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The role of debris jets in the evolution of diatremes: field and experimental evidence

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The volcaniclastic fill of kimberlitic diatremes is often described as “homogenized” or “mixed” because although the components come from different sources, the deposits display “a crude degree of textural and lithological consistency” (Clement and Reid, 1989). Nevertheless, Mitchell (1986) reports that diatremes can be separated into several varieties of kimberlite which “may differ with respect to the size, shape and type of xenoliths or cognate clasts and ultramafic inclusion content. Sharp contacts are found between the different varieties”. Similar features are found in the lower parts of some non-kimberlitic diatremes: the whole pipe contains both juvenile fragments and accessory lithics and xenocrysts derived from different stratigraphic levels – suggesting mixing – yet within the pipe, different columnar bodies of volcaniclastic material occur.

These columnar bodies have a different grain size, componentry, colour, etc. than the enclosing host – but sometimes the difference between the columnar body and the host can be subtle and the contacts gradational, potentially making the recognition of such bodies difficult in drill core. Good examples of columnar bodies of volcaniclastic material within diatreme fills are known from Arizona (White, 1991; Fig. 1) and Antarctica (McClintock and White, 2006; Ross and White, 2006; Fig. 2). These bodies have been called “feeder conduits” by Lorenz and Kurszlaukis (2007) and Kurszlaukis and Lorenz (2008). An example of a vertical columnar body in a Russian kimberlite is given by Kurszlaukis et al. (2006).

Both the “homogenized” aspect of many diatremes, and the generation of the columnar bodies, have been attributed to whole-pipe fluidization by some workers (e.g., Woolsey et al., 1975; Walters et al., 2006) but this process is unlikely to occur in large pipes because it would take a very large amount of gas being emitted at a sufficient rate to fluidize the whole pipe, and the feeder dikes – from which the fluidizing gases would presumably be emitted – tend to be small compared to the pipe diameters (e.g., Lorenz and Kurszlaukis, 2007).

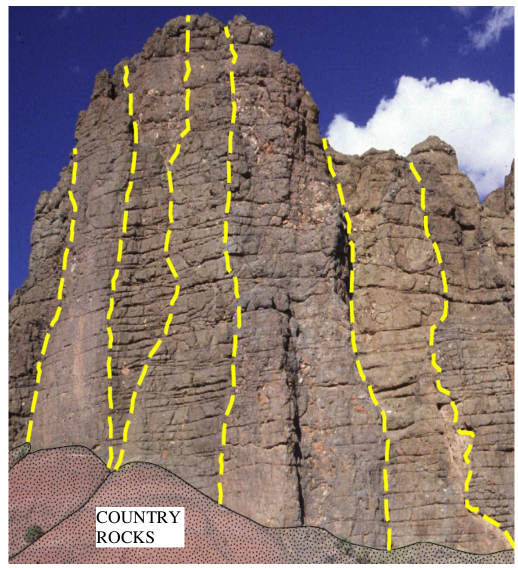

Figure 1. Erosional remnant of a diatreme structure at Standing Rock in the Hopi Buttes Volcanic Field on the Colorado Plateau, USA (White, 1991) (near-vertical rock cliff several tens of meters high). The bold dashed subvertical lines represent contacts between bodies of volcaniclastic material within the diatreme. Vertical drill holes within such a diatreme would not allow easy recognition of the columnar bodies, which in a kimberlite pipe may contain different diamond grades.

Instead of attributing the non-bedded “homogenized” aspect and the columnar bodies to post-explosive processes, or late-eruptive processes, other authors propose that the eruptions themselves are responsible. Specifically, to explain the “homogenized” aspect of many diatremes, White (1991) suggested that “mixing was accomplished by repeated upward ejection of debris by [...] explosions, followed by repeated falling-back into the vent.” He also added that “this violent, episodic, circulatory system also accounts for [...] the sub-vertical lithologic boundaries”.

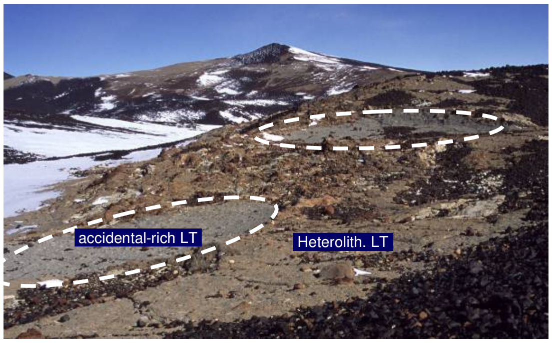

Figure 2. Low angle outcrop exposing steep bodies of accidental-rich lapilli-tuff with elliptical cross-sections and diameters of a few meters (dashed outlines). These occur within a vent complex (a "nest of diatremes") over 5 km wide at Coombs Hills, Ferrar Large Igneous Province, Antarctica (Ross, 2005; McClintock and White, 2006). We propose that such columnar bodies result from the passage of debris jets within existing vent fills. Here the dominant vent fill consists of heterolithic lapilli-tuff which overall has a "well mixed" character but in detail is characterized by lateral variation in componentry, at meters to tens of meters scale, with only subtle and discontinuous contacts. Because phreatomagmatic interactions at Coombs Hills did not generate large proportions of new juvenile clasts (Ross and White, 2006), it is possible that the componentry variations within the heterolithic lapilli-tuff reflect the presence of numerous columnar bodies having very slight grain size and componentry differences. Post-depositional shaking or movement of the tephra would have had the effect of further diffusing and blurring the boundaries between these columnar bodies. In contrast, the bodies that can be easily discerned and mapped are those that possess a good componentry contrast to the enclosing rock and were emplaced last in the evolution of the vents. In the case of accidental-rich lapilli-tuff bodies, debris jets may have been generated by explosions near the walls of the vents, where they incorporated large proportions of country rock material, liberated by shock waves from phreatomagmatic explosions (e.g., Zimanowski et al., 1997; Büttner et al., 2002).

To explain the columnar bodies, McClintock and White (2006) and Ross and White (2006) called upon upward traveling mixtures of juvenile particles, country rock fragments, magmatic gases, and in some cases externally derived fluids; they called these mixtures "debris jets". The debris jets propagate within the existing diatreme fill and may or may not reach the surface; they are generated by explosions in deeper portions of the pipe or in the root zone (see also Lorenz and Kurszlaukis, 2007). Because debris jets are largely subterranean (unobservable) features, the manner in which they propagate and deposit their load remains poorly constrained.

New experimental studies (Ross et al., 2008, *in press*) suggest that ejection of debris outside the vent is not necessary to explain the columnar bodies of volcaniclastic material: these can be generated by entirely subterranean debris jets. Analogue materials (glass beads or sand) and a finite amount of compressed air were used in the laboratory to physically model such debris jets. Injections of gas and colored particles into a granular host were brief (<1 s), discrete events. The injections assumed a bubble shape while expanding and propagating upwards (Fig. 3).

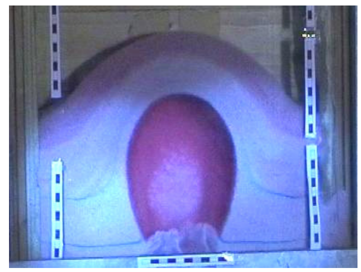

Figure 3. View of an analogue experiment through the glass window of a rectangular container. Scale bars are graduated in centimeters. The host particles consist of white glass beads which were laid down in a 14 cm-thick layer containing blue markers. Red beads of the same grainsize than that of the host (200-300 µm), originally placed in a crucible below the rectangular container, were pushed upward using a 1.0 MPa gas pressure, released all at once from a reservoir blocked by a magnetic valve. In this frame, the red beads are dispersed in the injected gas, the injection assuming a bubble shape at this stage. Doming of the host is very pronounced and later, the injection breached the original "ground" surface. Doming is less pronounced for deeper injections (thicker hosts).

When the initial air pressure was comparatively low, the gas eventually decoupled from the entrained beads, below the host surface, and left behind more or less cylindrical bodies of colored beads (Fig. 4). When the gas pressure was enough to produce an "eruption" of the two-phase flow, injected beads produced both a flaring upward or conical body below the ground surface and "fallback" layers on top. Such injections – whether erupting or wholly subterranean – provide a compelling explanation for the origin and characteristics of multiple cross-cutting bodies that have been documented for diatreme and other vent deposits.

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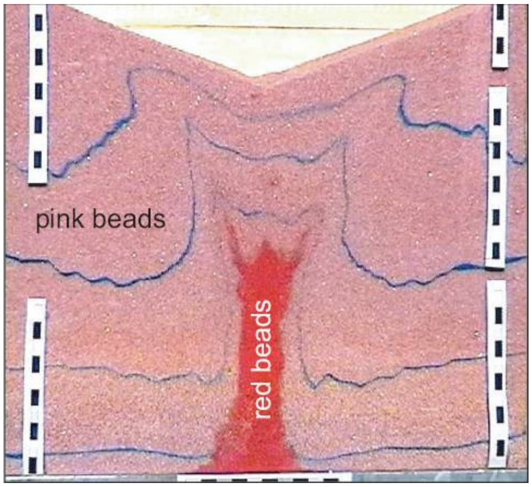

Figure 4. Final result of an experiment in which 28 cm of pink glass beads (white beads contaminated by prior use) where utilized as a host and red beads where emplaced using 1.5 MPa of air pressure in the reservoir. Note the column of red beads, partly similar to the columns of volcaniclastic material found in diatremes (the “devil horns” are due to post-eruptive subsidence into the underlying crucible). The blue markers which were initially horizontal are not overturned because the emplacement of the red beads did not involve breaching of the pre-eruptive surface in this case.

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