The importance of the transport system in shaping the growth and form of kimberlite volcanoes

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Transport of kimberlite magma from the mantle to the surface is a complex process that involves many, often sudden and dramatic, changes in transport style. The pace and magnitude of changes in the transport system acclerate as the magma nears the surface, culminating in eruptions during which multiple transport events take place simultaneously as well as single transport events that change significantly from their point of origin to final deposition. Understanding the range of transport styles recorded by kimberlite deposits is key to describing the type and style of eruptions, the growth of cones and craters, and the distribution, geometry and structure of the deposits that make up kimberlite volcanoes. In an economic context, building a clear picture of the processes that shape deposits is essential for selecting exploration targets and evaluating the grade and value of diamond-bearing kimberlites. Variations in diamond grade reflect differences in the diamond content of different magma parcels erupted during the lifetime of the kimberlite volcano, sorting during transport of eruption products, or re-working of diamonds during crater growth, cone collapse and erosion.

Deep transport systems control delivery of magma and diamonds to eruption sites

The initial stages of kimberlite transport involve rise of magma in narrow, interconnected networks of fluid-filled fractures. There is compelling evidence that kimberlite magmas are extracted from their source region and erupted without significant residence times in the crust. Many single kimberlite volcanoes have significant variations in diamond grade between different kimberlite phases, suggesting eruption of distinct (perhaps unrelated) magma parcels at the same site.

In some kimberlites, different magma batches erupted at the same site during short-lived pulses of activity separated by long periods of volcanic quiescence. For example, single kimberlite complexes in the Fort á la Corne field in Canada have been constructed by up to 7 brief episodes of activity over more than 6 million years (Kjarsgaard et al. 2008). Persistent re-occupation of the deep magma transport system by kimberlite melts suggests that stable, deeply tapping magma pathways are the key feature of the deep kimberlite transport system. Pre-heating of magma pathways by early magma batches may also focus transport. Because small volumes of kimberlite magma are thermally challenged during their ascent from the mantle, they may only successfully reach the surface if they follow a pre-heated pathway created by ascent of an earlier magma batch (e.g., Nemeth et al. 2003; Strong and Wolff 2003). Dike networks that have been successfully exploited by kimberlite magma thus become favoured sites for future magma transport.

Depending on the structural regime at higher crustal levels, rising magmas can exploit pre-existing faults and fractures or can forge a new fracture network. Magma is often preferentially channelled into zones of structural permeability such as fault intersections. Where few older pathways exist and magma lacks sufficient buoyancy to punch through overlying rock, magma ponds in the shallow crust to form sills linked by dikes and sheets.

Shallow transport systems shape volcanoes

The form of the kimberlite volcano is determined when the magma arrives at or just below the surface. If magma comes into contact with external ground or surface water, transport will be driven by a combination of magmatic gases + steam (phreatomagmatic eruptions). On the other hand, if external water is very limited or if the conduit is rapidly sealed by chilled melt, the transport system is driven by magmatic gases alone (magmatic eruptions).

The characteristic of phreatomagmatic eruptions is short-lived, powerful explosions that fragment magma and wall-rocks and rapidly accelerate a mixture of debris+water+steam out of the vent. Phreatomagmatism involving groundwater forms craters whereas interaction with surface water forms cones. Pauses between explosions allow debris to collapse into the throat of the vent; subsequent explosions re-eject older debris and newly formed fragments. In shallow vents the erupted mixture rapidly expands to form dense to dilute pyroclastic density currents and convecting plumes. If eruptions are relatively weak, fall deposition is more dominant than flow deposition, building steep cones of debris around vents. Oversteepening leads to frequent cone collapse, redistributing ejecta and reshaping the inner and outer cone flanks. Transport of debris and diamonds away from vents is limited, and deposits are mostly poorly sorted. More powerful eruptions are dominated by density currents (flows and surges) and pyroclastic fall that spread debris over a wider area, forming low-profile rings around vents that transition outward into sheet-like deposits. Debris and diamonds can be carried hundreds of metres or kilometres from vent sites. Flowing currents rapidly sort debris by grainsize and density to form moderately to well sorted deposits.

As phreatomagmatic vents deepen and cut craters into underlying wall-rock (diatremes), subaerial transport is dominated by upward-directed jets of debris along with downward-directed collapse as material is excavated from depth (McClintock and White 2006). Because eruption bursts are episodic and mostly happen toward the base of the diatreme, transport of debris follows a cycle from upward-dominated transport to downward-dominated transport. Local transport styles such as wall-rock collapse sideways and downward into the vent, slumping and surface fallback play key roles in the transport system as and immediately after ejecta moves through it. As the volcano grows, the diatreme will become larger than any single vent site within it. When the vent and crater are of about the same size early in an eruptions, single shallow eruption bursts can eject all the debris from the diatreme and effectively empty it. On the other hand, when the crater is larger than the vent, single euption bursts might be able to punch through crater-filling deposits and disrupt them but the crater remains mostly full of debris from one eruption burst to the next. Unit contacts inside craters are mostly vertical; vertical contacts form as a result of debris jets passing through to the surface through older deposits filling the diatreme (Ross and White 2006). At this point, the diatreme becomes the key depocenter for fragmented magma and diamonds, progressively capturing more and more ejecta as it grows.

In contrast, magmatic eruptions are more continuous and transport systems more stable, dominated by pyroclastic fall and flow. Because the transport system is driven by magmatic degassing, variation in the balance between magma rise speed and bubble rise speed determines whether transport processes are continuous or episodic. Continuous eruption styles result in stable transport systems that build cones close to the vent and blanket more distal areas with moderately to well-sorted debris. Episodic magmatic eruptions are driven by the bursting of large bubbles and thus are weak, resulting in limited transport of mostly coarse debris that piles up adjacent to vents. Importantly, wall-rock typically makes up only a limited proportion (<10%) of magmatic deposits; because most fragmentation takes place by bubble-bursting in the upper part of the conduit as magma rises and decompresses, energy and transport is directed upward rather than outward into wall-rocks. From an economic standpoint, magmatic deposits will have lower dilution effects from wall-rock than phreatomagmatic deposits. An exception are deposits formed during intense but short-lived vent-forming (or widening) eruption phases.

High eruption rates accompanied by limited transport can lead to formation of spatter-fed (clastogenic) flows that form where hot ejecta piles up close to vents and fragments weld together. Although initial particle transport is very limited, still-hot welded deposits may be carried hundreds of metres from vents by secondary transport in spatter-fed flows. Lava flows also form as gas contents of magma begin to fall. Both spatter-fed flows and other lavas produce almost zero sorting of material in the magma such as megacrysts, and will therefore have diamond content and distribution that is close to that of the erupting kimberlite magma.

Secondary transport (reworking) of kimberlite takes place at the surface during and after eruptions. The degree of reworking will depend on the type of deposits exposed at the surface, the energy of the sedimentary environment and the length of time deposits are exposed to erosion. Craters trap a significant proportion of reworked debris and accompanying diamonds because they are often the most significant local depocentre. On the other hand, cones quickly degrade unless rapidly buried, and diamonds are redistributed to form local or far-field placer deposits. Diatremes are relatively immune to surface erosion and reworking unless regional tectonics causes much later large-scale uplift.

Transport shapes diamond distribution

Diamonds are rapidly transported to the surface by kimberlite (or lamproite) magmas that are channeled by deep, stable magma pathways. The transport system changes dramatically when magmas arrive at the surface, and the mode of diamond transport with it. Although the style of magma fragmentation in kimberlites is hotly debated, kimberlite deposits suggest a range of weak to strong explosive activity. During eruptions, the diamond transport system abruptly changes from one in which diamonds are suspended in magma to one in which diamonds are part of a mixture of fragmented magma and wall-rock, magmatic gases, water and steam. Depending on the style of eruption (magmatic or phreatomagmatic), eruption intensity and the processes involved in moving debris from fragmentation sites to depositional sites, diamonds may retain their original concentration relative to the kimberlite magma, or become enriched or depleted by size or density sorting.

Sorting is reduced in diatremes, welded spatter deposits and lava. Sorting is enhanced by expansion of the transport system above the surface in fall and flow deposits. Deposits that have experienced limited sorting such as well-mixed deposits in diatremes or weakly fragmented spatter likely have fairly homogeneous diamond grades, whereas better-sorted fall or density current deposits probably have highly variable diamond grades. Sorting during extra-vent transport is especially effective with water, compared to in air. Contrasts in sorting, and thus diamond grade, can be dramatic. One example is a situation where well-sorted fall deposits alternate with non-sorted spatter-fed flows. These contrasts may also occur in deposits of a single transport event, such as where a dense, weakly sorting tephra jet cascades down the flanks of an emergent cone into standing water and transforms into a strongly sorting subaqueous density current.

One significant unknown is the role of fragmentation and transport during eruptions on breaking large diamonds into smaller pieces. Some of the largest diamonds found are apparently fragments of even larger stones (the Cullinan diamond, for example). Many kimberlite eruptions are powerful enough to fragment hard wall-rocks; the same eruptions very likely fragment diamonds, either during initial fragmentation events or as debris is recycled at the base of the diatreme. In the light of the exponential increase in diamond value with size, a comprehensive dataset is urgently required to address this question. A preliminary prediction is that for any given original diamond size range, the deposits of weak eruptions will have suffered less reduction in diamond grainsize by breakage than the deposits of powerful eruptions.

Summary

Evaluating the full range of transport styles recorded in kimberlite deposists is crucial to accurate resource evaluation. Diamonds are sorted during transport; transport events have the capacity to significantly upgrade deposits or to modify the distribution of diamonds derived from a single magma batch. From an exploration perspective, diatremes make the most attractive targets because they survive erosion and form large geophysical anomalies. Surface deposits are vulnerable to reworking and are often removed completely, leaving only narrow dikes (the sub-volcanic transport system) and distal placer deposits as the only record in eroded terrains.

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