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Experimental constraints on phreatic eruption processes at Whakaari (White Island volcano)

Klaus Mayer [a,*], Bettina Scheu [a], H. Albert Gilg [b], Michael J. Heap [c], Ben M. Kennedy [d], Yan Lavallée [a,e], Mark Letham-Brake [d,f], Donald B. Dingwell [a]

[a] Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München (LMU), Theresienstrasse 41/III, 80333 Munich, Germany
[b] Lehrstuhl für Ingenieurgeologie, Technische Universität München, Arcisstrasse 21, 80333 Munich, Germany
[c] Laboratoire de Déformation des Roches, Équipe de Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France
[d] Geological Sciences, University of Canterbury, Private Bag 4800, 8140 Christchurch, New Zealand
[e] Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool L69 3GP, United Kingdom
[f] Kakapo Disaster Resilience Trust, 2/48 Brockworth Place, Riccarton, Christchurch 8011, New Zealand

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ABSTRACT

Vigorous hydrothermal activity interspersed by sequences of phreatic and phreatomagmatic eruptions occur at Whakaari (White Island volcano), New Zealand. Here, we investigate the influence of sample type (hydrothermally altered cemented ash tuffs and unconsolidated ash/lapilli) and fragmentation mechanism (steam flashing versus gas expansion) on fragmentation and ejection velocities as well as on particle-size and shape. Our rapid decompression experiments show that fragmentation and ejection speeds of two ash tuffs, cemented by alunite and amorphous opal, increase with increasing porosity and that both are significantly enhanced in the presence of steam flashing. Ejection speeds of unconsolidated samples are higher than ejection speeds of cemented tuffs, as less energy is consumed by fragmentation. Fragmentation dominated by steam flashing results in increased fragmentation energy and a higher proportion of fine particles. Particle shape analyses before and after fragmentation reveal that both steam flashing and pure gas expansion produce platy or bladed particles from fracturing parallel to the decompression front. Neither fragmentation mechanisms nor sample type show a significant influence on the shape. Our results emphasize that, under identical pressure and temperature conditions, eruptions accompanied by the process of liquid water flashing to steam are significantly more violent than those driven simply by gas expansion. Therefore, phase changes during decompression and cementation are both important considerations for hazard assessment and modeling of eruptions in hydrothermally active environments.

1. Introduction

Phreatic eruptions are one of the Earth's most common, diverse and unpredictable types of eruption. They typically present a significant proximal hazard (e.g. Breard et al., 2014; Fitzgerald et al., 2014). Phreatic eruptions disintegrate and eject rock by the expansion of water as liquid, gas, or super-critical fluid (Morgan et al., 2009). Even though the ejecta contain no juvenile magma, magma at depth is nevertheless the heat source that provides the energy for the eruption. Expansion is triggered either by rapid decompression or by the heating of the system (Buttinelli et al., 2011). The pre-eruptive monitoring signals, typically associated with eruptions that yield juvenile material, may be wholly absent for phreatic eruptions (Hurst et al., 2014). At Whakaari also known as White Island volcano, New Zealand (Fig. 1), phreatic eruptions are associated with an increasing number of 1–5 Hz harmonic tremors (e.g., Nishi et al., 1996; Sherburn et al., 1998) and recent analysis has linked these events to progressive fracturing and fluid flow within the system (Chardot et al., 2015; Heap et al., 2015). Phreatic eruption dynamics vary between different hydrothermal systems, including individual eruption type from the same system and may not always follow the same patterns (Mastin, 1995; Foote et al., 2011). Phreatomagmatic processes have been investigated for over two decades using molten fuel–coolant interactions (e.g., Zimanowski et al., 1991), yet phreatic phenomena have been largely overlooked (cf. Scheu et al., 2011) in the relatively young field of experimental volcanology.

Crucial for all eruptions is decompression accompanied with the expansion of a fluid ascending to the surface. The favored model for eruptions within a hydrothermal system involves pressure build-up below a low-permeability cap rock, which fails once the pore fluid pressure exceeds the sum of lithostatic pressure and rock tensile strength (Browne and Lawless, 2001). This process may involve the flashing of water,

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* Corresponding author.
E-mail address: klaus.mayer@min.uni-muenchen.de (K. Mayer).

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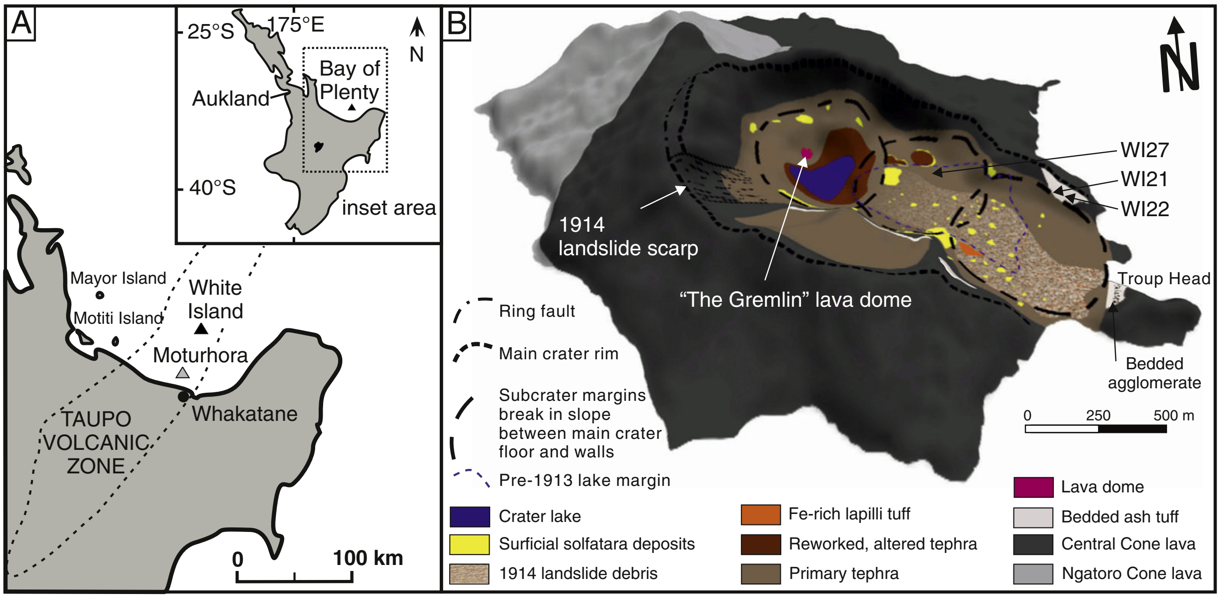

Fig. 1. (A) Location map of Whakaari (White Island volcano) approximately 50 km offshore in the Bay of Plenty within the Taupo Volcanic Zone. The inset shows a map of the North Island of New Zealand (modified from Moon et al., 2009). (B) Geological map of Whakaari showing in detail the distribution of unconsolidated crater fill (modified from Letham-Brake, 2013) and sampling sites for this study.

nearing boiling conditions, to steam and concomitant expansion due to a sudden depressurization event (Browne and Lawless, 2001). Phreatic eruptions occur over a wide range of pressure and temperature conditions and, thus, the system perturbations that give rise to phreatic eruptions may be triggered in multiple ways. Phreatic eruptions involving a reduction in the lithostatic pressure include dome collapses, landslides, and crater-lake drainages, whereas those involving an increase in temperature accompanying pressurization include adjacent magmatic intrusion and rapid magma ascent (Foote et al., 2011). Furthermore, anthropogenic interventions, such as geothermal drillings, may potentially lead to decompression events that trigger the sudden expansion of fluid within these porous media. As observed at Whakaari and many other volcanoes, phreatic eruptions can also serve as an opening phase of a later phreatomagmatic and/or magmatic eruption phreatic events (28 phreatic eruptions since 1826) exhibited at Whakaari (Fig. 2), the risk associated with the high number of tourists (>13,500 annual visitors; Letham-Brake, 2013) visiting Whakaari on a daily basis, and the relatively detailed knowledge of rock mechanics available (Moon et al., 2005; Heap et al., 2015) make Whakaari an exemplary case study for a detailed experimental investigation of phreatic processes.

A detailed survey of the literature revealed that >30 phreatic and phreatomagmatic eruptions (Fig. 2) have been recorded at Whakaari since 1826 (Letham-Brake, 2013). The recent eruptive event of 5th August 2012, associated with phreatic eruptions, led to the formation of a spiny lava dome in the crater (Global Volcanism Program, 2014). Past studies at Whakaari have focused on the surveillance and the prediction of future eruptive activity via monitoring of seismicity (Nishi et al., 1996; Sherburn et al., 1998; Jolly et al., 2012) and ground deformation (Clark and Otway, 1982; Fournier and Chardot, 2012; Peltier et al., 2009) as well as the emission (Werner et al., 2008; Bloomberg et al., 2014) and characterization of gases and fluids (Giggenbach et al., 2003). Furthermore, studies of the petrology (Graham and Cole, 1991), the origin and storage of magma (Cole et al., 2000), and the geotechnical characterization and geomorphic development of the edifice have been conducted (Moon et al., 2005, 2009; Heap et al., 2015).

Despite the abundance of previous phreatic eruptions at Whakaari and the preservation of deposits (e.g., Wood and Browne, 1996), no adequate constraints on the explosive parameters and mechanisms exist. Although the geological setting and hydrothermal system are relatively well-constrained, their interplay in general, as well as in view of the mechanisms triggering phreatic eruptions, is not yet fully understood. Adding to this complexity is the fact that the physical properties and mechanical behavior of Whakaari rocks are highly altered due to the activity of the hydrothermal system (Pola et al., 2013; Wyering et al., 2014; Heap et al., 2015). Changes in state of alteration during thermal stressing, as is the case during shallow (~500 m below sea level) magma intrusion, commonly induce mineral breakdown, which leaves a skeletal porous rock with deteriorated mechanical strength (Peltier et al., 2009; Heap et al., 2012).

The porosity of a rock controls the amount of gas stored and therefore the energy available for release during fragmentation for a given decompression step (Spieler et al., 2004; Alatorre-Ibargüengoitia et al., 2010). Earlier studies have defined the fragmentation threshold (the minimum pore pressure differential required to fully fragment the sample) as being inversely proportional to the porosity (Spieler et al., 2004). Foote et al. (2011) and Rager et al. (2013) have presented results of experimental phreatic fragmentation induced by both inert gas overpressure and steam flashing in vesicular rocks, and made an initial evaluation of the influence of pressure, sample alteration and sample saturation on these processes. Here, we present the results of a systematic experimental campaign employing a shock-tube apparatus (Aldibirov and Dingwell, 1996a) to perform decompression experiments on both hydrothermally altered consolidated and loose deposits, inferred to reflect those deposits existing at depth at Whakaari (Heap et al., 2015). Specifically, we have investigated the influence of sample type and fragmentation mechanism (steam flashing versus gas expansion) on grain size and shape and on fragmentation and ejection velocities.

2. Geological setting

Whakaari is New Zealand's most active volcano and is characterized primarily by phreatic and phreatomagmatic eruptions, interspersed by occasional strombolian events (Cole and Nairn, 1975; Simkin and Siebert, 1994). Located 50 km offshore from the North Island of New Zealand (Fig. 1), this andesitic–dacitic, stratovolcano exhibits strong fumarolic activity and outgassing (Bloomberg et al., 2014) interspersed by eruptive events. Whakaari is the northernmost active volcano within the Taupo Volcanic Zone (TVZ), which is itself a 250-km-long belt of mainly rhyolitic and andesitic, Quaternary to present volcanism