**Circum-crater variability of deposits from discrete, laterally and vertically
migrating volcanic explosions: experimental evidence and field implications**

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Abstract

Circumferential variation in sorting, thickness, granulometry, and componentry of tephra ring deposits can result from instabilities in the eruptive jet and interactions with the confining crater. Jet instabilities result in fingers of high particle concentrations that form deposits radiating away from a crater, referred to as rays. Two major types of rayed deposits are described from subsurface explosion experiments: (1) symmetrical rayed deposits with an axisymmetric ejecta blanket, which result from vertically-directed eruptive jets; and (2) zones of rays that extend out from sectors of a crater, with an asymmetrical proximal ejecta skirt, that result from inclined jets. Variations within each group are also associated with variations in the explosion depth relative to the energy of the explosion. Although the surface morphology of rays is likely to be lost in natural tephra rings due to overlapping deposits of numerous explosions, rayed deposits are expected to be preserved in cross section as lenses of relatively coarse and poorly sorted material compared to surrounding deposits. Asymmetrical deposits of inclined jets are anticipated to be particularly distinctive. The experimental facies associations indicate that these deposits would be easily distinguished, given sufficient exposure, from other heterogeneities caused by wind influence, collapse of the crater rim, or the influence of topography on density currents. These experimental results can also be used to further the discussion of deposits from inclined jets from other explosion scenarios, such as Vulcanian blasts and hydrothermal explosions. The experimental rayed deposits described here indicate that the classic interpretation of clast concentration zones in tephra ring deposits must be reevaluated.

1.0 Introduction

The deposits of maar-diatremes have been observed to contain significant variability in grain size, sorting, and componentry reflecting a combination of eruptive, transport, and deposition processes. In addition to proximal to distal changes, variations in deposit facies and

thickness *around* the crater (referred to here as circum-crater or circumferential) are common in maar tephra rings (Kienle et al. 1980; Büchel and Lorenz 1993; Brand et al. 2009; Ort and Carrasco Nuñez 2009; Son et al. 2012; Jordan et al. 2013). These variations have been attributed to crater wall collapse and recycling processes, lateral vent migration, wind, and variable transport in pyroclastic density currents. Here we focus on circum-crater variations in experimentally-produced deposits in order to explore additional mechanisms that produce this lateral diversity in natural deposits.

Meter-scale crater experiments provide an analog for explosions through debris-filled vents such as are characteristic for maar-diatreme volcanoes, but can occur at nearly any subaerial volcano. These experiments have provided a unique opportunity to observe jet processes resulting from explosion configurations and the resulting deposits. Previous investigations have highlighted the importance of scaled depth and surface conditions (presence of crater or other topographic features and disruption level of materials over an explosion) on the explosion jets, crater formation, and ejecta distribution (Taddeucci et al. 2013; Graettinger et al. 2014, 2015; Valentine et al. 2015). The variations in ejecta distribution with distance from the eruption location (vent) indicated that in multiple-explosion craters, most explosions would produce predominantly proximal ballistic ejecta, dilute density current deposits, and rare isolated fall deposits. These experiments also enable the investigation of circum-crater heterogeneities within ejecta deposits in the absence of wind or complicated topography, with well-constrained explosion energies and locations. A key observation is that discrete explosions produce, among other deposit types, depositional rays. Rays are here defined as narrow depositional structures that extend radially away from a crater (vent) as linear accumulations of ejecta that are thicker than surrounding deposits. Individual rays form subtle positive landforms that thin with distance, and are composed of relatively coarser material than surrounding deposits from the same explosion. They are lenticular in cross section

(perpendicular to ray axis) and may present unique componentry to surrounding deposits. Rays present circum-crater variations in deposit thickness, grain-size, and componentry that vary with explosion conditions, eruption history and scaled depth. Rays, **high albedo features containing fine dust radiating away from a circular crater**, have been described in the meteorite impact literature (Melosh 1989; Neish et al. 2013 and references therein), but unlike impacts, volcanic centers typically involve multiple explosions and ejection events with sources that can migrate vertically and laterally. Additional circum-crater variations in ejecta deposits result from explosions beneath slopes (such as during lateral explosion migration within a crater, or on the side of a larger volcano), which produce inclined jets that result in asymmetrical ejecta deposits characterized by thick proximal ejecta deposits on one side of a crater and a zones of rays on the opposite side.

2.0 Methods

Experiments were conducted in rectangular pits filled with granular materials with conditions that varied between experimental sets (Graettinger et al. 2014; Valentine et al. 2012, 2015). The experiments were conducted through layered and unlayered materials; charges were placed in holes at the depths of interest, and the charge holes were backfilled (with a unique material to serve as a tracer). Experiments had between one and six individual explosions where charge position was varied vertically and laterally. Explosions are described as either primary, through undisturbed ground with flat topography, or secondary, through previously exploded material or a range of surface morphologies. The resulting craters ranged from 0.5 to 2.7 m in diameter and ejected material up to 25 m away from the explosion locus. Circum-crater variations in deposit thickness, sorting, and componentry from subsurface explosion experiments were documented using oblique photography, photogrammetry, and ejecta samples collected after each explosion. Photogrammetry of the near crater area

produced 1 cm resolution digital elevation models (DEMs) after each explosion. Two arrays of sample boxes were deployed radially away from the crater at 1 m increments to measure the mass loading of ejecta. The starting material for these experiments varied for the different experiments and included: one material of poorly sorted crushed limestone sand (0.1-9 mm), or multiple layers of crushed limestone sand, recycled asphalt (2-16 mm), moderately sorted sand (0.1-4 mm) and well sorted quartz sand for charge fill material (0.1-1 cm). As the results discussed here are from multiple experimental set ups the grain size distribution is discussed in relative terms of sorting, where poorly sorted material consists of a range of these available grain sizes in the absence of grading or other bedding structures and well sorted material consists of similar sized particles, typically the finer grained sands. Samples were later analyzed for componentry and supplemented qualitatively from images and observations. The maximum distance of deposit components, including rays, was measured using sample boxes, or manually based on visual identification of components. The results were compared with the charge configuration, high speed and high definition videos, and weather conditions for each explosion.

Explosion conditions are described in terms of the depth of the charge below the surface (surface directly above the explosion) and the energy of the charge (Valentine et al. 2014; Sonder et al. 2015). This is parameterized as a scaled depth (physical depth divided by the cube root of the explosion energy, units of $\text{m/J}^{1/3}$). Conditions that produce the largest craters and largest volume of ejecta for a given energy occur at an optimal scaled depth ($\sim 0.004 \text{ m/J}^{1/3}$; Sonder et al. 2015). Explosions with relative smaller scaled depths are described as shallower-than-optimal scaled depth, and those that are larger are described as deeper than optimal scaled depth. Ejecta processes and crater morphology are related to scaled depth (Graettinger et al. 2014, 2015) as well as to the topography of the ground surface above the explosion point (Valentine et al. 2015).

Ejecta facies typically display variable morphologies with distance away from a crater. Deposits that form the rim of the crater dip away in steep slopes of >20 degrees to form the proximal ring. The proximal ring transitions outward into a thinner medial blanket (dip < 10 degrees) that forms a continuous sheet that mantles topography and can extend up to 15 times the crater radius (Graettinger et al. 2015). Distal ejecta occurs as isolated clasts that define the farthest extent of deposition, up to 24 times the crater radius.

3.0 Experimental circum-crater deposit characteristics

Circum-crater variations in ejecta deposits from the experiments were dominated by the presence and distribution of depositional rays and the degree of symmetry of proximal deposits. Rays occurred in isolation, in zones of rays, or symmetrically around a crater. Individual rays were broadest near the crater and narrowed with distance, with maximum accumulations along the axes of the rays. If the ray materials were well sorted this accumulation was expressed only as an increased thickness along the ray axis (Figure 1a-b). In these experiments the thicknesses of rays were as much as 6 cm near the crater, thinning with distance to individual clasts. If the ray was poorly sorted, coarse clasts were concentrated along the ray axis coincident with maximum thickness. Many rays displayed a greater abundance of coarser clasts relative to the associated medial blanket deposit from the same explosion (Figure 1c). If a diversity of components existed in the experimental pad, the componentry of a ray varied relative to the associated medial blanket, relative to other rays, and/or as a function of grain size (Figure 1d). The farthest extent of the ray was typically delineated only by isolated clasts and was difficult to distinguish from more symmetrically distributed isolated distal clasts of underlying deposits or, when present, associated medial blanket deposits. Rays ranged in length from 2 m to 25 m from the parent craters (Table 1).

Ray deposits were associated with a proximal ring (Graettinger et al. 2015) that had a smooth or hummocky surface as dictated by the grain size distribution of the material within each eruptive jet (Figure 2a). Proximal rings ranged from 3 to 18 cm in thickness and either thinned out within two times the crater radius or transitioned into a medial blanket. In most cases the rays were distinguishable in the proximal zone, but their expression was more subtle on the steep slopes than on the flat topography farther from the crater (Figure 1a, b). The proximal deposits were either complete and symmetrical, or open at one end, in which case it was called an asymmetrical skirt.

Symmetrical proximal rings occurred alone or transitioned into symmetrical medial blankets of ejecta. Medial blankets consisted of a continuous ground cover of poorly sorted material from the jet that was on the order of 0.5-3 cm thick (Figure 2b). This blanket mantled topography and then graded outward into isolated clasts of a distal deposit (e.g. Graettinger et al. 2014; 2015). The medial blankets extended up to 15 times the crater radius away from the explosion locations (Table 1). These symmetrical deposits contained either a single ray, or symmetrically distributed rays around the crater that extended beyond the proximal ring. Symmetrical rayed deposits included between four and twenty or more rays, with some uncertainty at high numbers due to experimental conditions.

Asymmetrical skirts were a variation on proximal deposits that surrounded only ~2/3 of a crater, forming a crescent shape around the crater that was open on one end where it transitioned into a zone of rays (Figure 2c). Asymmetrical skirts had steep slopes (>20 degrees) and were limited to less than twice the crater radius away from the explosion location (Table 1), but widened and decreased in thickness as it transitioned into the zone of rays on the opposite side of the crater. There were no medial blanket or distal isolated clast deposits beyond the edges of the asymmetric skirts. Asymmetrical skirts were between 7 and 14 cm thick at their maximum and graded into thinner zones (0.5-2 cm thick) of rays in the opposite direction. In

map view (Figure 2c) the zones of rays were typically 1.3-2 times wider than the crater radius proximal to the crater and either narrowed to a point or widened to up to 4 times the crater radius at large distances. The zones contained between one and three rays with more diffuse distribution of poorly sorted clasts between the rays. No isolated clasts were deposited outside the zone of rays.

3.1 Jet results

High speed and high definition videos of the experiments were used to identify a range of jet behaviors with a focus on clast-concentration zones, or fingers, within the jet. These jet types were then associated with the deposit types described above. Jets were divided into vertical and inclined jets. Vertical jets resulted from explosions under flat topography, or cratered topography where the explosion occurred under the center of the previous crater feature. Inclined jets formed as a result of an explosion under a sloped crater wall, representing lateral migration of the charge location (Valentine et al. 2015). Vertical jets developed elongate clast concentration zones (fingers) that advanced ahead of the main jet, or were visible through more dilute parts of a jet (Figure 3a). Fingers were observed in both cases to deposit before the more dilute portions of the jet (Supplemental Video1). The collapse of the fingers occurred as an outward advancing front followed by the collapse of the main jet body that formed a ballistic curtain (Figure 3b; Graettinger et al. 2015). Collapsed fingers produced the rayed deposits, while the collapse of the dilute or more evenly concentrated portions of the jet formed the proximal ring and medial blanket. The relative extent of the medial blanket was related to the height of the main jet for vertical jet cases. When the fingers advanced beyond the more dilute portion of the jet body the ray deposits extended beyond the medial blanket (Figure 3c). When the fingers did not extend beyond the more dilute jet the medial blanket was broader and partially covered the rays. When explosions occurred under an established crater the jet was more focused and frequently formed a single narrow column, or a single finger (Taddeucci et al.

2013; Graettinger et al. 2014). This jet mostly collapsed back into the crater and produced minimal extra-crater deposits, typically contributing only to the proximal ring (Graettinger et al. 2015). While the bulk of the jet material collapsed into the crater the top part of the focused jet was occasionally observed to lean outward as it fell and produced a single short ray (Figure 3c; Supplemental Video 2).

Inclined jets consisted of three components that developed from an initial doming of the ground surface during an explosion: subvertical ejecta skirt, central finger, inclined fingers. The subvertical ejecta skirt collapsed in the direction opposite to the angle of jet inclination to form the asymmetrical skirt deposit while the vertical and inclined fingers collapsed in the direction of inclination to form a broad zone of rays (Figure 3). The central finger rose to a height comparable to vertical jets of the same scaled depth, but collapsed laterally to contribute material back into the crater and contribute to the zone of rays. The center of the inclined jets was between 45 and 65 degrees above the ground surface (Supplemental Video 3).

3.2 Explosion conditions: scaled depth and material configuration

The conditions that produce the various jet types, and consequently, the depositional patterns described above, are related to the presence or absence of a crater and the scaled depth of the explosion. Explosions that occurred through undisrupted materials and flat ground (primary explosions) formed wider jets with well-formed fingers, which resulted in symmetrical rays (Figure 4). For primary explosions, as scaled depth increased the length of the rays and farthest extent of distal ejecta decreased until confining depths were achieved and no ejecta was produced (Table 1; Valentine et al. 2014; Graettinger et al. 2015). Conversely, the number of rays increased as scaled depth increased. At shallower-than-optimal scaled depths, the extent of the medial blanket increased with increasing scaled depth until optimal scaled depth conditions were achieved. In greater-than-optimal scaled depth conditions the medial blanket,

like the rays, was reduced in extent until confining conditions were achieved (Figure 4). The relationship between the rays and the medial blanket can be represented by a ratio of the maximum extent of the medial blanket and the maximum extent of the rays (Table 2). This ratio increased for explosions under undisturbed flat ground with increasing scaled depth, and exceeded 1 only for deeper than optimal scaled blasts.

In multiple explosion systems (i.e. where explosions interact with previously disrupted materials) the pattern was more complicated. Where explosion location varied vertically, ray length was greatest at optimal scaled depth conditions and decreased for all other scaled depth conditions. Ray number was generally higher than for equivalent explosions through undisturbed material. The extent of the medial blanket was similar to the extent of rays at shallow scaled depths (Table 2). The distribution of distal ejecta was greatest at shallow scaled depths and decreased as scaled depth increased. At greater-than-optimal scaled depths the extent of rays, distal ejecta and medial blanket (if present) was limited. Greater-than-optimal scaled depth explosions through previously disrupted material occasionally formed a single short ray that extended beyond the narrow medial blanket as a result of the top of the focused jet leaning outward as it collapsed (Figure 4).

Inclined jets were formed when explosions occurred under the sloped inner wall of a well-formed crater (Valentine et al. 2015). While inclined jets have only been investigated at slightly greater-than-optimal scaled depths and at very large scaled depths to date, it was determined that inclined jets were formed only after a conical crater was formed by preceding explosions. Explosions with scaled depths greater than $0.006 \text{ m/J}^{1/3}$ frequently formed hummocky crater fills, or even positive topography, such as a retarc, rather than well-formed craters (Graettinger et al. 2014); subsequent explosions through these complicated morphologies did not produce inclined jets. However, multiple greater-than-optimal scaled depth explosions can produce a crater, enabling subsequent explosions to produce inclined jets.

Consequently, the sequence of explosions in the crater system influences the occurrence of inclined jets. For detailed discussion on crater morphology in multiple blast sequences, and the potential for forming a crater versus hummocky depressions the reader is referred to Sonder et al. (2015).

Explosions through crater slopes produced maximum jet heights comparable to vertically-oriented jets of the same scaled depth (Figure 5); however, the maximum distance of ejecta from inclined jets was significantly greater than vertically-oriented jets of the same scaled depth (Table 2). There are insufficient data to indicate the specific conditions that produced these extreme ray extents of some inclined jets; however, they were likely related not only to the angle above the ground, which was close to 45° for most blasts, but also the geometry of the crater that the jet must escape to expand. This is an area of ongoing investigation.

4.0 Discussion

The experiments demonstrate transport and deposition of granular jets from subsurface explosions. The rayed deposits described here would form part of the depositional history at a natural maar-diatreme (Graettinger et al. 2015), and we can infer how these rays might be preserved and how they can aid in the reconstruction of eruptive histories. The preservation and subsequent observation of rays in tephra ring deposits are dependent on several factors: grain size distribution of the deposit, eruption sequence, and variations in componentry.

The grain size distribution and sorting of the rayed deposits is controlled by the source material, instabilities in the jet, and expulsion of fine particles during emplacement. Explosion jets predominantly source material from above the explosion location (Graettinger et al. 2014). Consequently, the grain size distribution of the jet will be influenced by the host material strength, juvenile material abundance, and explosion history. This material is then disrupted by the explosion to produce an expanding particle-gas mixture, or jet. The heterogeneities of the

ground surface produced during the passing pressure wave of the explosion, visible as cracks in the doming surface at the initiation of explosion, are imparted to the expanding jet (Supplemental video 4). As the jet continues to expand, multiphase processes within the particle-gas mixture result in variable concentrations of clasts (e.g., Darteville and Valentine 2007), or fingers, that contain a range of grain sizes, **limited by availability**. The dilute portions of the jet were observed to also be poorly sorted, but appear to contain fewer of the largest clasts. In the deposit, these larger clasts are concentrated in the rays, with fewer as isolated clasts. A wider grain size distribution, as common to maar-diatreme systems, will accentuate these trends as the coarse clast concentrations of the rays will stand out from the narrower grain size distributions of the medial blanket. Additionally, the characteristics of underlying and overlying deposits will contribute to the visibility and preservation of rays in the deposit.

Investigations of the ejecta deposit distribution with distance (Graettinger et al. 2015) and crater morphology (Sonder et al. 2015) indicate that the number of explosions, in addition to scaled depth of explosions, contribute to the production of extra-crater ejecta and thus available stratigraphy. Similarly, an eruption sequence that produces multiple deposits with similar maximum extents for rays and medial blankets will produce a very complicated deposit where the identification of individual rays may be difficult. After the initiation of a maar-diatreme eruptive episode, most explosions will occur within previously disrupted material, resulting in deposits dominated by rays. As rays become diffuse with distance they may become difficult to distinguish from isolated clasts from the same jet or previous/subsequent deposits. However, the identification of rays may be improved if a rayed deposit is composed of distinct components. Jet, and thus deposit, componentry can vary during an eruption through the input of variable quantities of juvenile material, changes in the texture of those juvenile particles, and the excavation and upward mixing of variable quantities and types of host rock material. Our experiments revealed variations in the componentry between rays as a result of heterogeneities

in the material above and around the explosion (Figure 1d). Numerous explosions produce subvertical domains of different mixtures of materials below a crater (Graettinger et al. 2014; Valentine et al. 2015). These domains of distinct componentries contribute to the material excavated by later explosions and can result in variable componentries within individual rays from the same explosion.

It is significant that the deposits that contain fewer rays would likely be more obvious than those produced by numerous symmetrical rays. Isolated rays formed by the collapse of a vertically focused jet are typically short and associated with a symmetrical proximal ring. However, for an eruption at the same scaled depth the length of the zone of rays is dramatically increased for an inclined jet. Additionally, associated asymmetrical skirts produce dramatic variations in near crater deposit thickness, with the thickest being on the side of the crater opposite to the direction of jet inclination. The preservation of these zones of rays and asymmetrical skirt may be limited by collapse, crater expansion, and topographic convolutions, and also must be contrasted with deposits produced by preferential deposition in windy conditions.

In order to highlight the unique properties of the deposits from inclined jets, deposits from the experiments were used to produce example stratigraphic logs (Figure 6). The stratigraphic logs represent relative variations in deposit thickness and distribution as observed from fixed locations around a crater that experienced multiple explosions at constant scaled depth, but laterally varying explosion location. Where the asymmetrical skirt is sampled, a thick deposit of poorly sorted material and mixed componentry is observed. Where rays are sampled, in the direction of jet inclination, the deposit is thinner, has higher concentrations of coarse clasts, and increased abundance of material from near the explosion location (juvenile tracer) represented by colored sand. As the explosion location moves, the logs record either asymmetrical skirt facies, zone of rays facies, or non-deposition. These logs indicate the

diversity of thickness and facies that may be observed in natural tephra rings that experience lateral explosion migration. In a natural system, where scaled depth is likely to fluctuate as well, the logs may contain even more complex deposits. This complexity may either hide or highlight the rayed deposits through the presence of interbedded density current deposits and ash fall deposits.

5.0 Identification and interpretation of rayed deposits in nature

Rayed deposits in natural tephra rings would be best observed in cross-section perpendicular to the radial direction. Rayed deposits are anticipated to be lenticular in cross-section and contain a distinct poorly sorted coarse-skewed grain size distribution (Figure 7). While fresh ray deposits influence the local surface morphology, these minor fluctuations are unlikely to be preserved at the surface of tephra rings. Asymmetrical skirts will be presented as thick accumulations of ejecta on one half to two thirds of crater rim. The skirt deposits would thin rapidly away from the crater and do not have a medial or distal equivalent, in contrast to asymmetric deposits produced by a dominant wind direction.

Previous descriptions of natural tephra rings indicate the potential presence of rayed deposits in the form of variations in the abundance of blocks (e.g. Lunar Crater; Valentine et al. 2011) or lenticular coarse clast-rich lenses (e.g. Easy Chair; Valentine and Cortés 2013). The coarse clast-rich lenses of rays resulting from inclined jets would be stratigraphically equivalent to the asymmetrical skirt deposits on the opposite side of the crater. Circum-crater variations in tephra thickness and facies have been observed at most maars described in the literature. Even historic examples investigated a few years after emplacement, such as Ukinrek, had deposits where “correlation of units was not easy because the units strongly vary in thickness and facies even at short distance” (Büchel and Lorenz 1993) and deposit thickness was notably asymmetrical (Kienle et al. 1980). Heterogeneities in deposit thickness have been associated with vent migration previously (Son et al. 2012), but must be distinguished from influences of

wind (Kienle et al. 1980), collapse of the crater rim (Brand et al. 2009), and overlapping of deposits by neighboring eruptive centers (Sottili et al. 2012). Also, coarse clast-rich lenses have been used previously to infer transportation by dense pyroclastic density currents (Vazquez and Ort 2006; Sottili et al. 2012; Valentine and Cortés 2013). These lateral heterogeneities in tephra ring deposits require reevaluation in light of the additional mechanisms revealed by subsurface explosion experiments. The presence of a zone of coarse clast-rich lenses, the stratigraphic association of proximal thickness variations with zones of rays, and the absence of medial and distal components of thick asymmetrical skirt deposits may prove useful in the identification of lateral explosion migration within a maar. In particularly well-preserved deposits, it may even be possible to use the ratio of medial blanket to ray length to identify lateral migration of explosion locus and distinguish greater-than-optimal scaled depth explosions from those with optimal or shallower scaled depths.

Other examples of asymmetrical deposits produced by discrete inclined explosions include Vulcanian explosions (Cole et al. 2015) and hydrothermal explosions (Breard et al. 2014). In both of these examples, the inclination of the jet and resulting deposit asymmetry are attributed to asymmetric vent geometries. Similarly, our experimental results indicated that inclined jets were formed by explosions through slopes of well-formed craters, further supporting the influence of vent geometry on the production of inclined jets. As the deposit distribution of inclined jets in experiments and natural cases was observed to exceed that of equivalent vertical explosions, further research into these conditions is of critical importance to hazard mitigation plans.

6.0 Conclusion

Buried explosion experiments with vertical and lateral explosion migration enabled the description and interpretation of circumferential variations in ejecta sorting, thickness,

componentry, and granulometry. Rayed deposits are likely common in maar tephra rings. The distribution of rays is controlled by crater condition and scaled depth. Deposits produced by inclined jets are unique relative to those produced by vertically-oriented jets. Symmetrically distributed rays are associated with vertically-oriented jets, while inclined jets have asymmetrical deposits with a zone of rays in one direction and thick, proximally-limited deposits in the opposite direction. Preservation of deposits is dependent on grain size distribution, componentry, and eruption sequence. Rayed deposits are most likely to be recognized in cross-section as lenticular concentrations of coarse clasts. In light of these results, previous interpretations of coarse clast concentration zones and asymmetrical proximal tephra deposits may benefit from re-assessment.

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Figure Captions:

Figure 1 Examples of ray deposits from subsurface blast experiments and their distinctive features, black arrows indicate rays. All rays featured are symmetrically distributed, but are representative of the important features of individual rays. A) Rayed deposits expressed as minor topographic ridges that extend from the crater rim outward. Hillshade produced from 1 cm photogrammetry-derived DEM (2014P4B1). B) Visible image of rays in A, but are less obvious from color and grain size **distribution** alone. C) Rays dominated by larger clasts (2013bP3B1). D) Three different clast componentries are obvious in rays from the same explosion. Black horizontal scale bars are 1 m in length. Vertical scale markers are 10 cm increments.

Figure 2 Depositional features associated with rayed deposits. A) proximal ring deposits have steep slopes >20 degrees and may be smooth or hummocky, as in this example. These deposits only extend two times the crater radius from the explosion locus. B) Medial blanket

deposits are symmetrical continuous deposits around a crater and can extend up to 15 times the crater radius. C) Asymmetrical skirt and zone of rays are specific forms of proximal and medial deposits formed by inclined jets where steep angled proximal deposits only occur around 2/3 of the crater (black curve), which widen and transition to a zone of rays (dashed line).

Figure 3 Schematics and photographs of jets and the formation of end-member rayed deposits. A) Schematic of jet showing clast concentration zones (fingers) and their interaction with the rest of the dusty jet. B) Deposition of fingers, dusty gas mixture, and isolated clasts. Rays collapse progressively from the crater rim outward and more dilute portions of the jet follow (ballistic curtain). C) Relative distribution of rays and associated deposits: proximal ring or asymmetrical skirt, medial blanket if present, rays or zone of rays, and distal isolated clasts. Dashed line indicates crater rim. D) Images of jets from experiments with fingers which are associated with rayed deposits.

Figure 4 Generalized schematic of deposit characteristics as related to scaled depth and the nature of interaction with a pre-existing crater. Deposits are composed of medial blankets, rays, asymmetrical skirts, and isolated distal ejecta. The preservation of a ray within the deposit will be dependent on its characteristics and the other components of the deposit. See text for discussion.

Figure 5 The maximum distance of ejecta collection from subsurface explosion experiments as scaled depth decreases. The height of the jet produced by an explosion at a given scaled depth is consistent for vertical and inclined jets. The maximum distance of ejecta distribution is much larger for some inclined jets for a given scaled depth.

Figure 6: Example logs from two experimental craters produced by lateral migration of the explosion location, but fixed scaled depth. The logs (a-d) are located 2 m from the crater center. Logs show variations in thickness, componentry, and appearance of juvenile tracers. The tracer material was uniquely colored and located only around and above the charge (within the 10 cm charge hole). The general direction of explosion migration is indicated with a white arrow. A) Crater 2014Pad1 the depositional units featured are the final three in a series of six explosions where the first three explosions did not produce appreciable deposits due to very large scaled depths (Valentine et al. 2015). Unit 1 was the result of a vertically oriented jet that leaned over during collapse to form a small ray. Unit 2 and 3 were the result of inclined jets. B) Crater 2014Pad 2 Unit 1 was the result of a vertically oriented jet and Units 2-4 were produced by inclined jets (Valentine et al. 2015). Thicker deposits are concentrated in the direction opposite of the zone of rays (i.e. logs a and b), but only when the sample location was close enough to the crater to collect proximal deposits (A, log a).

Figure 7 Schematic cross-sections of experimental deposits from Crater 2014Pad2 (same as Fig 6 B). Line A-A' cuts deposits of asymmetrical skirts from jets inclined toward the opposite side of the crater (Units 2-4). These deposits overly a ray deposit from a vertical jet formed by the first explosion in the series (Unit 1). Line B-B' cuts through deposits of symmetrical rays (Unit 1) and zones of rays (Unit 2-4). When rays are exposed perpendicular to the ray axis a lenticular zone coarse clast concentration zone is visible. Asymmetrical skirt deposits are massive and poorly sorted in cross-section and have a greater thickness relative to ray deposits (and medial blanket deposits, not featured).

Table 1: Major characteristics of proximal, medial, and distal facies relative to rayed deposits for experimental cases discussed in the text. Values listed are maximum values.			
	Proximal and medial deposits	Ray	Isolated clasts
<OSD Flat ground	Circular medial blanket close to crater (3 m)	Symmetrical , few, long (15 m)	Many scattered between rays (15 m)
OSD Flat ground	Large circular medial blanket (12 m)	Symmetrical, few, extend beyond medial blanket (16 m)	Many scattered between rays (16 m)
>OSD Flat ground	Proximal dominated with circular medial blanket close to crater (2.5 m)	Symmetrical, many, extend slightly beyond medial blanket (2 m)	Few, only at the end of rays (2 m)
<OSD through crater	Circular medial blanket dominates deposit with wide extent (15 m)	Symmetrical, subtle topographic expression in medial blanket near the crater rim (15 m)	Few beyond medial blanket (18 m)
OSD through crater	Circular medial blanket dominates deposit with wide extent (14 m)	Symmetrical, subtle, within medial blanket (14 m)	Few beyond medial blanket (14 m)
>OSD through crater	Proximal only or limited medial blanket (2 m)	If present, only one that extends beyond blanket (3 m)	Few but near crater rim (3 m)
>OSD through crater wall	Thick asymmetrical proximal deposits around only half or 2/3 of crater rim (1 m)	Asymmetrical zone of rays may widen away from crater, with several clast concentration zones (25 m)	Many, but concentrated within zone of rays (25 m)
OSD= Optimal scaled depth			

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Table 2: Ratio of the maximum extent of medial blanket* to ray length.									
	<OSD			OSD			>OSD		
	Blanket (m)	Ray (m)	Ratio	Blanket (m)	Ray (m)	Ratio	Blanket (m)	Ray (m)	Ratio
no crater	3	15	0.2	12	16	0.75	2.5	2	1.25
Crater	15	15	1	14	14	1	2	3	0.67
Inclined jet							1*	25	0.04
* Asymmetrical skirt for inclined jets OSD= Optimal scaled depth									

500

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7