12TH INTERNATIONAL KIMBERLITE CONFERENCE
30 YEARS OF DIAMONDS IN CANADA
8–12 July 2024 • Yellowknife

12th International Kimberlite Conference Extended Abstract No. 12IKC-011, 2024

# The last 10-15 years of research on non-kimberlitic diatremes, with implications for kimberlite emplacement

**Pierre-Simon Ross[1], Greg A. Valentine[2], James D.L. White[3]**
[1] *Institut national de la recherche scientifique, Canada, pierre-simon.ross@inrs.ca*
[2] *SUNY Buffalo, USA, gav4@buffalo.edu*
[3] *University of Otago, New Zealand, james.white@otago.ac.nz*

## Introduction

Maar-diatreme (M-D) volcanoes are relatively small volcanoes (<1 $km^3$) that typically have only one eruptive episode. Other examples of small volcanoes include lava domes, scoria scones, tuff rings, and tuff cones. The last two types, and M-D volcanoes, are predominantly generated by explosive magma-water interaction (phreatomagmatism; White and Ross 2011). M-D volcanoes have two defining characteristics that set them apart from other small volcanoes: (1) the crater is excavated up to several hundred metres below the previous ground surface; (2) the crater is underlain by a significant diatreme, the underground part of the volcano, filled mostly by pyroclastic rocks. The composition of the magma responsible for M-D volcanoes ranges from ultramafic to felsic (Ross et al. 2007). Likely kimberlitic examples include Renard 2 in Quebec (Fitzgerald et al. 2009), Yubileinaya in Russia (Kurszlaukis et al. 2009) and Victor in Ontario. Other phreatomagmatic volcanoes occur in the Fort à la Corne field of Saskatchewan (e.g., Kjarsgaard et al. 2009). Unfortunately, in the kimberlitic M-Ds, exposures can be limited to drill cores; even in operating mines, there can be issues with dust cover or sampling. The tops of kimberlitic volcanoes are often eroded, and many diamond mines exploit large diatremes, yielding a biased record of kimberlitic volcanism (Brown and Valentine 2013). Furthermore, post-emplacement modification to the primary textures and mineralogy is a common problem for kimberlites, which makes physical volcanology studies challenging.

In this context, non-kimberlitic M-Ds provide relevant insights due to locally excellent 3D exposures, at a range of paleo-depths, and generally better preservation of primary textures. Our premise is that kimberlitic and non-kimberlitic diatremes are *not* fundamentally different in terms of physical volcanology (McClintock et al. 2009; White and Ross 2011; Kurszlaukis and Lorenz 2017, 2018). This may seem difficult to accept but Ross et al. (2007) show that while olivine melilitite and rhyolite are completely different magmas chemically and rheologically, the M-D volcanoes formed from those magmas are surprisingly similar in terms of diatreme shape, lithofacies organization, and types of pyroclastic rocks. A possible explanation is that ultramafic to felsic magmas can all be affected by phreatomagmatism, and the dominant fragmentation mechanism has a large influence on what type of small volcano forms. Since the last major M-D review in 2011, there have been interesting research developments, especially for the diatreme portion of the system, that we believe will be of interest to the kimberlite community. Aside from the traditional field-based studies of diatremes and maar ejecta rings which have continued, a number of relevant experiments and modeling exercises have been reported, and those are also summarized here. The recent progress in understanding the detailed emplacement processes and evolution of non-kimberlitic diatremes has potential implications for diamond exploration and mining.

## Higher diamond grades in the diatreme?

Studies of M-Ds in volcanic fields with variable erosion levels exposed (e.g., Hopi Buttes volcanic field, Arizona) have shown that the maar ejecta ring is typically richer in lithic clasts than the diatreme, which is richer in juvenile clasts (Lefebvre et al. 2013). Lithics are fragments of the country rock, whereas juvenile clasts are fragments derived from the magma. The cone-shaped volume of intact country rock that will eventually become the diatreme starts out as 100% lithic material. Although phreatomagmatic explosions can happen at a range of depths (Valentine and White 2012), explosions within the upper 200 m are the most likely to eject material out of the ground (Valentine et al. 2014). The first relatively shallow explosions will therefore eject lithic-rich material (perhaps something like 80-90% lithics from the country rock and 20-10% juvenile clasts from the fragmenting dike) upwards and outwards. Some material will fall on the ejecta ring beyond the crater, and some will fall back into the crater, as documented during cratering experiments using chemical explosives (e.g., Ross et al. 2013). The proportion of juvenile material grows in the diatreme over time, as the original volume of country rock in the diatreme is progressively replaced by juvenile-bearing pyroclastic rocks (Bélanger and Ross 2018). Each explosion involves a certain amount of new magma and creates new juvenile fragments which get added to the diatreme volume. Equilibrium is maintained by ejecting existing (and some new) fragments onto the ejecta ring.

> *Implication: since diamonds are carried by the kimberlitic magma, in kimberlitic M-Ds, the diatreme as a whole, being more juvenile-rich, should have higher diamond grades than the lithic-rich ejecta ring. [On the other hand, because material within a mature diatreme might have been involved in more explosions, the early beds in the ejecta ring might contain larger (less fragmented) diamonds.]*

## Debris jets: variable diamond grades in the lower diatreme

Not all explosions have to move material out of the diatreme, however. Explosions in the diatreme create debris jets, defined as "upward-moving streams of volcaniclastic debris, steam, magmatic gases +/liquid water droplets" (Ross and White 2006). This phenomenon has been studied in the laboratory using dm-scale analogue experiments involving glass beads and compressed air injected into other glass beads or sand (Ross et al. 2008) and more recently with numerical modelling (Sweeney and Valentine 2015). One goal was understanding which debris jets stay confined in the diatreme and which do not. In nature and the analogue experiments, debris jets leave behind columnar bodies of material with potentially different properties (e.g., grain size, componentry) to the adjacent material, often with steep contacts (Lefebvre et al. 2013; Latutrie and Ross 2019). Although some contacts between columnar bodies are sharp and obvious, others are quite cryptic. Note that in large mature diatremes, each debris jet and the resulting pyroclastic deposits only occupy a small portion of the diatreme. The lower portion of many diatremes is unbedded and occupied largely by these columns.

> *Implication: in kimberlitic M-Ds, those vertical columns might have different diamond populations (McClintock et al. 2009 and references therein). It is therefore quite important to map those different lithofacies in the lower diatreme. Vertical drill holes are unlikely to capture lithofacies boundaries, making angled holes potentially more efficient.*

## Upper versus lower diatreme, and the transition zone

The upper portion of diatremes tends to be bedded, especially for large diatremes in which there is space in the crater for bedding to develop through pyroclastic density currents such as surges, and fallback. These bedded deposits form before at least some of the non-bedded columns, which are often seen to truncate them (Bélanger and Ross 2018; Latutrie and Ross 2019). Furthermore, bedding is progressively destroyed in the lower diatreme through a combination of subsidence, new debris jets, and perhaps local liquefaction. Due to the general juvenile-enrichment process over time described above, earlier-formed bedded deposits might therefore be more lithic-rich on average than partly later-formed non-bedded deposits, as demonstrated in a specific diatreme from the Navajo volcanic field of New Mexico (Bélanger and Ross 2018). On most schematic M-D models, the transition between the typically bedded upper diatreme, and the typically unbedded lower diatreme, is shown as a simple line. Detailed field studies have now demonstrated that this transition is actually a distinct zone up to several hundreds of metres thick (Bélanger and Ross 2018; Latutrie and Ross 2019). This transition zone should be included in future generalized models.

> *Implications: in kimberlites, the non-bedded lower diatreme might be richer in juvenile fragments and therefore diamonds, on average, than the bedded upper diatreme. When exploring kimberlitic M-Ds, the transition zone is more complex, in terms of lithofacies arrangement, than the upper or lower diatreme, as it combines bedded and non-bedded pyroclastic rocks. It should be located and given particular attention.*

## References

Bélanger C, Ross P-S (2018) Origin of nonbedded pyroclastic rocks in the Cathedral Cliff diatreme, Navajo volcanic field, New Mexico. Bull. Volc. 80:article 61

Brown RJ, Valentine GA (2013) Physical characteristics of kimberlite and basaltic intraplate volcanism and implications of a biased kimberlite record. GSA Bulletin 125:1224-1238

Delpit S, Ross P-S, Hearn BC (2014) Deep-bedded ultramafic diatremes in Missouri River Breaks volcanic field, Montana, USA: 1 km of syn-eruptive subsidence. Bull. Volc. 76:article 832

Fitzgerald CE, Hetman CM, Lepine I, et al. (2009) The internal geology and emplacement history of the Renard 2 kimberlite, Superior Province, Quebec, Canada. Lithos 112(S):513-528

Graettinger AH, Valentine GA, Sonder I, et al. (2014) Maar-diatreme geometry and deposits: subsurface blast experiments with... Geochemistry, Geophysics, Geosystems 15 (DOI 10.1002/2013GC005198)

Kjarsgaard BA, Harvey S, McClintock M, et al. (2009) Geology of the Orion South kimberlite, Fort à la Corne, Canada. Lithos 112(S):600-617

Kurszlaukis S, Lorenz V (2008) Formation of "Tuffisitic Kimberlites" by phreatomagmatic processes. J. Volcanol. Geotherm. Res. 174:68-80

Kurszlaukis S, Lorenz V (2017) Differences and similarities between emplacement models of kimberlite and basaltic maar-diatreme volcanoes. Geological Society, London, Special Publications 446:101-122

Kurszlaukis S, Mahotkin I, Rotman AY, et al. (2009) Syn- and post-eruptive volcanic processes in the Yubileinaya kimberlite pipe, Yakutia, Russia, and implications for… Lithos 112(S):579-591

Latutrie B, Ross P-S (2019) Transition zone between the upper diatreme and lower diatreme: origin and significance at Round Butte, Hopi Buttes volcanic field, Navajo Nation, Arizona. Bull. Volc. 81:26

Lefebvre NS, White JDL, Kjarsgaard BA (2013) Unbedded diatreme deposits reveal maar-diatreme-forming eruptive processes: Standing Rocks West, Hopi Buttes… Bull. Volc. 75:1-17

McClintock M, Ross P-S, White JDL (2009) The importance of the transport system in shaping the growth and form of kimberlite volcanoes. Lithos 112(S):465-472

Ross P-S, White JDL (2006) Debris jets in continental phreatomagmatic volcanoes: a field study of their subterranean deposits in the Coombs Hills vent complex…. J. Volcanol. Geotherm. Res. 149:62-84

Ross P-S, White JDL, Zimanowski B, et al. (2008) Rapid injection of particles and gas into non-fluidized granular material: volcanological implications. Bull. Volc. 70:1151-1168

Ross P-S, White JDL, Valentine GA, et al. (2013) Experimental birth of a maar-diatreme volcano. J. Volcanol. Geotherm. Res. 260:1-12

Ross P-S, Carrasco-Núñez G, Hayman P (2017) Felsic maar-diatreme volcanoes: a review. Bull. Volc. 79:article 20

Sweeney MR, Valentine GA (2015) Transport and mixing dynamics from explosions in debris-filled volcanic conduits: Numerical results and implications for... Earth Planet. Sci. Lett. 425:64-76

Valentine GA, White JDL (2012) Revised conceptual model for maar-diatremes: subsurface processes, energetics, and eruptive products. Geology 40:1111-1114

Valentine GA, Graettinger AH, Sonder I (2014) Explosion depths for phreatomagmatic eruptions. Geophys. Res. Lett. 41:2014GL060096

Valentine GA, Graettinger AH, Macorps E, et al. (2015) Experiments with vertically- and laterally-migrating subsurface explosions with applications to the geology of... Bull. Volc. 77:Art 15

White JDL, Ross P-S (2011) Maar-diatreme volcanoes: a review. J. Volcanol. Geotherm. Res. 201:1-29