Simulating maar–diatreme volcanic systems in bench-scale experiments

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Abstract: Maar–diatreme eruptions are incompletely understood, and explanations for the processes involved in them have been debated for decades. This study extends bench-scale analogue experiments previously conducted on maar–diatreme systems and attempts to scale the results up to both field-scale experimentation and natural volcanic systems to produce a reconstructive toolkit for maar volcanoes. These experimental runs produced via multiple mechanisms complex deposits that match many features seen in natural maar–diatreme deposits. The runs include deeper single blasts, series of descending discrete blasts, and series of ascending blasts. Debris-jet inception and diatreme formation are indicated by this study to involve multiple types of granular fountains within diatreme deposits produced under varying initial conditions. It is not possible to infer the energies of single blasts in multiple-blast series from the final deposits. The depositional record of blast sequences can be ascertained from the proportion of fallback sedimentation versus maar ejecta rim material, the final crater size and the degree of overturning or slumping of accessory strata. Quantitatively, deeper blasts involve a roughly equal partitioning of energy into crater excavation energy versus mass movement of juvenile material, whereas shallower blasts expend a much greater proportion of energy in crater excavation. 

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At the onset of an explosive eruptive burst during discrete or discontinuous volcanic eruptions, there may be no pre-existing conduit, or one that is effectively closed by backfallen debris (e.g. White & Ross 2011). Analogue experiments have been carried out to investigate how rapid gas expansion, mimicking a volcanic explosion, opens a conduit to the surface while entraining and dispersing particles from the explosion source (Ross et al. 2008b; Nermoen et al. 2010). The recent study by Andrews et al. (2014), a precursor to this paper, found that the initial mobilization and entrainment of both source particles and those of the overlying host may be complex. From these bench-scale experiments, this study attempts to scale results up, qualitatively and quantitatively, to field-scale explosion experiments (Goto et al. 2001; Valentine et al. 2012; Ross et al. 2013; Graettinger et al. 2014), and to geological maar–diatreme systems (Geshi et al. 2011; White & Ross 2011; Lefebvre et al. 2012).

For any discrete volcanic explosion at depth, gases rapidly expand and propagate upward towards the surface during an explosive decomposition phase. Pyroclasts are generated at the explosion site and variably entrained, along with particles from the enclosing host debris. The moving mass of pyroclastic and host-derived material driven upward by expansion has, particularly for maar–diatreme systems, been referred to in the literature as ‘debris jets’. These explosion-generated upward moving low-density mixtures of pyroclastic debris and gases, with or without liquid water entrained in them, enclosed by a pre-existing, non-fluidized, non-consolidated fill, characteristically shape the diatreme-structure infill through an initial explosive expansion phase succeeded by within-cavity sedimentation (White & Ross 2011). In maar–diatreme systems, it has long been inferred that the deepest subterranean explosions are generated at the chaotic base of the system, known as the ‘root zone’ (Lorenz 1986; Lorenz & Kurszlaukis 2007; White & Ross 2011). Crosscutting deposits are interpreted to preserve the traces of debris jets through the host, and it has been argued (White & McClintock 2001; Ross et al. 2008a; Murtagh et al. 2011; White & Ross 2011; Lefebvre et al. 2012; Valentine & White 2012; Valentine et al. 2014) that other explosions commonly occur vertically higher in the system than the diatreme’s root zone.

A problem with this conception of a ‘debris jet’ is that there is a dynamic succession of events that take place in response to subterranean explosions, many of which do important work in the system yet cannot be considered jets. Ross et al. (2008a,b) demonstrated with experiments related to those reported here that an explosive expansion within a granular host generates an open cavity in which particles from the explosion source move and are sedimented, with closure of the cavity capturing the sedimenting particles to yield crosscutting features highly comparable with natural examples. Andrews et al. (2014) have revealed additional complexities, including a delay in mobilization of the source particles while a cavity opens, followed by expulsion of source particles in a momentum-driven granular jet. This paper reports additional phenomena observed during the same experiment series, and focuses on how cavity opening and collapse in the experiments are related to surface phenomena observed in volcanic eruptions and field-scale experiments, and to the geometry and constituents of deposits formed beneath the crater. It builds on the work of Ross et al. (2008a,b) by examining effects of multiple explosions at different depths at a single epicentre, and takes advantage of much higher-resolution imagery to reveal subtle depositional phenomena that have real-world implications. These experiments, although only analogues to natural volcanic systems, provide important insights.
Methods

These experimental runs use a set-up modified from that of Ross et al. (2008a,b). A variable initial, pressure-dependent, volume of compressed gas was released quickly (300 ms), through an orifice of constant radius, at the base of a crucible filled with monodisperse 300 μm dark glass beads (Fig. 1). These beads represent the pyroclasts formed during a volcanic explosion and were placed between the outlet for the gas, released under pressure from 0.5–2 MPa, and the overlying host beads. The orifice is smaller in diameter than the crucible, and before the dark beads in the crucible were entrained upwards they had to couple with the expanding gas. This coupling was imperfect (Andrews et al. 2014), and when the argon gas in our experiments was released it expanded explosively upwards through the crucible dark-bead mass, entraining only a small proportion of the beads, and then through the overlying 24 cm thick host layer of well-sorted (300 μm) white glass beads. In this study we treat all the entrained-at-the-source dark beads as a proxy for the particles that form the bulk of ‘juvenile’ pyroclastic ejecta in maar–diatreme systems (Büttner et al. 2002). The host white-bead layer in our experiments was marked at intervals with narrow ribbons of equally uniform-sized blue glass beads visible on the viewing window (Fig. 1). These experiments focus on the kinematics and mechanics of the discrete explosions and on their deposits.

Experiments were filmed through a vertical glass window with a high-speed (1000 frames per second) high-resolution (1 megapixel per frame) camera imaging an area of 400 × 500 mm at 5 pixels mm⁻². Several time-dependent physical parameters, including the vertical force applied to the setup by the accelerating mass of particles, the driving pressure beyond the valve, and pressure fluctuations both in the crucible and in the overlying stratigraphy, were recorded. Two pressure sensors were aligned vertically upwards from the opening of the crucible behind the host white beads, and one was located at the base of the crucible opposite the gas line.

Scaled depth, scaled crater diameter and optimal depth of burial calculations were not determined for this set-up before our experiments, so crucible depths were set at even increments below the original host surface: ‘shallow’ releases at 8 cm below the surface, ‘medial’ ones at 16 cm, and ‘deep’ ones at 24 cm. The solenoid valve opened at t = 0 ms; the entire set volume of compressed argon gas was released rapidly into the crucible containing the ‘juvenile’ dark-bead mass, at a set initial overpressure (0.5, 1, 1.5 or 2 MPa). Run series comprised three ascending runs with blasts from deep to shallow crucible depths, three descending runs from shallow to deep crucible depths, or repeated blasts at identical depths, with each burst at the same overpressure.

Experimental results

This paper focuses on the physical characteristics of these bench-scale experiments that have parallels in geological field examples of maar–diatreme systems (see White & Ross 2011) and field-scale explosion experiments (e.g. Valentine et al. 2012; Ross et al. 2013). A detailed discussion of the dynamic segregation effect has been presented by Andrews et al. (2014). Following a note on nomenclature, the present paper proceeds through basic quantitative descriptions of the system’s geometrical change through blasts. This is followed by observations from above, such as would be possible for real eruptions, of specific aspects of the runs, coupled with additional insights gained from the cross-sectional view.
afforded by our set-up. Activity in the subsurface is then detailed; such observations are impossible in real eruptions, and reveal processes by which subsurface deposits are formed. Following assessment of sources and expenditures of energy in specific parts of the experimental system, we discuss the applicability of different experimental observations to natural volcanic eruptions and to field-scale experiments.

**Nomenclature**

To aid in description, key terms for bench-scale runs are defined here. A blast is the rapid expansion of compressed gas released into the base of a crucible filled with dark beads that are a proxy for juvenile grains from the explosion source. The blast depth is measured downward from the pre-run host surface to the top of the crucible. The crucible lies within a host granular mass of white beads, which enclose and overlie the crucible. Lines of blue beads at the inner wall of the rig help visualize behaviour of layers (strata) in the bead mass. The explosion opens a (primary) cavity by the process of cavitation as expanding gas pushes the bead mass aside and upwards. The cavity begins growing below the surface of the bead mass, but domes the overlying beads upward, above the surrounding bead surface. Fully developed, a cavity has a domed roof, and walls where the white-bead mass has been pushed aside. Cavity collapse takes place as walls flow inward and the roof breaks up or falls downward. A granular fountain is the approximately cylindrical uprush of dark beads from the crucible, sometimes followed by opening of a secondary cavity in the granular mass. A successful eruption takes place when the dome bursts and material rising through the cavity is expelled to the bead-mass surface; a contained blast occurs when the dome fails to burst and the entrained material does not breach the host bead-mass surface. The transitional zone represents the material within or below the crater that is irreversibly modified but not significantly mobilized during the explosion.

An experimental ‘diatreme deposit’ is a cylindrical to cone-shaped infill of dark beads that cut into the host white-bead mass, and typically underlies a simulated maar crater. The diatreme deposit is generated during the eruptive sequence through a mixture of debris jet emplacement and fallback sedimentation. We recognize that the deposits of these small, three-blast experiments in homogeneous granular materials do not capture many features and processes of real maar–diatremes, but in this paper we refer to the experimental structures as diatreme deposits for brevity. Deposits of real maar–diatremes will be clearly identified as such where addressed in the discussion.

We describe three types of diatreme deposits formed during these experimental runs. A diatreme formed through one blast at depth is a single-blast diatreme deposit. The diatreme deposit of an ascending run series is a compound stacked diatreme deposit, wherein the lowest part of the pre-existing diatreme deposit is left untouched by succeeding blasts. The final diatreme deposit of a descending run series, where each successive run remobilizes the pre-existing diatreme deposit, is a compound deepened diatreme deposit.

To effectively compare these bench-scale experiments with field-scale and geological examples of both maar–diatreme systems and any discrete subterranean blast in a granular material, terminology utilized by Ross et al. (2013) is used. The transient crater is delineated by the floor and walls of a cavity opened to the surface by the blast; it exists only during the blast. Fallback refers to material, lifted by the explosion, that has subsequently fallen back into the transient crater. The post-shot crater is the remaining crater. The ejecta is material permanently ejected by the explosion, landing on or beyond the rim of the post-shot crater. Deposits of beads ejected from the structure and accumulated on top of the host beads are ejecta, analogous to a maar ejecta rim (White & Ross 2011), the ring of ejecta deposited on the pre-eruptive ground around a natural maar crater.

Regimes of behaviour associated with subsurface explosions are commonly described in terms of the scaled depth $D_x = dE_x$, where $d$ is the physical depth and $E$ is the mechanical energy produced by the explosion, with $x$ representing a scaling factor determined experimentally (Valentine et al. 2012). A single blast occurring at the optimal scaled depth, or optimal depth of burial, would produce the largest crater by diameter (Ross et al. 2013; Graettinger et al. 2014).

It is worth noting that glass beads do not share the same mechanical properties as rock or gravel used in the recent field-scale experiments (e.g. Ross et al. 2013; Graettinger et al. 2014; Valentine et al. 2014, 2015), or as rock fragments produced in natural diatreme-forming eruptions. It is partly for this reason that complex diatreme deposit features known from natural examples of maar–diatreme volcanoes have not been formed here. Another reason is that most natural maar–diatremes are inferred to have formed from hundreds or thousands of single explosions (e.g. White & Ross 2011), not the three blasts of our work or the recent field-scale experiments (e.g. Ross et al. 2013). We suggest also that the effect of a pre-existing crater on the geometry of a subsequent crater through a second discrete blast will be less significant in these bench-scale runs than in field-scale blasts (Taddeucci et al. 2013; Graettinger et al. 2014; Valentine et al. 2015) for the same reason: glass beads are homogeneous, elastic and highly unconsolidated compared with rock materials. Nevertheless, the glass beads do provide a good proxy for unconsolidated granular deposits within the structures of erupting maar–diatreme volcanoes (Ross et al. 2008a,b; Andrews et al. 2014), and allow simple physical quantification that would not be possible with more complex particle mixtures.

The most common features listed above are labelled in Figure 1, which presents two frames from a typical run.

**Particle image velocimetry analysis**

Particle image velocimetry (PIV) analysis was carried out on the blast series used in this study. The JPIV® open-source software package was employed to obtain kinematic data on particle motion. We used PIV to calculate the displacement of the various moving bead masses of single runs, including the piercing gas jet, the doming roof mass, the granular fountain, the primary and secondary cavities, and the subsurface slumping and host-material convection. Each pixel represents 0.3 mm in real distance. PIV images illustrate motion during specific stages of each blast, showing displacements over periods of $x$ milliseconds ($=x$ frames) just before the lofted particles begin to sediment downward. During this period the transient crater, enclosed by the floor and walls of a cavity opened to the surface by the blast, is open. Vector arrows represent peak particle displacements detected between the two frames in each example, with longer lines and thicker arrowheads indicating greater regions of displacement. These PIV images reveal minimal peak displacement where the vectors are short and arrowheads thin, with larger displacements exceeding 3 mm indicating by large, thick arrowheads on dark lines.

**Explosion-generated deformation: excavation mechanisms**

**Doming, cavitation and excavation observations**

The first event observable in each experimental run is doming of the host-bead surface, and this is inferred from force and pressure records to occur concurrently with the emergence from the orifice of the gas jet (Fig. 2a–c). After a brief period in which the surface
domes and marker horizons in the white beads start to bend, the gas bubble, or cavity, becomes visible at the viewing wall. The time between the valve release at $t=0$ ms and the deformation of the white beads at both the surface level and the viewing wall varies depending on the initial pressure of the blast. In both shallow and medial depth blasts, the surface level and viewing wall level white bead deformation commences simultaneously; in the case of the deeper blasts, there is a slight delay between the deformation of the viewing wall area and the surface dome. For these deep runs, this deformation lag time often depends on how deep the previous crater is: deeper craters will begin to dome simultaneously with the deformation of the viewing wall, whereas shallow craters will begin to dome $2$–$5$ ms after deformation becomes visible at the viewing wall. The delay is related to the travel distance of the released gas to the surface.

Surface doming begins rapidly: a thick-roofed central dome emerges with low slope angles, which then extends and narrows to form a dome with high slope angles, at times even inward dipping, as the cavity decompresses most prominently along a central, upwards, vertical vector. At the same time, the host bead ground surface deforms all the way to the edge of the rig, often subsiding as the dome rises. Within $c. 10$ ms or less after it has begun to form, the dome expands both upwards and partially outwards beyond the view of the camera, dispersing across the ‘ground’ surface white beads from the dome roof and walls, as well as any dark beads pushed ahead of the cavity as it passes through the mass in the crucible (Fig. 2b). The upper segment of the cavity is always the primary cavity with a growing dome as the cavity decompresses it forces the majority of the dark beads upwards into the cavity as a granular fountain. (c) The granular fountain moves up into the cavity; the cavity roof (the dome) opens outwards. Gravity-driven granular flow of the bead mass into the cavity is expressed as liquid-like closure of cavity walls. (d) The granular fountain begins to partially decelerate. Sedimentation takes place on either side of the transient crater as the dome remnants descend. Granular flow of the white-bead mass continues to close the cavity. (e) Particle impacts within the granular flows in this central convergence zone lead to a rebound effect, occasionally opening up a secondary cavity beneath the granular fountain. The granular fountain continues to rise and decelerate above the system. (f) The granular fountain, and a portion of entrained white beads at the base, begins to fall back into the transient crater. The dome remnants have sedimented, leaving behind ‘overturned ejecta flaps’ at the rims. The rebound that formed the secondary cavity ceases and the cavity walls begin to flow back inwards in a zipping motion, trapping the dark beads of the granular fountain to form a crosscutting deposit.
ity walls begin to close by inward flow of the host-bead walls, beginning at the base of the cone, before the upward and outward expansion of the surface dome has ceased.

The cavity is opened by the explosive decompression and expansion of argon gas within the overlying host, with opening accomplished largely by upward displacement of host beads into the dome, which creates the space for the cavity to form below (Fig. 2b). When cavity growth begins, the pressure sensor in the gas line shows a rapid drop in pressure because the decompression is being accommodated by deformation in the growth of the dome roof, allowing pressure in the gas line to drop. Similar growth cavities and doming were described by Ross et al. (2008a,b).

At high initial pressures and large explosion depths, there is significant apparent ‘overturning’ of host layers at depth, and at the surface apparent ‘folded flags’ of cohesionless beads form by upward and outward motion and redeposition of particles that form part of the rising dome; flap deposition follows outward motion as beads in the dome ‘walls’ descend, with the walls’ simultaneous outward advance forming two mirrored depositing curtains herein referred to as sedimentation sheets. Domes that expand and sediment outwards characterize runs with explosions at shallower crucible depths and higher initial pressures; predominantly inwards cavity collapse is typical with large crucible depths and lower initial pressures.

Outwards motion of the ‘walls’ of the steepened dome continues beyond the visible flap, laying down a sheet of beads (Fig. 2e and f) to form the ejecta rim (e.g. Fig. 2c). Inward collapse of the cavity results in significant mixing of crucible-originated dark beads with overlying white beads. Cavity collapse continues while material from the roof of the dome, and along the cavity walls, descends back into the closing cavity (Fig. 2e). Throughout the process, there is also backfalling of other red and white beads, which rose within the cavity, back into the transient crater (Fig. 2f).

‘Overturning’ and ‘folded flags’ are in inverted commas as this is not precisely what is occurring: the cohesionless beads are being disassembled then reassembled in inverse order during deposition, giving the illusion of overturning flap deposits. The terms are nevertheless used as they describe the net effect of the inversion process.

Cavity collapse begins, first at the bottom of the cavity, when the upward and outward momentum of the material surrounding the cavity is expended; the cavity progressively closes by inward granular flow that ‘zips up’ the subterranean cavity (Fig. 2e and f). This is observed most clearly for explosions at depth, which creates the space for the cavity to form below. The top of the cavity shows high levels of upward and outward displacement, mostly forming two mirrored bead masses. Cavity collapse continues while material from the roof of the dome, and along the cavity walls, descends back into the cavity, which depicts the surface doming. At the margins of the cavity, particularly at its sides, there appears to be lateral ‘compression’ of bead masses, as the beads moving outwardly from the cavity walls strike the larger bead masses directly adjacent to them. At the base of the cavity, roughly symmetrical inward and downward displacement is noted, depicting the beginning of the zipping of the primary cavity, and marking the imminent impact of two mirrored bead masses.

The secondary cavity in Figure 5 is distinctly different from the primary cavity that preceded it: displacement is mostly horizontally outwards from the walls of the cavity, a direct consequence of the mirrored impact of the two aforementioned inwardly moving masses seen in Figure 4, which apparently rebound when they meet. The symmetrical upward and outward movement of the surface sedimentation waves can be seen, along with the roughly symmetrical but skewed granular fountain, both showing high levels of displacement.

Figure 6 plots initial pressure values against dome basal diameters (i.e. a measure of dome size) showing a positive correlation between the two variables. It also appears to show that dome basal diameters increase as detonation depth decreases, albeit with overlap of data points across this range of depths. As detonation depth decreases, the doming angle increases. Although the trend lines are approximate (there are insufficient data to produce reliably high $R^2$ values) the general trend across the range of initial pressures used in this study is fairly clear. This graph also appears to show (despite overlap in the 1 MPa set across all initial pressures) a positive correlation between the initial pressure and the subsequent doming angle. The velocities of the doming roof masses (and their associated fountaining masses) have been investigated in detail by Andrews et al. (2014).

**Post-shot crater morphology**

In most runs a roughly symmetrical (in semi-two dimensions) post-shot crater is produced as a result of either (1) strong doming during cavitation, which carries much of the overlying white-bead mass outwards to be deposited as sheets that build up the crater rim, or (2) ejection of white beads from the transient crater in sufficient volumes, coupled with subsequent inward collapse of the cavity walls, resulting in a dominance of fallback sedimentation into the transient crater. In contained runs, a roughly symmetrical post-shot crater is formed as a result of (1) the ejection of white-bead material through rapid surface doming and (2) dome collapse, synchronous with a subterranean cavity collapse, into the transient crater. Thus, a successful eruption, with dark-bead material breaching the surface, is not required to generate a crater; rather, the argon gas escapes through to the surface, and enough white-bead mass is ejected and displaced outwards from the transient crater to form a post-shot crater. This type of post-shot crater will contain only host material, with no primary juvenile dark beads.

The initial pressure and the depth of the blast both appear to influence the division of erupted bead mass into either central fallback sediment or crater rim ejecta. The shallowest blast at equivalent or similar initial pressures excavates more material than in other runs, suggesting that these blasts are occurring at near-optimal scaled depths (e.g. Valentine et al. 2012). Shallow blasts tend to generate outward-collapsing primary cavities, which emplace proportionally more material as crater rim ejecta than do deeper blasts. The juvenile dark-bead fountain mass, with shallower explosions, often falls back to both form central fallback sediment...
and contribute to crater rim ejecta. Far more white beads are thrown outwards by the blast, however, ensuring formation of a crater. The deeper the blast at an equivalent initial pressure, the more cylindrically focused the mobilized white-bead material is, leading to a greater proportion of material sedimenting by fall-back; deep blasts generate shallow post-shot craters, or sometimes no crater at all. In the case of three descending runs the crater rims are only marginally higher than the central crater.

Treating the post-shot craters as an inverted cone, their volumes are calculated. The volume of the primary cavity can be approximated: at the point at which the cavity appears to resemble an inverse teardrop shape, the volume can be estimated by treating the top as a half-sphere and the base as an inverted cone. The post-shot crater itself is treated as an inverted cone.

Table 1 summarizes the quantitative cratering phenomenological data associated with the experimental runs used in this study.

**Explosion-generated deformation: fountaining mechanisms**

As the cavity nears its maximum volume and the dome begins to collapse, most of the juvenile dark beads within the crucible are fountained vertically upward from the crucible, along with a generally small volume of entrained white beads (Fig. 2d). The dark-bead fountain retains an approximately cylindrical shape within the collapsing (inwards or outwards) cavity (Fig. 2e). By the time the cavity has fully collapsed, a proportion of the dark-bead mass has been effectively frozen into a vertical, thin, cylindrical form by the zipping effect of cavity closure (Fig. 2f). The thin blue markers reveal symmetrical deformation, and a symmetrical crater is generated at the surface (Fig. 2f). This fountaining is observed in runs at initial pressures of 0.5 MPa or more at the deepest explosion depth, for both successful eruptions and contained blasts. At the shallowest depths, fountaining is still observed, but with a dome that collapses outwards, rather than inwards. The fountaining is noted to be increasingly delayed after initial doming as the gas pressure is increased and, more significantly, as crucible depth is reduced. As described by Andrews *et al.* (2014) the decrease in blast depth, and thus a decrease in the overlying mass, allows the cavity to form far more rapidly than it would at depth; this increases the time delay between its formation and the subsequent fountaining.

A secondary, smaller cavity may appear beneath the first when there is strong fountaining (Fig. 2e), again taking the form of an
inverted teardrop, very similar to the primary, initial cavity. Small eddy currents occasionally trail the fountainhead.

Together, cavitation and collapse, the latter commonly simultaneous with fountaining, represent what is referred to in the literature as a ‘debris jet’ (Ross & White 2006; White & Ross 2011; Lefebvre et al. 2012). In all runs, with the exception of the shallowest blasts, a new diatreme-like structure resembling those seen in field examples (White & Ross 2011; Lefebvre et al. 2012) is formed. In every case, they take the form of vertical, thin, cylindrical structures, frozen into place by the zipping effect of the mobilized white-bead host material (Fig. 2f).

Figure 7 depicts the granular fountain emerging from the transient crater over the region of greatest vertical and subvertical displacement between 240 and 300 ms. The rapidly collapsing

| Blast depth (m) | Range of maximum doming angle from horizontal (deg.) | Range of doming base diameters (m) | Range of crater diameters (m) | Range of crater depths (m) | Range of diameter/depth ratios | Range of crater volumes (m³) |
|-----------------|-----------------------------------------------------|----------------------------------|-----------------------------|---------------------------|-------------------------------|----------------------------|
| 0.08            | 51–95                                               | 0.145–0.230                      | 0.047–0.138                 | 0.011–0.050                | 2.693–7.100                   | 0.000006–0.000249            |
| 0.16            | 57–84                                               | 0.130–0.205                      | 0.075–0.141                 | 0.009–0.029                | 3.261–9.028                   | 0.000013–0.000125            |
| 0.24            | 19–69                                               | 0.100–0.200                      | 0.075–0.141                 | 0.006–0.035                | 2.857–16.667                  | 0.000016–0.000094            |
| Initial pressure (MPa) |                                             |                                   |                             |                           |                               |                             |
| 0.5             | 19–66                                               | 0.100–0.145                      | 0.047–0.075                 | 0.009–0.023                | 3.261–8.333                   | 0.000006–0.000034            |
| 1               | 50–69                                               | 0.135–0.175                      | 0.075–0.100                 | 0.006–0.035                | 2.693–16.667                  | 0.000016–0.000092            |
| 1.5             | 30–95                                               | 0.200–0.205                      | 0.113–0.125                 | 0.028–0.044                | 2.841–4.036                   | 0.000094–0.000180            |
| 2               | 60–96                                               | 0.180–0.230                      | 0.131–0.141                 | 0.010–0.050                | 2.760–13.100                  | 0.000045–0.000249            |

The table shows ranges from minima to maxima, grouped by both initial pressures and, separately, blast depths. Run 23 has been excluded as in terms of crater dimensions it is considered anomalous.
sedimentation sheets moving outwards from the centre barely register on the PIV image as their lateral velocity component by this stage is low; however, two mirrored zones of high downward displacement are noted, which denote the collapsing sedimentation sheets depositing beads on the ejecta rims. Downward and inward slumping of beads beneath the granular fountain from the subsurface peripheries to the centre of the transient crater at moderate velocities are noted. Chaotic sediment trajectories are observed in the background above the surface.

There are clear differences in the crater morphologies. Runs A and B terminate on deep blasts, but whereas a single deep blast of case A produces a small crater, the descending blast series depicted in case B has culminated in an almost non-existent crater. The ascending series in case C produced a crater that resembles that of the single, deep blast in case A, but owing to the increasing shallow runs permanently ejecting more material from the crater, the crater in case C is more voluminous.

There are two major differences between the results from three descending runs (case B) versus three ascending runs (case C). One is in the distribution of juvenile dark beads. With deepening runs, the increasing depth of explosion excavating material into a pre-existing crater focuses the blast more cylindrically and, as a result, more juvenile dark-bead mass falls back into the post-shot crater rather than outwards onto the maar ejecta rims. The deeper blasts also allow for greater remobilization of the bead strata, with more pronounced slumping and flow producing folded symmetrical strata either side of the post-shot crater. Each subsequent run remobilizes beads of the previously formed, shallower diatreme deposit, and the final run in this case determines the morphology of the diatreme deposit. Thus, the final structure can be said to be a compound deepened diatreme deposit. This can be contrasted with a diatreme formed through one blast at depth (case A), termed a single blast origin diatreme deposit.

Explosion-generated deformation: descending v. ascending blast series

Differences in maar–diatreme (crater–subsurface) deposit architecture

Different crater and diatreme-deposit features form depending on whether excavation takes place from one blast or multiple blasts, and whether multiple blasts are successively deeper or shallower (Fig. 8). Case A represents a single-blast diatreme deposit, whereas cases B and C represent compound diatremes generated by three blasts at successively different depths. Deposits of cases B and C contain the cumulative juvenile output of three runs, each supplied with 68 g of juvenile dark beads in the crucible.

Fig. 5. Particle image velocimetry (PIV) analysis for the emergence of a secondary cavity phase of a deep blast (JPIV® open-source software) over 45 frames (milliseconds) of Run 10. The two frames to the left show the emergence of a secondary cavity. Black bar indicates blast depth or top of crucible. In the PIV vector image to the right the continuous white line depicts the blast depth or top of the crucible. The dashed white teardrop indicates the position of the secondary cavity. The continuous-line arrow represents the emergence of a granular fountain; the dashed arrow depicts the upward propagation of the tip of the dome. The clusters of large arrows represent maximum displacement across the timeframe between the two frames. At c. 150–200 px depth, mirrored surface sedimentation waves register as regions of high displacement.
Simulating maar–diatreme volcanic systems

For shallowing runs, the reduced depth of successive explosions allows for more dark beads to be carried above the surface as both ejecta and fallback sedimentation. Consequently, the juvenile dark beads are more evenly distributed between the maar ejecta rim and the post-shot crater, whilst leaving the lower diatreme deposit intact from the previous blasts. The final result is three connected, stacked diatreme deposits forming a compound stacked diatreme deposit.

The other major difference has already been alluded to: the final explosion in a shallowing sequence excavates a crater, whereas the final explosion in a deepening sequence is more likely to result in loss of the surface crater owing to intense fallback sedimentation from a narrowly focused jet (Taddeucci et al. 2013). It is worth noting that changes in the initial pressure (from 0.5 to 2 MPa) do not alter the types of diatremes formed; it is the cavity or cavities that are altered significantly by the initial pressure changes.

The increase in dark-bead mass in the diatreme deposits and inside the post-shot layered crater deposits in cases B and C is simply due to there being three blasts involved, and thus three times as much dark-bead mass. It should be noted that most of these additional dark beads have ended up high in the diatreme deposit; upward transport of debris through repeated blasts has also been reported from field-scale experiments (Ross et al. 2013; Graettinger et al. 2014), and inferred for natural systems (e.g. Lefebvre et al. 2012, 2013).

Differences in descending and ascending runs: PIV analysis

The PIV analysis can be summarized as follows. In all cases, from descending to ascending blast series, shallowest runs show the greatest amount of sedimentation onto the maar ejecta rims, the medial runs show the most expansive zones of peripheral subsurface subsidence, and the deepest runs show the greatest amount of material deposited onto the surface of the transient crater. Furthermore, pre-existing craters vertically focus the subsequently deeper blasts.

Secondary cavities and the zipping effect

As noted, in many runs with high driving pressures and pronounced fountaining, a secondary, smaller cavity appears after the first has formed, opening at the base of where the first one has just closed. Opening of this new cavity is not associated with any spikes on the pressure sensors; it is often deformed by the emerging granular fountain.

Occasionally at high pressures and (only) at medial depths, the initial secondary cavity is followed by an additional larger secondary cavity as the closure of the secondary cavity appears to rebound and reopen.

The zipping-up of primary and secondary cavities, always from the base upwards, has the same depositional signature, and thus it is impossible to tell which type of zipping took place from the deposit.

Discussion

Doming and cratering energetics

Doming energetics

As shown in Table 1, increasing initial pressure positively correlates with increasing doming base diameter. The initial pressure represents the available blast energy; thus, with increased available blast energy, more material is removed from the host bead mass. The doming base diameter (Fig. 6) is therefore effectively a proxy measure of the blast energy that is available to lift the overlying material at or near the surface. This suggests that more energetic blasts in general produce larger domes, as more energy is available to lift the overlying material. Furthermore, despite the overlap, there is some evidence that larger domes are produced at shallower detonation depths; this suggests that the largest domes are also produced when lower quantities of overlying mass are required to be moved by the blast.
Cratering energetics

The crater diameters in these experimental runs were measured from rim to rim, as would occur in the field. Like maar craters, the examples produced in these bench-scale experiments are roughly symmetrical (White & Ross 2011), and for single blasts with no pre-existing crater, larger craters formed with increasing initial pressures (Fig. 9). These data follow strongly linear trends for each depth, and it is also apparent that explosion depth (crucible depth) has a lesser control on crater diameter across this range of pressures. Some runs do not erupt, a clear indication of a detonation depth far below the optimal scaled depth, but owing to the limited size of the experimental rig, the range of depths available within this set-up is too limited to effectively see this concept in action.

The largest crater volumes in this semi-2D rig correlate well with both increasing initial pressures and reduced crucible blast depths (Fig. 10). There is, however, an apparent outlier: the largest crater was generated as a result of a blast at 0.24 m crucible depth and 2 MPa initial pressure using a slightly different configuration of the rig, wherein the crucible was covered with a paper diaphragm. In calculating the trend lines, this point has been removed from the analysis.

Cavitation mechanisms

Primary cavities

Figure 11 plots crucible depths and their associated initial pressures against both the duration and volume of the primary cavities. The duration time of the primary cavities is measured from the first observed deformation of the subsurface bead mass against the viewing screen to its closure by zipping (when the base of the cavity is parallel to the horizontal original surface of the bead mass). The volume measurement is a maximum, calculated when the cavity takes on an inverted teardrop morphology at its greatest observed extent, composed of a half-sphere at the top and an inverted cone at its base. Four observations can be made from Figure 11: (1) in general, as detonation depth increases, the volume of the primary cavity decreases; (2) in general, as detonation depth increases, the duration of the cavity increases; (3) cavity durations overlap considerably across initial pressures; (4) cavity volumes do not overlap across depths nor initial pressures. From these observations, it can be said that (1) primary cavity durations are controlled only by detonation depth (positive correlation), and (2) primary cavity volumes are controlled by both detonation depth (negative correlation) and blast energy (positive correlation).

In terms of the primary cavity volumes, this can be interpreted as follows: at depth, there is a greater amount of overlying glass bead mass. Therefore, after a deeper blast occurs, the decompressing argon gas will not be able to move as much of the greater overlying mass out of the way to form a cavity as would shallower blasts; consequently, the cavity has a smaller volume. Furthermore, higher blast energies allow greater amounts of mass to be moved out of the way of the decompressing argon gas, thus generating more voluminous cavities. With regard to the durations of the

Fig. 7. Particle image velocimetry (PIV) analysis for the granular fountain phase of a shallow blast (JPIV® open-source software) over 60 frames (milliseconds) of Run 22. The two frames to the left show the emergence of a granular fountain. Black bar indicates blast depth or top of crucible; the dark-bead structure below it resulted from previous, deeper, blast. In the PIV vector image to the right the continuous white line depicts the blast depth or top of the crucible. The white arrow points to the centre of the granular fountain. The dashed white arrows represent the displacement of the collapsing high-angle flaps. The clusters of large arrows represent maximum displacement across the timeframe between the two frames.
Case A – One blast (Run 20)  
Case B – Final of three descending runs (Run 19)  
Case C – Final of three ascending runs (Run 22)

Pronounced morphological crater, strong deformation of host layering defines diatreme structure.  
Diatreme: Single Blast Origin

Minor morphological crater, subtle shallow host layer deformation; thick, broad upper diatreme fill, thin crosscutting beads in lower segment of diatreme fill.  
Diatreme: Compound Deepened

Pr. 9. Initial pressure v. crater diameters for all runs used in this study. The mean for all three trend lines is displayed, along with the mathematical relationship between the two variables. At the shallowest blast depth, increased blast pressure causes a greater increase in crater size. The overlapping trend lines suggest that scaled depth (e.g. Valentine et al. 2012; Graettinger et al. 2014) is not predictive within this narrow range of depths owing to the restricted size of the experimental rig.

primary cavities, once again, at depth, there is a greater amount of overlying glass bead mass. Hence, after a deeper blast occurs, the decompressing argon gas will take longer to escape to the surface of the glass beads; thus, the cavity will last longer.

Figure 12 plots the primary cavity volumes against the crater volume. A positive correlation between the two variables is depicted; importantly, the crater volume scales exponentially with primary cavity volume, and the y-intercept is not zero. The line equation can be rewritten as follows, where $C_v$ is the crater volume and $k$ is the primary cavity volume:

$$C_v = 2 \times 10^{-5} e^{1000k}$$

This equation (with a relationship determined by calculating the highest $R^2$ value) suggests that a crater with a volume of 0.00002 m$^3$ can be produced with no primary cavity being generated. Therefore, it can be concluded that with this set-up, across this range of depths and pressures, a crater can be generated with a virtually non-existent (very small, non-visible) cavity. If the blast pressure is low enough and the detonation is deep enough, the argon gas will probably diffuse to the surface and cause minimal glass bead movement. This, however, still generates a crater, but not through an explosion that successfully erupts at the surface and causes any excavation. Instead, a crater is generated in this case by subsidence: PIV analysis shows subsurface bead masses beneath the crater moving to the periphery during the blast, allowing for the space...
positively correlated with initial pressures (bottom). Are positively correlated with detonation depth (top), whereas primary points, for each initial pressure set are shown. Primary cavity durations depth v. primary cavity volume. Only the trend lines, not single data Fig. 11. Top: crucible depth v. primary cavity duration. Bottom: crucible depths are required to investigate this further.

ulation is unclear; more experimental runs across a greater range of whether they are deep or shallow blasts. The reason for this corre-

cavities contain no decompressing gas whose escape to the surface is controlled by detonation depth or initial blast pressure; their potential energy will be released upon impact. The resulting secondary cavity will therefore be smaller. On the other hand, higher blast energies allow greater amounts of mass to be moved out of the way of the primary cavity, thus generating more voluminous primary cavities. In this case, with more mass able to subsequently flow back towards the base of the primary cavity, more elastic potential energy will be released upon impact. The resulting secondary cavity will therefore be larger. However, it is unclear why there is a lack of secondary cavities at some higher volume secondary cavities.

When comparing secondary cavity durations and secondary cavity volumes there is again a weak positive correlation between these two variables. As mentioned above, more voluminous secondary cavities are generated as a result of a greater elastic potential energy release at the base of the primary cavity. Secondary cavities contain no decompressing gas whose escape to the surface is controlled by detonation depth or initial blast pressure; their morphology is controlled only by the elastic potential energy release. A more energetic ‘bounce’ outwards after the initial impact will form the most voluminous secondary cavities; in addition to this, this secondary cavity will take longer to subsequently collapse inwards. Therefore, more voluminous secondary cavities will also have longer durations. Figure 13 illustrates the relation of primary to secondary cavities.

It should be noted that in most runs the kinetic energy transferred by the blast to the surrounding white beads fails to exceed a certain threshold, and the initial secondary cavity simply collapses in on itself during the general zipping up with no second rebound, and thus no additional secondary cavities, occurring.

On occasion, at high pressures and at medial depths, a larger additional secondary cavity does emerge after the initial secondary cavity. This can perhaps be attributed to the greater degrees of inward slumping from the peripheries at higher pressures and medial depths based on the PIV analysis. In these cases, the amount of mass involved in the mirrored, inward slumping from the peripheries is greater, generating two ‘bounces’. The first phase sees two mirrored masses impact underneath the primary cavity quickly, but with a relatively low total mass, generating a small secondary cavity. At the same time, the subsurface white-bead stored within the individual glass beads. As glass objects, the beads can store elastic energy. The elastic potential energy within the glass beads is built up as they are initially individually compressed; they contract then rapidly expand and release this energy. The beads act en masse as a granular fluid when mobilized, and in these experiments they are mobilized by the explosive release of gas from below. The greater the initial pressure, the greater the total kinetic energy transferred to the beads. If the kinetic energy given to the beads by the opening blast was sufficiently high, as the secondary cavity collapsed in on itself, the mirrored, inward-flowing white beads meeting at the collapse centre rebound as their stored elastic potential energy is released to create another secondary cavity. This rebound cavity formation is physically comparable with the collapse and ringing of bubbles in liquids; recent models for collapse and ringing (e.g. Rogers & Szymczak 1997) treat the flow of granular fluids as inertially flowing.

Across all pressures and depths, there is a weak positive corre-

Secondary cavities

Based on the PIV analyses and taking into account the very low compressibility of the glass beads, many secondary cavities are likely to be generated by the release of the elastic potential energy below the transient crater to produce this subsidence effect. This can be somewhat corroborated with Run 13, wherein a deep blast (0.24 m) at low pressure (0.5 MPa) produced a contained run and a subsidence-formed post-shot crater with a very small observed primary cavity and no ejecta. This is also comparable with the Graettinger et al. (2014) field-scale blasts, which also featured deep runs that produced depression pits generated through subsidence rather than any significant surface excavation.

Figure 12 also shows that the second blasts in any sequence, which are always the medial depth blasts, appear to correlate more closely with the overall trend line than the first or final blasts, whether they are deep or shallow blasts. The reason for this corre-

relation is unclear; more experimental runs across a greater range of depths are required to investigate this further.

Secondary cavities

Based on the PIV analyses and taking into account the very low compressibility of the glass beads, many secondary cavities are likely to be generated by the release of the elastic potential energy stored within the individual glass beads. As glass objects, the beads can store elastic energy. The elastic potential energy within the glass beads is built up as they are initially individually compressed; they contract then rapidly expand and release this energy. The beads act en masse as a granular fluid when mobilized, and in these experiments they are mobilized by the explosive release of gas from below. The greater the initial pressure, the greater the total kinetic energy transferred to the beads. If the kinetic energy given to the beads by the opening blast was sufficiently high, as the secondary cavity collapsed in on itself, the mirrored, inward-flowing white beads meeting at the collapse centre rebound as their stored elastic potential energy is released to create another secondary cavity. This rebound cavity formation is physically comparable with the collapse and ringing of bubbles in liquids; recent models for collapse and ringing (e.g. Rogers & Szymczak 1997) treat the flow of granular fluids as inertially flowing.

Across all pressures and depths, there is a weak positive corre-

lation to this, this secondary cavity will take longer to subsequently collapse inwards. Therefore, more voluminous secondary cavities will also have longer durations. Figure 13 illustrates the relation of primary to secondary cavities.

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Deformation processes are not noticeable in the depositional cal dark-bead cylindroid. The secondary cavity can temporarily deform the developing verti-

granular fountain; conversely, the ringing or rebounding effect of the cavity.

ond time around and thus will create a larger additional secondary velocity, which will release more elastic potential energy the sec-

ary cavities, they required explanation.

Fountaining mechanisms

Generation of granular fountains

It is highly likely that the granular fountain is produced by an inefficient transfer of kinetic energy from the argon gas to the dark beads that leads to delayed particle entrainment, as outlined by Andrews *et al.* (2014). In this model, the released gas penetrates the dark-bead mass immediately above the crule for the piercing jet, where vertical driving pressure is highest, before expanding within the overlying white beads to initiate the cavitation process. This piercing jet entrains only the dark beads directly above the small orifice, which form a minority of the total dark-bead mass. However, not all of the gas escapes through the piercing jet: some of the released gas spreads out horizontally at the base of the crule, then re-expands back into the centre of the cavity pierced through the crule dark beads. The porosity of the glass beads, which are monodisperse and spherical, is not low (according to the manufacturers, it has a minimum of 23%); however, it is presumably low enough to allow some gas to be temporarily trapped beneath the majority of the dark beads. This causes, soon after the primary cavity begins growing, the majority of the dark beads to leave the crule as a granular fountain upwards into the open cavity. This two-stage consequence of a single, discrete blast has been explored in detail by Andrews *et al.* (2014). It is supported by two small pressure spikes on SIKAs 1 and 2, the two pressure sensors on the wall of the rig behind the white beads, which record the passage of the piercing jet. Documentation of this passing pressure pulse, attributed to gas expanding and opening the cavity, argues against a purely elastic origin for the cavity.

![Fig. 12. Primary cavity volume v. crater volume for all runs used in this study. Each data point corresponds to a first, second or third blast in a blast series.](image)

**Fig. 13.** Schematic illustration (not to scale) showing the relation of primary cavities to secondary cavities. (a) A typical blast at a lower initial pressure and/or deeper blast depth. (b) A typical blast at higher initial pressure and/or shallower blast depth. The continuous-line arrows represent glass-bead masses being pushed by the expanding, decompressing argon gas (dashed arrows). The cruciform arrows represent the release of elastic potential energy. Secondary cavities form when the masses flowing symmetrically towards the base of the primary cavity bounce off each other; at higher pressures and/or at shallower blast depths, more elastic potential energy is released and the bounce effect is greater, producing longer lasting and more voluminous secondary cavities.
Instead, while the cavity is being opened by the first gas provided by the piercing jet, the remainder of the gas isquestered within the crucible, beneath the majority of the dark beads. When this gas decompresses and expands within the crucible, it drives the dark beads upward in an approximately cylindrical granular fountain. As the fountain passes through white beads to emerge into the cavity, some white beads are entrained upwards with it. In some runs, these white beads strike each other and white beads 'splash' upwards into the fountain.

This 'splashing' of the white-bead material may give additional kinetic energy to the fountain, or absorb some of it. To determine which, PIV has been used. The velocity change induced in the fountain by this splash effect was investigated, and in every case the upward splash of white beads moved more slowly than the fountain. The net effect is to marginally slow the fountain, but by no more than −0.03 m s\(^{-1}\). This is an insignificant proportion of the overall velocity of the fountain.

In any case, these processes are currently impossible to spot in field-scale experiments (Taddeucci et al. 2013) or in natural maar–diatreme systems, whereas these bench-scale runs provide an opportunity to directly connect eruptive processes with their associated depositional features.

It is worth pointing out that maar-type depression craters are morphologically similar to bolide impact craters. Recent work focusing on the sedimentary features generated by high-energy meteor impacts (e.g. Dypvik & Jansa 2003; Kenkmann et al. 2005) has described a similar central crater uplift process to that of our experiments' granular fountain generation. Notably, researchers in this field are now pursuing investigations similar to ours (Loranca-Ramos et al. 2015), highlighting the importance of such experiments to investigate this phenomenon implied to exist in both volcanological systems and impact cratering.

**Inertial flow regimes**

A recent overview of granular material flows by Campbell (2006) assessed the various mechanical behaviours between particles in different flow regimes. It commenced with the sentence: 'Under the correct conditions, a granular solid can flow like a fluid', a physical characteristic observed during this experimental study. This detailed paper described granular fluids as collections of discrete, cohesionless solid particles, immune to the effects of interstitial fluids. This is an ideal description of the monodisperse glass beads used in this experimental set-up.

There are two ways in which force is internally transmitted throughout a granular material flow: (1) ‘contact’ or ‘collisional stress’; (2) ‘streaming stress’ (Campbell 2006). The former transmits momentum from one particle to the next through collision. The latter transmits momentum through the overall flow by moving with other particles through the system in a manner comparable with that of the random motion of the particles in a dilute gas. Campbell (2006) stated that contact stresses dominate in most macroscopic flows as the concentration of large particles in common granular flows is high enough to ensure a high frequency of particle–particle collisions. As such, streaming stresses can often be neglected.

Campbell (2006) detailed various flow regimes for granular materials. The one most appropriate for the granular fountains generated by the discrete blasts in this experimental set-up is the inertial non-collisional regime, wherein many particles interact simultaneously, not just through binary collisions. It is one of two types of inertial flow, in which force is transmitted by interparticle inertia and force chains, quasi-linear structures that support and transmit the majority of the internal stress within the material, are lacking.

Key features observed in our experiments clearly show why the granular fountains fall into the inertial non-collisional regime as described by Campbell (2006). For example, during fountaining most particles rise along subparallel paths and do not collide, and the jet is expanding (particles more separated with time) so that there can be no sustained force chains.

**Cratering and diatreme analogues**

**Maar crater generation**

White & Ross (2011) reported that the crater diameter–depth ratio for maars ranges between 3:1 and 7:1. A similar assessment was carried out on the crater formed in these experimental runs. The ratios vary from a minimum of c. 2.8 to c. 16.7, with a mean value across all pressures and depths of c. 6.2, fitting within the expected field example ratio noted by White & Ross (2011). The three high outliers (13.1, 16.7, 12.8) are all at the deepest crucible depths of 0.24 m; all other ratio values are approximately between 3:1 and 7:1, giving credence to the idea that single, discrete blasts can, individually or in a succession, create the correct dimensions expected of maar craters both in the laboratory and in natural systems. This also suggests that subsidence is a major factor at depth, and is possibly responsible for creating the three outliers.

The most well-defined maar crater morphologies generated in these experiments are produced mostly by shallower or medial blasts; the deeper they go, the more pronounced the compound diatreme deposit is, but the flatter and shallower the resulting crater is, in most cases. This is probably due to the presence of vertical foci or the blasts at depth, allowing a greater proportion of material to settle back into the transient crater as fallback sediment, rather than ejecta. Furthermore, the shallower blasts allow greater excavation of the surface of the stratigraphy, whereas deeper blasts at the same initial pressure distribute the same amount of energy through much more overlying material, permitting less excavation at the surface to occur. Both these effects are noted in the field-scale experimentation of Valentine et al. (2012), Ross et al. (2013) and Graettinger et al. (2014). In addition to this, the study by Taddeucci et al. (2013) once again demonstrates that pre-eruption craters focus explosively generated jets, leading to increased centralization of fallback of erupted particles. It can be inferred that similar focusing takes place in this experimental set-up. However, for this to be tested further, future experimentation will require multiple blasts at the same, set detonation depth, to compare the proportion of fallback sedimentation with that observed during ascending or descending runs with pre-existing craters.

In some cases, the deepest crater is produced as a result of the second, medial depth blast or the deepest blast. This is observed to occur owing to slumping and sedimentation into the transient crater at a higher rate in such cases. This chaotic behaviour is attributed to small, convective, fluid motions within the glass bead host as it responds to the release of the argon gas, which may vary slightly at a level not picked up by the instruments.

It is noted that in field-scale experiments the strength of single blasts is difficult to ascertain by analysing the morphology of a crater produced by three shallowing blasts, each blast produced using the same chemical explosive energy (Valentine et al. 2012; Ross et al. 2013; Graettinger et al. 2014). As field-scale crater features are replicated at bench scale in this study, it can be inferred that crater diameter can be a good indicator of total explosion energy and depth if well formed; however, as this study indicates, some craters are almost (or entirely; e.g. Graettinger et al. 2014) nonexistent, as the proportion of fallback sedimentation is too high and/or the degree of crater excavation is too low to produce a crater.

**Subsurface structures and surface deposit analogues**

Maar–diatreme systems can be generated in these experiments by single blasts at depth, or with a series of ascending or descending blasts. One clear way to tell from the resulting structures which...
blast pattern has occurred is by examining the internal structure of the maar crater rims. In a series of ascending blasts, the overturned ‘flaps’ of juvenile material were destroyed by the increasingly shallow blasts. With descending runs, the overturned flaps of dark beads, formed by lofting and progressive resedimentation, were preserved: the deeper blasts did not destroy the structures formed by previous, shallower blasts. The opening of the primary cavity allows downward flow of the previously deposited juvenile layers into the zipping cavity, further preserving them.

Recent field-scale explosion experimentation (Valentine et al. 2012; Ross et al. 2013; Taddeucci et al. 2013; Graettinger et al. 2014) again demonstrates that explosions below the optimal depth of burial produce more-vertical ejection of material, and fallback that is strongly localized into the syn-eruption crater. This vertical focusing of the deeper explosions within the diatreme helps explain the deficit of deep wall-rock lithic fragments observed in rim deposits of maar–diatreme volcanoes (White & Ross 2011). Similarly, these glass-bead experiments, when diatreme deposits were produced, were certainly at greater than optimal depths of burial; these runs vertically focused discrete blasts into an uprush of granular material with limited lateral grain movement throughout, and fallback sedimentation was observed dominantly during the fountaining phase, which contained most of the mass of ‘juvenile’ material. Furthermore, the deeper the blasts were, the greater the ratio of fallback sedimentation to ejecta. Thus these two experiment types, bench and field scale, together imply that maar–diatreme system eruptions, or any discrete explosions at depth, feature vertical fallback sedimentation, which can be critical to forming a diatreme-like structure and determining the relative depth of the post-shot crater.

As Ross et al. (2008b) noted, volcanic vents generally narrow with depth. Thus, it can be suggested that an explosion within debris that fills such a tapering vent structure could generate a primary cavity into which a granular fountain may enter. If the particles entrained by the blast produced a granular fountain rich in solid juvenile fragments within a maar–diatreme system, they would be concentrated by rapid fallback and zipping into a narrow subvertical column. Such juvenile particles would retain most of the heat they carried when entrained, and their within-diatreme deposit would be hot and prone to welding, depending on the time scales and mechanical properties of any such naturally occurring granular fountain of pyroclasts, a topic for an entirely new study.

Diatreme morphologies in these experimental runs do not vary significantly apart from the volume of juvenile dark-bead ‘magma’ produced during the conclusion of three different runs to one singular blast. As expected, three ascending blasts force more ‘magma’ into the post-shot crater; three descending runs force more ‘magma’ into the overlying stratigraphy.

According to the PIV analyses, there are higher rates of peripheral subsurface slumping detected at medial (and to some extent, shallower) blasts. In natural examples, this means that sufficiently deep blasts will not draw down peripheral subsurface stratigraphy and significantly alter its original appearance, although post-eruption subsidence cannot be ruled out.

The PIV work also reveals that, conversely, ascending blast series at constant blast energies best preserve the central subsurface stratigraphy, as the lower sections generated by earlier blasts are left untouched by successively shallower blasts; thus, in natural examples formed by ascending blast series, we would hypothetically expect a similarly well-preserved subsurface central stratigraphy.

Field-scale experiments (Ross et al. 2013; Taddeucci et al. 2013; Graettinger et al. 2014) and some natural examples of diatreme deposits (e.g. Lefebvre et al. 2013) demonstrate that downward transport of host material is common, and in natural examples large fragments or aggregates dropped from their sites of origin are prominent. The glass beads in our experiments are all the same size and do not form aggregates, and in our experimental deposits the only direct evidence for downward motion is the down-bent stratal markers. These experiments, and others (e.g. Roche et al. 2004), show that granular systems can behave fluidly when given enough initial kinetic energy. Intra-diatreme–maar deposits would not sustain unsupported steep walls when an explosion cavity forms, and significant collapse or flow behaviour, although probably less granular–fluidal, is inferred to take place in diatreme structures developing through series of discrete explosive blasts.

Recent numerical modelling by Sweeney & Valentine (2015) acts as a numerical model equivalent to our bench-scale experiments, and provides numerous correlative results. Significantly, these numerical models show that deeper blasts produce granular fountains, there referred to as ‘debris jets’ (e.g. Ross et al. 2008a,b), that incrementally transport deep-seated lithic fragments up towards the surface crater and out onto the ejecta rims; this is a key process that occurs in the generation of our simulated maar–diatreme systems. Sweeney & Valentine (2015) also noted that the shallowest explosions in diatremes are the most efficient at transporting and excavating material, a conclusion entirely supported by our own study. It is important to note that these numerical models also used an overall homogeneous material fairly similar to our monodisperse glass beads, which oversimplifies the results somewhat. Depressurizing cavities in homogeneous granular material will probably produce more fluid-like behaviour in both studies than they would in larger scale experiments with more heterogeneous material (e.g. Taddeucci et al. 2013; Graettinger et al. 2014).

Further discussion: synthesis with field-scale experiments

The 2012–2015 field-scale experiments used buried TNT explosives to investigate the generation and architecture of experimental maar–diatreme structures, effectively representing a scaled-up version of our bench-scale runs (Nordyke 1961; Valentine et al. 2012, 2015; Ross et al. 2013; Taddeucci et al. 2013; Graettinger et al. 2014).

In general and with few exceptions, these experiments demonstrate, with respect to the optimal depth of burial (ODB), that just above or at the ODB the most voluminous craters per explosion energy are produced because much of the blast energy goes into the crater excavation. In addition, just above or at the ODB, the blasts form cavities that expand both vertically and horizontally, with the vertical (and subvertical) velocity component being particularly high. This leads to a greater proportion of crater rim ejecta being generated in comparison with fallback sedimentation into the crater.

In contrast to this, below the ODB, less voluminous craters are generated as a result of more of the blast energy being absorbed by a greater mass of overlying material, and thus less is excavated. Furthermore, the vertical velocity and horizontal velocity components are proportionally more equal, even though the presence of a pre-existing crater vertically focuses the debris jets. The overall lower momentum value of this mobilized mass, in combination with this vertical focusing of the jet, means that most of it falls back as fallback sedimentation into the crater, often generating a small depression pit rather than a true crater. Significantly, diatreme deposits are produced only with blasts below the ODB.

Despite the fact that scaled depth and the ODB could not be calculated for the bench-scale experiments, these conclusions from the 2012–2015 field-scale studies are applicable to the glass bead runs.

In addition to this analysis of the role of the ODB, the following additional conclusions from both sets of experiments are noted,
again applicable to natural examples. First, subsidence and mixing both play greater roles as blasts deepen, although at sufficient depth upper periphery subsurface architecture remains untouched syn-eruption. Slumping in the subsurface peripheries is almost certainly proportional to the frequency and magnitude of medial blasts, owing to their induction of subsidence. Second, surface-level overturned flaps are formed owing to more energetic lateral momentum components at shallower depths. Third, the upward folding of subsurface layers proximal to the transient crater boundary is generated by ascending blasts from depth forcing deeper material repeatedly up through shallow layers; this also leaves the central basement architecture intact. Fourth, craters can be generated not only through excavation by cavitation but also through just subsidence occurring in contained blasts. Corroborating morphologies of maar craters generated by discrete blasts in bench- to field-scale analogue experiments clearly demonstrate that maar craters fall within a 3:1–7:1 diameter–depth ratio.

Arguably the most important finding is that maar–diatreme systems can be generated by single discrete blasts at sufficient depth, and with ascending or descending blast series at sufficient initial depth. Recent fieldwork (e.g. Geshi et al. 2011; Lefebvre et al. 2012, 2013) on maar–diatreme volcanoes has found compelling evidence for the latter.

Conclusions

These bench-scale models not only innovate with a 2D, side-on (longitudinal) perspective on discrete blasts within a granular material, analogous to those of maar–diatreme systems that are found across the planet, but are successful in many ways at qualitatively and quantitatively replicating the morphological features found in natural volcanic systems and those generated in recent field-scale experimental studies. Importantly, the crater diameter–depth ratios, the sedimentation sheets from descending dome walls, the sunken post-shot crater, the fallback sedimentation, the maar ejecta rims, the diatreme formation and the general stratigraphy of natural maar–diatreme systems are all successfully replicated here. This not only means that these dynamic cratering experiments are highly accurate representations of maar–diatreme systems despite lacking any thermal component, but they all but confirm that maar–diatreme systems can form as a result of either a single discrete subterranean blast or multiple ascending or descending consecutive discrete blasts. Subterranean explosions involve complex physical processes that are currently very difficult to recognize from surface observations alone. In every case a primary cavity is opened by each blast, and there is particle transport within it. Also, under a wide range of conditions, a within-cavity granular flood forms, in which particles move upward within an inertial non-collisional flow regime. Although debris jets are commonly presented as a simple uprush of entrained material, these experiments reveal two distinct particle-transport phenomena: cavitation and granular fountaining. Lastly, the diatreme deposits and the deposits generated in these experiments, from single blast origin to both stacked compound and compound deepened diatremes, show a range of complexity that can be compared well with deposits of real diatremes. The distinction between upper and lower diatreme deposits cannot be made, however; owing to the uniform nature of the glass beads, true sedimentary layers cannot be created using this set-up.

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