Host Rock Variability Powers the Diversity of Steam-Driven Eruptions

Cristian Montanaro¹,² ©, Shane J. Cronin² ©, Bettina Scheu¹ ©, Ben Kennedy³ ©, Bradley J. Scott⁴ ©, and Donald B. Dingwell¹ ©

¹Ludwig-Maximilians-Universität München, Munich, Germany, ²School of Environment, University of Auckland, Science Centre, Auckland Central, New Zealand, ³School of Earth and Environment, University of Canterbury, Christchurch, New Zealand, ⁴GNS Science, Wairakei, New Zealand

Abstract  Steam-driven eruptions are explosive events that are fueled by pressurized water and steam trapped within rock and sediments. We show how rock properties modulate explosion size, dynamics, and hazard footprint based on examples from Lake Okaro (New Zealand). Laboratory decompression experiments demonstrate that fragmentation of strong/unaltered host rocks comes with a high energy cost (≈10%-11% of bulk explosion energy). Consequently a low energy fraction (≈7%-8%) remains for kinetic energy and thus particle ejection. In contrast, disaggregation of unconsolidated sediments requires little energy (<2%-7%), allowing higher outputs of kinetic energy (22%-25%), and more efficient debris dispersion. Experimental estimates of bulk explosive energies are consistent with both field observations and empirical models applied to Lake Okaro crater dimensions. This integration of experimental methods, field observations, and empirical modeling underscores the dominant role of alteration state and host rock lithology when estimating crater-forming and ballistic hazards in volcanic/geothermal areas.

Plain Language Summary  Steam-driven eruptions are explosions that frequently occur in volcanic and geothermal areas. They are powered by the sudden release and expansion of steam and liquid water trapped under high pressure within the pore spaces of host rocks. Here we have experimentally studied how the strength of rock hosting steam and liquid controls the nature of explosions. Specifically, we used experiments to estimate the relative amounts of energy that goes into breaking rock up, versus that required for ejecting particles upwards and outwards. We used natural rock samples collected from well-studied explosion craters at Lake Okaro (New Zealand). Experiments recreated pressures and temperatures of the geothermal system and allowed sudden decompression of water saturated rock. We demonstrated that the porosity, permeability, and strength of rocks is well reflected in different experimental behaviors. Experiment data was scaled to field settings and natural examples. This showed that stronger rocks require much energy to break, hence, if they are the dominant host rocks, less energy is available for particle ejection. This implies a smaller hazard footprint. Future hazard assessment for steam-driven eruptions should take these findings into account.

1. Introduction

Steam-driven, phreatic and hydrothermal eruptions are a common explosive phenomenon in volcanic and geothermal systems (Browne & Lawless, 2001; Stix & Moor, 2018). In active volcanic terrains, phreatic eruptions may be triggered by the sudden arrival of extra fluid (gas, waters or brines) interacting with heat from intruding magma (Browne & Lawless, 2001; Stix & Moor, 2018). In geothermal settings, hydrothermal eruptions may be triggered by depressurization and steam-flashing of trapped hot pressurized fluids, released by earthquakes, landslides, or other localized natural hydrological disturbances (Browne & Lawless, 2001; Mastin, 1995; Thiéry & Mercury, 2009). Moreover, in both active volcanic and geothermal settings, hydrothermal alteration and mineral sealing can promote high local overpressures and thus more readily an explosive destabilization (Mayer et al., 2015, 2016; Scolamacchia & Cronin, 2016). Irrespective of the presence of shallow magma, flashed water contains enough energy to efficiently fragment rock and violently eject material upwards and laterally (Montanaro et al., 2016a; Morgan et al., 2009). Often impulsive and short-lived relative to magmatic eruptions, they are still deadly due to their sudden onsets, and the generation of violent blasts (Breard et al., 2014; Hurst et al., 2014; Kaneko et al., 2016; Mannen et al., 2019). For instance, the unheralded 2014 Ontake eruption in Japan (Yamamoto, 2014), and the 2019 Whakaari (White Island)
eruption in New Zealand (Kennedy et al., 2020) resulted in ~100 combined fatalities. The multitude of unknowns about these deadly events warrants further investigation so that we may learn to forecast them, or better avoid their impacts.

Recent field (D’Elia et al., 2020; Kilgour et al., 2019; Mayer et al., 2017) and experimental studies (Haug et al., 2013; Mayer et al., 2015; Montanaro et al., 2016a, 2016b) show how the explosion dynamics, magnitude and likelihood of steam-driven eruptions depend on the porosity and permeability of host rocks. Rock type can also influence the behavior of cracks and their ability to form and heal during advection of hydrothermal fluids (Kennedy et al., 2020). While individual rock properties have been investigated, a systematic analysis of the role of lithology on eruption dynamics is still missing. Also missing is an evaluation of how explosive energy is converted to hazardous processes during an eruptive event. Linking lithological controls on energy partitioning may help simplify hazard evaluation for steam-driven eruptions.

We conducted a series of decompression experiments on diverse natural samples linked to field examples of past steam-driven eruptions in order to estimate systematic differences in bulk explosive energy division into rock fragmentation and kinetic energy. We used natural rock samples from Lake Okaro in New Zealand, and correlate our estimations with bulk explosive energies calculated from crater dimensions at that site (Montanaro et al., 2020a). The overall aim is to determine the role of host rock lithology and alteration on eruption dynamics. Specifically, we determine whether increases in the energy consumed in rock fragmentation reduces energy available for particle excavation and ejection. By linking energy partitioning to lithology we can provide a simple tool for assessing the eruption hazard in geothermal areas.

2. Field-Laboratory Insights into Lake Okaro Steam-Driven Eruptions

Lake Okaro is a large crater field that was formed during three separate phases of steam-driven eruptions (Figure 1a). Eruptions occurred in both unaltered and hydrothermally altered rocks, and in unconsolidated breccias from earlier explosive phases (Montanaro et al., 2020a). This situation is seldom observed (cf., Mary Bay crater complex in Yellowstone; Morgan et al., 2009), but valuable for informing our understanding of how host-rock conditions influence eruptions. At Lake Okaro, the host rock includes (Figure 1b): unconsolidated tephra between 0 and 10 m; the Earthquake Flat Formation (EFF) between 10 and 60 m, consisting of weakly compacted to slightly consolidated-at-depth, ash and pumice-rich tuff of an intermediate strength; the deeper (>60 m), firm ash-lapilli tuff and slightly welded Rangitaiki Ignimbrite (RI) of relatively high strength (Montanaro et al., 2020b). As described by Montanaro et al. (2020a), the Phase I phreatic eruption excavated mainly unaltered-to-altered RI along a fissure, and was caused by pressurized groundwater by magmatic fluids intruding below. Postintrusion, ongoing heat transfer caused hydrothermal fluids to circulate within the permeable EFF deposits and the explosion breccia/ crater fill. After extensive hydrothermal alteration, and sediment influx into the area, a seismic event fractured a seal over the hydrothermal reservoir and triggered a “top-down” steam-driven eruption (Phase II), excavating from near-surface to ~70 m and producing new craters and breccia. Following a further hiatus, a lake formed and the Phase III eruptions were triggered by a sudden drop in lake level, leading to hydrothermal explosions excavating into breccia deposits from previous eruptions (Hardy, 2005; Montanaro et al., 2020b).

We investigated the petrophysical properties (bulk/matrix density, connected porosity and permeability) of dominant lithologies collected within the erupted breccias from phase I and II (Figures 1b and 2) using a helium pycnometer and nitrogen gas permeameter under ambient laboratory temperature (Montanaro et al., 2016c; see also supporting information). We compared the breccia-derived samples to those from unaltered RI and EFF stratigraphic units from nearby outcrops and the Wai-o-tapu drill cores (Hedenquist & Henley, 1985).

Unaltered RI involved in Phase I shows a higher bulk density, and lower porosity-permeability than altered RI rock involved in Phases I and II (Figures 1b and 2b). Altered RI tuffs from the excavation and crater-widening stages of the Phase II eruption are also less porous and less permeable than those erupted during Phase I and opening stage of Phase II (insets in Figures 1a and 2b). This porosity and permeability variation in RI is caused by hydrothermal pore-filling precipitation and mineral growth after Phase I, typical of ignimbrites in hydrothermal environments (Heap et al., 2020). EFF is here assumed to have a bulk porosity of
Figure 1. Map of Okaro lake floor and conceptual section (X–X’) of the geology beneath the lake area (modified from Montanaro et al., 2020a). (a) Shaded relief (and depth scale) showing three sets of craters marked as Phases I, II, and III. In the inset, the total area for Phase I and the overlapping Phase II are shown, together with a sketch of the eruption stages during Phase II eruption. (b) Reconstructed stratigraphy at Lake Okaro, including averaged petrophysical properties of the main lithologies: bulk density ($\rho_{\text{bulk}}$), connected porosity ($\Phi$), and permeability ($k$). Porosity of EFF pumices and ash tuffs are measured, while (i) the bulk porosity* refers to the porosity estimated for weakly consolidated pyroclastic deposit (e.g. Gase et al., 2018), and (ii) the “bulk” permeability# is the estimated one of EFF by Tschritter and White (2014).
Figure 2. Connected porosity-permeability trends for unaltered and altered tuffs, pumices, ash tuffs. (a) Core samples prepared from each of the blocks and breccia matrix collected for this study, divided according to the eruptive phase (I-II) and eruptive stages (during Phase II). Only the connected porosity was measured from the matrix and the ash tuffs. (b) Permeability as a function of connected porosity of representative substrate lithologies involved in the Phase I (11 unaltered and 4 altered RI samples) and II eruptions (29 altered tuffs, 14 pumices, 6 ash tuffs, and 3 matrix samples). The inset shows a semi-log plot of porosity-permeability of blocks erupted during the different stages of Phase II eruption.
approximately 30%–50%, similar to that of other pumice-rich pyroclastic deposits (Gase et al., 2018). A bulk permeability of $\sim 10^{-12}$ m$^2$ is estimated for EFF by Tschritter and White (2014). These values are comparable to our measured values from ash tuffs and pumices (Figures 1b and 2b). The surface breccia deposit from phase I has a silt-rich matrix, supporting subrounded to angular lapilli and blocks (Montanaro et al., 2020b), and is likely very similar to the crater fill at shallow depth and pressure (Heap et al., 2015; Nooraiepour et al., 2019). Slightly cohesive silt/sand-rich samples from the Phase I matrix (pIm), which were taken as representative source lithology for Phase II eruption, have a bulk density of 1.6 g/cm$^3$ and 26.6% porosity.

Thirty-nine water-saturated samples from the investigated lithologies were rapidly decompressed in shock-tube steam-flashing experiments (e.g., Mayer et al., 2015, 2016; Montanaro et al., 2016c; see also supporting information). These experiments were designed to mimic decompression conditions of heated and pressurized fluids driving the Lake Okaro eruptions. We assume that fluids during phase I eruptions were primed by dike intrusion, and at <100 m-depth reached $\sim 300^\circ$C, and an overpressure of up to 10 MPa (Germanovich & Lowell, 1995). For Phase II hydrothermal eruptions, we assume that the exploded reservoir fluids were at a temperature of $\sim 200^\circ$C–220$^\circ$C, confined by pressures of 3–5 MPa (Browne & Lawless, 2001; Hedenquist & Henley, 1985).

3. Explosive Parameters of Variably Triggered Steam-Driven Eruptions

3.1. Crater Size-Derived Bulk Explosive Energies

Studies of natural explosion craters (Lube et al., 2014; Montanaro et al., 2016b; Valentine et al., 2015; Yokoo et al., 2001), and outdoor explosion experiments using variably compacted material (Goto et al., 2001; Graettinger et al., 2014; Sato & Taniguchi, 1997; Sonder et al., 2015; Taddeucci et al., 2013) show that crater shape and size result from an interplay between explosion energy and scaled depth. Further, the ejecta volume depends on the host rock strength (Galland et al., 2014; Macorps et al., 2016). Natural craters are, however, often composite features formed by multiple events and crater wall collapses (Valentine et al., 2014). Empirical energy:crater size ratios can only be applied if individual subcraters can be distinguished and measured (Graettinger et al., 2014; Montanaro et al., 2016b; Taddeucci et al., 2013; Yokoo et al., 2002). Lake Okaro craters were excavated mostly into weakly compacted EFF and unconsolidated ejecta from Phase I (Montanaro et al., 2020b). Thus, the relationships described by Sato and Taniguchi (1997) and Goto et al. (2001) can be used to calculate the bulk explosion energy and the ejecta bulk volume as:

$$D = 0.97 \times V^{0.36}$$

$$\log D = 0.32 \times \log E - 2.06$$

where $D$ is the crater diameter (m), $V$ is the ejecta volume (m$^3$), and $E$ is the explosive energy (J). By dividing the last two terms, bulk explosive energies per unit volume (J/m$^3$) can be estimated.

Craters from Phase I are represented only by arc remnants of their original crater walls, enclosing an estimated total area of 0.12 km$^2$, including the overprinted Phase II eruption craters (Figure 1a). Hence, a reconstructed diameter of $\sim 411$ m is estimated, yielding a total ejecta volume of $\sim 2 \times 10^7$ m$^3$, and a bulk explosive energy of $\sim 2.1 \times 10^7$ J/m$^3$.

For Phase II, crater morphology and breccia componentry indicate that explosions started in the south and migrated northward creating the entire northern lake basin (Figure 1a). The energy of formation from each crater along the chain is important to estimate energy partitioning (Montanaro et al., 2016a; Raue, 2004). Recognizable craters range between 34 and 198 m in diameter (Montanaro et al., 2020b), indicating that ejecta volumes were between $1.8 \times 10^5$ m$^3$ and $2.3 \times 10^6$ m$^3$ (summing to $7 \times 10^6$ m$^3$), and bulk explosive energies between $8.5 \times 10^6$ J/m$^3$ and $1.6 \times 10^7$ J/m$^3$ (summing to $1.4 \times 10^7$ J/m$^3$). More craters are likely buried beneath the landslide deposits that blanket the northern part of the lake (Figure 1a). Thus, considering a total area of $\sim 0.24$ km$^2$ for Phase II eruption, an equivalent diameter is 549 m yielding a total ejecta volume of $\sim 4.4 \times 10^7$ m$^3$ and a bulk explosive energy of $\sim 2.3 \times 10^7$ J/m$^3$. 
3.2. Experimentally Derived Bulk, Fragmentation, and Kinetic Energies

Experimental bulk explosive energies (Figure 3) are estimated assuming an irreversible (isenthalpic) flash- ing of pore waters (Montanaro et al., 2016c; Thiéry & Mercury, 2009) as:

\[
E_{\text{Expl}} = m_w \times P_{\text{atm}} \times \left[ x \times v_{\text{vap}} + (1 - x) \times v_{\text{liq}} - v_{\text{initial}} \right]
\]  

where \(E_{\text{Expl}}\) is the irreversible explosive energy released (in J), \(m_w\) is the mass of water (g) in the pore space, \(x\) represents the steam fraction, \(v_{\text{vap}}\) and \(v_{\text{liq}}\) are the molar volume (in m³/kg) of steam and liquid water, and \(v_{\text{initial}}\) is the molar volume at the initial condition of the system (see also supporting information). By dividing the calculated irreversible energy for the sample volume, bulk explosive energies per unit volume (J/m³) can be estimated.

Under phase I conditions (300°C–10 MPa), bulk explosive energies average between \(\sim 1.7\) and \(\sim 3.2 \times 10^7\) J/m³ for unaltered and altered RI, respectively (Figure 3). The variable porosities of unaltered and altered RI indicate that fragmentation requires minimum gas overpressures of 5.9 and 3.4 MPa, respectively, equating to minimum fragmentation energies of \(1.7\) and \(1.6 \times 10^6\) J/m³ (Koyaguchi et al., 2008). During the decompression experiments, most kinetic energy is released at the initial stage of an explosion, with >4 phi-sized particles being rapidly ejected (Figure 3a; Alatorre-Ibargüengoitia et al., 2010). Thus, by using the ejection front velocities and >4 phi particle masses of unaltered (109.5 ± 23.5 m/s; \(1.5 \times 10^{-3}\) kg) and altered particles (221.5 ± 30.5 m/s; \(2.4 \times 10^{-3}\) kg), we estimated minimum kinetic energies that range between \(8 \times 10^5\) J/m³ and \(3 \times 10^6\) J/m³, respectively.
For Phase II, the breccia lithology shows that the eruption began in the south, excavating mostly breccia from Phase I (pIm), before expanding into undisturbed and altered EFF and RI substrates to the north (Figure 1a; Montanaro et al., 2020b). Experimental bulk explosive energies under initial conditions of 200°C–220°C and 3–5 MPa, averages to: 1.2 × 10^7 J/m^3 for slightly cohesive and low porosity pIm (~27%); 1.7 × 10^7 J/m^3 for altered medium-porosity RI tuff (~41%); 2.0 and 2.1 × 10^7 J/m^3 for highly porous EFF ash tuff (~53%) and pumice (~59%), respectively (Figure 3). In terms of rock fragmentation threshold, altered RI from phase II requires between 3.2 and 3.9 MPa to fragment, while EFF pumice fragments under pressures of only 2.3–2.5 MPa. The pIm and EFF ash tuff are friable and thus assumed to have very low to no effective tensile strength (σ_t ~1.5 MPa). For these, pressures of 2.7 and 0.9 MPa are required for disaggregation (Koyaguchi et al., 2008). Such overpressures indicate minimum (averaged) fragmentation energies of ~1.7 and ~1.5 × 10^6 J/m^3 for altered RI and EFF pumices, and 8 and 4 × 10^5 J/m^3 for disaggregating pIm and EFF ash tuff. We measured averaged front velocities of: 144 ± 19 m/s for altered RI, 156 ± 26 m/s for EFF pumice, 179 ± 35 m/s for plm, and 216 ± 12 m/s for EFF ash tuff (Figure 3a). Rock masses >4 phi for these units in the same order are: 1, 1, 5, and 3.5 × 10^{-3} kg. Based on these data, we estimate minimum kinetic energies of between 4.8 × 10^5 and 23.6 × 10^6 J/m^3, with the highest for the weakest lithologies (pIm and EFF ash tuff particles), and the lowest for those of highest strength (altered RI and EFF pumice).

4. Energy Partitioning Versus Rock Properties

The style and dynamics of steam-driven eruptions are controlled by the total energy involved and the split of energy exerted into primary work (fragmentation and kinetic energy) and secondary sinks (e.g. elastic and inelastic deformation, shock waves, heat, friction/drag, etc.). Volcanic hazard and impact assessments require knowledge of hazard intensity metrics (Wilson et al., 2014), which are usually derived from energy; e.g., impact energy in the case of ballistic hazards (Williams et al., 2017). Energy partitioning budgets thus are a practical pathway to improve hazard assessment and scenario planning (Montanaro et al., 2016a; Rosi et al., 2018). Our experimental estimates show that different physical and lithological properties of reservoir host rocks lead to systematically different bulk explosive energies and energy partitioning. The new data yield results comparable to those obtained when applying an empirical rule to crater dimensions at Lake Okaro (Lube et al., 2014; Montanaro et al., 2016b; Valentine et al., 2015). As a first-order approximation, we can quantify the explosive energy partitioning between reservoir rock fragmentation (or disaggregation) and ejection (kinetic) energies, assuming that: (i) no additional mass/energy was supplied from magma (Germanovich & Lowell, 1995); (ii) that there are no explosivity-enhancing gases (e.g. CO_2; Hurwitz et al., 2016; Thiéry et al., 2010) within hydrothermal fluids; and iii) no temporary compaction affected shallow (<100 m) and friable host materials (Dasgupta & Mukherjee, 2020; Heap et al., 2015; Nooriaiepour et al., 2019).

During the phase I eruption, the minimum fragmentation energies calculated for RI indicate that the percentage of total explosive energy that is spent on fragmentation averages to 10.3% for unaltered RI, but only to 5.3% for the altered equivalent (Figures 3c and 4a; Koyaguchi et al., 2008; Montanaro et al., 2016a). Unaltered RI shows lower fragmentation velocities in comparison to altered samples, highlighting the weakening effect of alteration (17 ± 14 vs. 42 ± 7 m/s; Mayer et al., 2015, 2016; Kennedy et al., 2020). Alteration does not, however, change fines production, indicating an equivalent efficiency of fragmentation (10.4 vs. 9.5 wt% at >4 phi; Kueppers et al., 2006). Considering the minimum energies associated with ejected fine material, an average conversion rate of 7.5%–10.5% of bulk into kinetic energy is estimated for unaltered versus altered rocks, respectively (Figures 3d and 4a). Thus, our experimental results, supported by field observation at Lake Okaro (Montanaro et al., 2020b), indicate that high strength rock consumed large amounts of energy during phase I eruptions. This explains the relatively small ejecta volume (i.e. low cratering efficiency), and restricted debris dispersion that reflects low ejection velocities.

Phase II eruptions involved mostly lower-strength lithologies, as well as lower inferred pressure/temperature conditions. Less porous altered RI show comparable fragmentation and ejection velocities as for Phase I (47 ± 9 m/s and 144 ± 19 m/s; Figure 3a), but fragmentation is less efficient, producing less fines (1.6–6.6 wt%; Figure 3b). This is due to reduced porosity by mineral precipitation that decreases the fluids available, and in turn the unit-volume explosive energy (Montanaro et al., 2016a; Mueller et al., 2011). Highly permeable EFF pumices have a very low fragmentation speed (25 ± 6 m/s), but produce a similar fraction of fines to RI (7.2–8.1 wt%). Thus, despite high permeability, fragmentation due to steam-flashing remains...
highly efficient (Montanaro et al., 2016c). The EFF ash tuffs, with plm, requires less energy, as they need only disaggregate compared to the fragmentation required of RI and EFF pumices. The slight cohesive nature of the plm, in contrast to the friable and very fine-grained structure of the ash tuff, may explain its comparatively low fragmentation velocity and its low production of fines (65 ± 16 m/s vs. 163 ± 33 m/s and 5.4–18.9 wt% vs. 8.3–25.6 wt%, respectively; Figures 3a and 3b). Overall, during Phase II more energy is spent on fragmenting RI tuffs and EFF pumices (7%–11.8% and 6.1%–8.9%), than on disaggregating/unloading plm and EFF ash tuffs (6.6%–6.7% and 1.9%–2.2%). Consequently, a lower percentage of kinetic to explosive energy results for RI tuffs and EFF pumices (0.5%–9.5% and

Figure 4. Sketch (not to scale) of the Lake Okaro phreatic-hydrothermal (steam-driven) eruptions (Montanaro et al., 2020b) and associated bulk explosive, fragmentation and ejection energies. (a) During Phase I more energy is consumed in fragmenting an unaltered and stronger substrate, compared to Phase II in shallower and weakened materials. Bulk energies and conversion ratios (%) are averaged from Table S1. (b) Conceptual sketch of fragmentation and ejection driven by the flashing steam for the different lithologies involved in eruptions at Lake Okaro. Greater fragmentation and ejection velocity of weakly consolidated material (matrix and ash tuffs) reflects the higher conversion of mechanical into kinetic energy.
than for pIm and EFF tuffs (24.6% and 14.4%–32.1%; Figures 3c and 3d and 4a). The dominantly weak and unconsolidated lithologies disrupted during the Phase II eruption required less energy (lower energy cost) than Phase I, so that a larger (final) crater was formed. With a greater conversion of energy into kinetic energy, the preserved volume of ejecta is greater and dispersed more widely (i.e. with high ejection velocities).

The experimentally based energy conversion ratios for fragmenting consolidated rocks (unaltered to altered) fits well with the range estimated for andesitic tuffs and breccias at Tongariro volcano, or for cemented breccias at Ruapehu volcano (9.5%–15.2% and 5%–15%, respectively; Kilgour et al., 2010; Montanaro et al., 2016a). Further, energy conversion into kinetic energy is comparable with previous estimates for steam-driven eruptions in cemented, consolidated or highly fractured rocks (0.1%–6%; Browne & Lawless, 2001).

In the case of unconsolidated lithologies such as the pIm and the EFF ash tuffs, more mechanical energy is used in the ejection of material. A recent example of such an explosive event within weak/unconsolidated host materials is the 2016 eruption involving crater-fill tephra at Whakaari/White Island (Mayer et al., 2015). Here small steam-driven explosions, produced very energetic blasts, ejecting particles at >60 m/s over hundreds of meters (10^4–10^5 J/m^3 of kinetic energy; Kilgour et al., 2019). We suggest that the unconsolidated lithologies sourcing the Whakaari 2016, and likely the 2019 eruptions, favored the production of more fines, increasing the likelihood of pyroclastic density currents.

The Phase I eruption (stronger host rocks) had less blocks per meter (based on proportions of blocks at the outcrop) than Phase II (Montanaro et al., 2020b). If compared to recent steam-driven explosive events at Whakaari/White Island (high blocks density per meter; Kilgour et al., 2019) and Te Maari (low blocks density per meter; Breard et al., 2014), Phases I and II might represent different ends of a spectrum implying different types of hazards. For instance, we can extrapolate for the larger Phase II eruption (unconsolidated lithologies-dominated) a footprint for ballistic hazard of 3–8 × 10^6 m^2. This area correspond to 10–3 m-thick block-rich breccias within approximately 150–350 m of the crater rim (Hedenquist & Henley, 1985). Using our estimates of: (i) clast size ranging from 15 to 60 cm, (ii) average densities from 1,100 to 2,000 kg/m^3, (iii) optimum ejection angles of 45°, and (iv) initial ejection velocity of 100 m/s (from experimental particles), we calculate final impact velocities of: 60–110 m/s. This equates to kinetic impact energies of 6 × 10^4, 1 × 10^5, 2 × 10^6, and 1 × 10^7 J, which are typical for denser and large ballistics with high individual impact energy ejected during Vulcanian and steam-driven eruptions (Alatorre-Ibargüengoitia et al., 2012; Fitzgerald et al., 2017; Maeno et al., 2013; Tsunematsu et al., 2016).

5. Conclusions

We have demonstrated that in volcanic and geothermal areas which are subject to steam-driven eruptions, rock strength is an important indicator of eruption outcome. For strong lithologies, there is likely a smaller ejecta volume, low particle ejection velocities, hence relatively small footprints for ejecta/deposition. For unconsolidated or weak lithologies, wider craters are favored, producing large ejecta volumes with high particle ejection velocities and large ejecta footprints. Quantifying further lithological influences on explosive energy partitioning is an excellent way to reduce uncertainty around estimations of the potential size and dynamics of future steam-driven eruptions in susceptible areas. The coupling of local geological and rock properties with experimental methods provides a valuable contribution to approximate the scale of crater excavation and ejecta production and relative ballistic versus ash hazards, and thus enables improved assessment of eruptive scenarios and associated hazards.

Competing of Interests

The authors declare no competing interests.

Data Availability Statement

Datasets for this research are available in Montanaro et al. (2020) (this study).
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