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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. 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-Núñez, 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,

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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. Methods

Experiments were conducted in rectangular pits filled with granular materials with conditions that varied between experimental sets (Valentine et al., 2012, 2015; Graettinger et al., 2014). 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 setups, 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 $m/J^{1/3}$). Conditions that produce the largest craters and largest volume of ejecta for a given energy occur at an optimal scaled depth (~$0.004\ m/J^{1/3}$; 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° to form the proximal ring. The proximal ring transitions outward into a thinner medial blanket (dip < 10°) 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. 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 (Fig. 1a and 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 2c). Asymmetrical skirts had steep slopes (>20°) 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 (Fig. 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