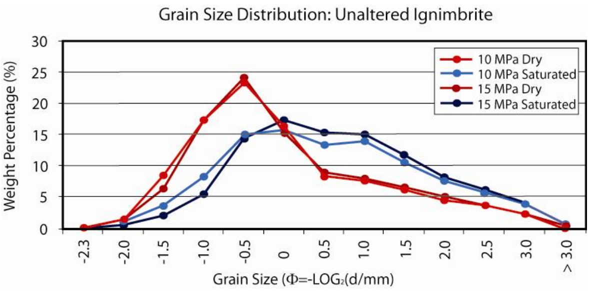

Figure 5: Grain size distribution for experiments on unaltered ignimbrite run at 300°C. Pressure has little influence but saturation causes a significant shift to smaller grain sizes with a greater spread.

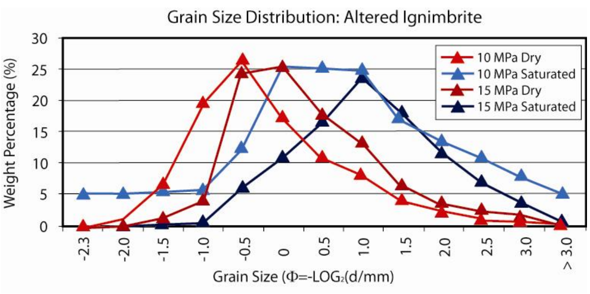

Figure 6: Grain size distribution for experiments on altered ignimbrite run at 300°C. In contrast to the unaltered samples here we can see a shift to smaller grain sizes with both pressure and saturation.

The key results can be summarised as follows:

1) Fragmentation thresholds for both unaltered and altered ignimbrites fit well with the trend of previously published results, indicating an inversely proportional relationship with porosity.
2) Fragmentation speed ranges between 14 and 42 m/s with no significant differences observed between dry and saturated samples, level of alteration or applied pressure.
3) Grain sizes are greatly reduced with saturation, independent of sample type or pressure.

6. DISCUSSION

The above findings derive from a series of rapid fragmentation experiments on samples collected to model a natural explosion occurring at Lake Okaro 700 years ago. As phreatic and hydrothermal eruptions occur rapidly with little warning, there are very few detailed observations or measurements that can be applied to understanding the fragmentation process. In most instances, information obtained from these explosions comes from deposits studied well after the eruptions have ceased. Here we have used experimental procedures to obtain an insight into these processes, gaining information that observations alone can not provide. We applied fragmentation parameters obtained from these experiments to the eruption forming Lake Okaro in order to gain a better understanding of how this eruption occurred.

The hydrothermal system beneath Lake Okaro was primed by degassing of a basaltic dyke (Figure 7). Fragmentation is initiated when decompression exceeds that of lithospheric pressure and the tensile strength of the overlying rocks. Combining assumed eruption depth (100 m) with the measured densities of ignimbrite (2.6 g/cm^3) and pumice from the Earthquake Flat Pyroclastics (1.0 g/cm^3) we can calculate an approximate minimum lithostatic load for this location. Assuming 60 m of pumiceous material and a maximum 40 m of ignimbrite we get a combined lithostatic load of 1.6 MPa. When added to the minimum fragmentation threshold of 4 MPa, which takes into account the tensile strength of the material, a reasonable estimate for the minimum pressure change required to trigger eruption at this location is less than 6 MPa (Figure 7).

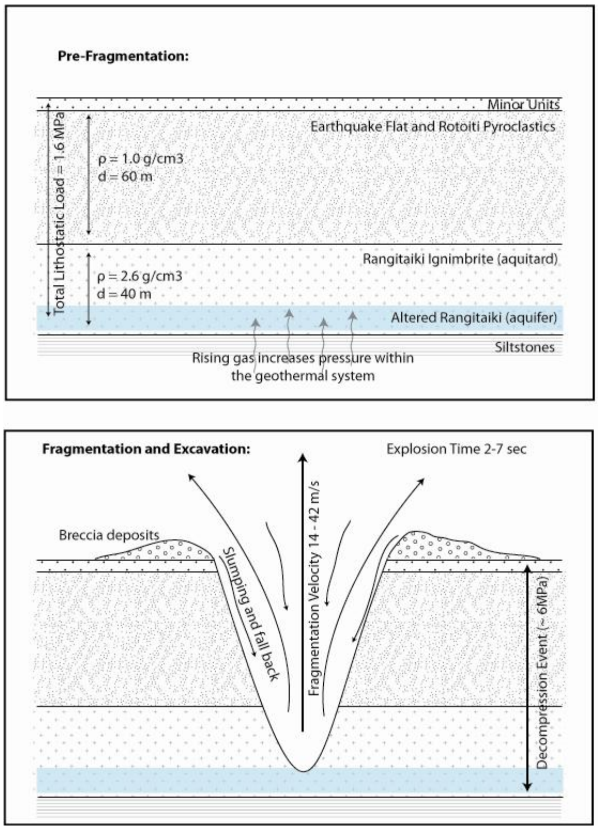

Figure 7: Schematic model of how the explosions at Lake Okaro occurred and the parameters influencing this.

Fragmentation energy is produced by gas expansion on decompression. Within the dry experiments this is simply expansion of the compressed argon gas, while in the saturated experiments liquid water flashes to steam. This represents hydrothermal systems where the phase transition between liquid and gas is not crossed (producing gas expansion explosions) compared to those that flash from liquid to vapour. The volume change and therefore energy produced within these two types of experiment is significantly different. Steam flashing produces a volume increase of about 1400 times, while the argon expansion is much smaller. This means that saturated conditions are much more explosive and release more energy than equivalent dry explosions. Additionally the water is known to cause a weakening effect on the strength of rocks thus further reducing particle sizes (Baud, et al., 2000).

When primed, only a small trigger may have been necessary to initiate fragmentation most likely from seismic activity, either through fault displacement or minor shaking (Browne & Lawless, 2001). After triggering, the explosion would occur rapidly. From eruption volume and depth calculated by Hedenquist and Henley (1985), combined with the experimental determination of fragmentation speed, eruption length can be estimated. Using the fastest and slowest fragmentation speeds from our study gives an eruption time of between 2 and 7 seconds, consistent with observations of true eruptions (Thuermer Jr., 2009).

As a result of the hydrothermal system and saturation of the source material our data indicates that much greater fragmentation energy is produced when the phase transition between liquid and vapour is crossed. This greater energy results in much finer grain sizes. As with magmatic eruptions finer grain sizes represent a greater hazard potential, as material can be transported over much greater distances. Around Okaro breccia deposits have been identified up to 1.3 km away from the lake (Cross, 1963) although fine material could have been transported further. Today only regional roads and farmland would be impacted by an eruption of this size but closer to a geothermal field or major infrastructure this would have major consequences. Results obtained through these experiments provide a quantitative measure of the effects of grain size reduction with saturation.

Findings such as these provide a starting point to quantify the decompression required to trigger explosions. Applied to geothermal drilling, these and future results will be able to significantly reduce the number of human induced explosions. Further experiments will enable a greater confidence in the reliability between fragmentation threshold and porosity, which acts as the basis for all further interpretations. This study has shown that the relationship holds not only for volcanic rocks but those that have undergone hydrothermal alteration as well. If porosity is known we can then estimate the fragmentation threshold, which combined with lithostatic pressure, indicates the minimum pressure change required to produce explosions. This indicates how stable the system is and hazard assessments can then be completed to determine if geothermal drilling is feasible.

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