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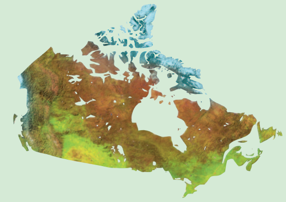

Abrasion of kimberlite pebbles in a tumbling mill: implications for diamond exploration

D.I. Cummings, B.A. Kjarsgaard, H.A.J. Russell, and D.R. Sharpe

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Abstract: Tumbling mill experiments were performed to quantify the rate at which pebble-sized kimberlite cubes abrade (lose mass) during transport relative to basalt, gabbro, tonalite, and sandstone clasts from the Canadian Shield. The kimberlite pebbles lost mass 3 to 3500 times faster than Canadian Shield pebbles. One massive volcaniclastic kimberlite cube disaggregated completely into sand- and mud-sized particles after only several hours of soaking before the experiments started. These results suggest that some kimberlite lithologies will break down rapidly to sand- and mud-sized particles upon entrainment, and that other kimberlite lithologies, while losing mass more slowly, may still abrade up to an order of magnitude faster than common shield lithologies as they are dispersed across the landscape.

Résumé : Des essais ont été effectués au moyen d'un tonneau de polissage afin de quantifier le taux d'abrasion (perte de masse) de cubes de kimberlite de la taille de cailloux pendant le transport, en comparaison avec des clastes de basalte, de gabbro, de tonalite et de grès du Bouclier canadien. La perte de masse des cailloux de kimberlite a été de 3 à 3500 fois plus rapide que celle des cailloux provenant du Bouclier canadien. Un cube de kimberlite volcanoclastique massive s'est complètement désagrégé en particules de sable et de boue après seulement quelques heures de trempage précédant le début des essais. Ces résultats suggèrent que les roches de certaines lithologies kimberlitiques se réduiront rapidement en particules de sable et de boue lors de leur entraînement, alors que des roches d'autres lithologies kimberlitiques, bien qu'elles perdent plus lentement de leur masse, peuvent quand même pendant leur dispersion s'abraser jusqu'à dix fois plus rapidement que les roches de lithologies communes dans le Bouclier canadien.

INTRODUCTION

In sediment-transport studies, the term *abrasion* is commonly used to refer to the mass loss experienced by clastic particles as they grind or impact against each other or against the bed during transport (Kuenen, 1956) or as they jostle in the sediment bed beneath the flow (Schumm and Stevens, 1973). Abrasion can cause downflow fining of particles in clastic dispersal trains, irrespective of whether the transporting fluid is air (Jerolmack and Brzinski, 2010), water (Brewer et al., 1992), or glacier ice (Dreimanis and Vagners, 1971). Previous research shows that abrasion varies strongly as a function of lithology (Dreimanis and Vagners, 1972; Lee and Rutter, 2004; Attal and Lavé, 2009). Softer clasts abrade faster and become smaller and commonly smoother, whereas resistant clasts abrade slowly and retain their size and shape (Kodama, 1994; Afanasev et al., 2008; but see Dredge et al., 1997, and Averill, 2001). Clast lithology, like clast size and shape, may therefore, in some cases, be a good proxy for transport distance: the softer the clast, the closer the source.

Kimberlite, the common host rock for diamonds, is typically perceived as a soft, easily abraded rock type. For example, kimberlite pipes on the Canadian Shield are commonly recessed (e.g. Kjarsgaard and Levinson, 2002), suggesting that glaciogenic processes eroded the pipes faster than the surrounding rock. A kimberlite clast, such as the boulder in Figure 1, may be typically softer than a shield clast, but by how much? How much faster do kimberlite clasts abrade (lose mass) during transport? Kimberlite pipes commonly contain different rock types in their upper and lower portions (Fig. 2) and the relative abrasion rates of these rock types is also unknown.

To estimate relative rate of abrasion for a number of lithologies, a simple experiment was conducted using a tumbling mill (Fig. 3). Tumbling mills have been used for over 100 years in experimental sedimentology (e.g. Daubrée, 1879). Clast abrasion within them is somewhat different than in nature: mud production from grinding is amplified, whereas sand and gravel production from crushing and splitting is muted (Lewin and Brewer, 2002). Results are therefore not specific to a particular fluid (air, water, ice) or depositional environment, and they cannot be converted to precise transport distances. Rather, the value of tumbling mill experiments lies in the *relative* measure of abrasion provided: they afford general insight into how rapidly clasts of different lithologies abrade relative to each other as they are transported across the Earth's surface.

With the exception of Afanasev et al. (2008), who used a vibrating tank to explore the abrasion of a single kimberlite pebble relative to several sand-sized kimberlite indicator minerals, the abrasion of kimberlite clasts has not been studied experimentally. In our experiments, pebble-sized cubes from different kimberlite rock types (volcaniclastic versus hypabyssal/coherent) and from different kimberlite pipes were subjected to abrasion in a tumbling mill, in addition to cubes from several common Canadian Shield bedrock lithologies. The objective of this paper is to document the experimental results, and to discuss their implications with respect to diamond exploration.

METHODS

Three separate but similar experimental runs were conducted. Each used a Lortone QT-6 tumbling mill equipped with a six-inch diameter rubber barrel (Fig. 3) and ten freshly cut, pebble-sized rock cubes (diameter ~2 cm) from six kimberlite and four Canadian Shield rock hand-samples (Fig. 4; Table 1). To prevent the appearance that the cubes gained mass at the start of the experiments, the rock cubes were pre-soaked to saturate pore spaces prior to the experiments, with the exception of the massive volcaniclastic kimberlite cubes (Samples 1 and 2), which were added dry because they disaggregated when soaked (Fig. 5). In experiment 1, ten cubes were introduced into the barrel along with 90 g of silicon carbide abrasive and enough water (340 g) to just cover the cubes. The experiment was run for a cumulative time of 476 hours (~20 days). The barrel was opened on average once every 24 hours to weigh and photograph the clasts. Nothing was introduced to, or extracted from the barrel. In experiment 2, the same materials

Figure 1. Kimberlite boulder from the Sharp Lake esker near New Liskeard, Ontario, Canada. Note that the boulder is rounded: abrasion (mass loss) has occurred during transport. Dispersal trains composed of clasts like this are used to find buried kimberlite pipes during diamond exploration campaigns (e.g. Kjarsgaard and Levinson, 2002). Photograph by M.B. McClenaghan. 2011-026

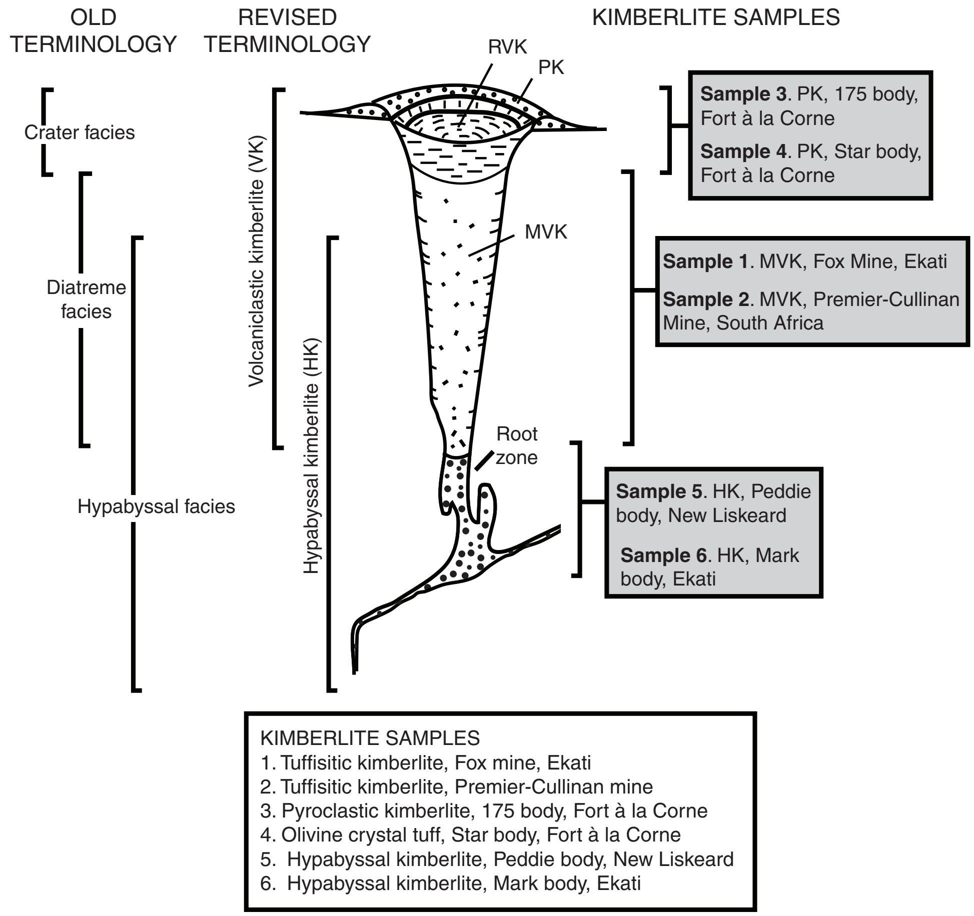


Figure 2. The 'classic South African model' of a kimberlite pipe with old nomenclature (far left side of figure) and a simpler, revised twofold nomenclature system (left side of figure) to describe rocks from kimberlite magmatic systems (Mitchell, 1995; Kjarsgaard, 2003; Sparks et al., 2006) that is used in this publication. VK = volcaniclastic kimberlite; PK = pyroclastic kimberlite; RVK = resedimented volcaniclastic kimberlite; MVK = massive volcaniclastic kimberlite; HK = hypabyssal (coherent) kimberlite. *Adapted from* Kjarsgaard (2003, 2007).

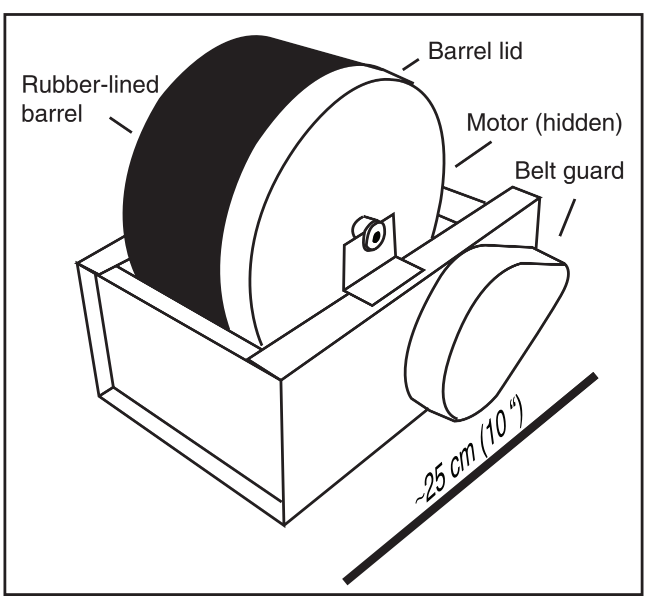


Figure 3. Sketch of the Lorton QT-6 tumbling mill used in the experiments. Inner diameter of barrel is approximately 6 inches.

and methods were used, except the mud fraction (<0.0064 mm) was sieved out each time the barrel was opened, on average once every 24 hours. Clear water was introduced each time to top up the barrel and preserve total mass. In total, experiment 2 ran for 467 hours (~19 days). Experiment 3 followed the same procedure as the second, with the mud fraction being removed, but no silicon carbide abrasive was used. Experiment 3 ran for a total of 520 hours (~22 days).

RESULTS

Several common trends were observed during the experiments, as follows.

1. The kimberlite cubes lost mass faster than the Canadian Shield cubes (Fig. 6, 7).
2. The massive volcaniclastic kimberlite (VK) samples lost mass the fastest — up to 3500 times faster than shield cubes (Fig. 6, 7). They disaggregated completely in minutes (Sample 1) to tens of hours (Sample 2). The two hypabyssal/coherent kimberlite (HK) samples (Samples 5 and 6) and the two pyroclastic kimberlite (PK) samples, namely the calcite-cemented juvenile lapilli tuff (Sample 3) and the olivine crystal tuff (Sample 4), lost mass slower than the massive VK samples, but still approximately three to seven times faster than the shield cubes (Fig. 6, 7). The PK and HK samples decreased in mass by 50% in two to ten days.
3. Abrasion occurred primarily by grinding and produced mud. Exceptions to this were the two massive VK cubes (Samples 1 and 2), which rapidly disaggregated into mud, sand, and gravel-sized particles, of which the latter subsequently disaggregated to mud and sand. Also, on one occasion a HK cube (Sample 6) split in two during experiment 3 (Fig. 6).

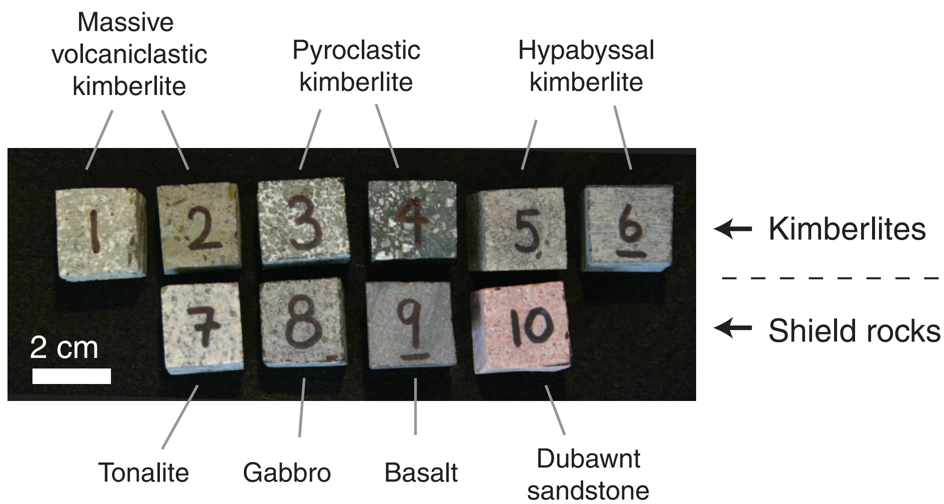


Figure 4. Rock cubes prior to abrasion. *See* Table 1 for sample details. Photograph by D.I. Cummings. 2011-025

Table 1. Sample details.

Sample	Details
1	Massive volcaniclastic kimberlite from diatreme zone of Fox Mine, Ekati, N.W.T., Canada.
2	Massive volcaniclastic kimberlite from diatreme zone of Premier-Cullinan mine, South Africa.
3	Pyroclastic kimberlite from tuff cone of 175 body, Fort à la Corne, Saskatchewan, Canada
4	Pyroclastic kimberlite (olivine crystal tuff) from tuff ring of Star body, Fort à la Corne, Saskatchewan, Canada.
5	Hypabyssal kimberlite from the root zone of Peddie body, New Liskeard, Ontario.
6	Hypabyssal kimberlite from root zone of Mark body, Ekati, N.W.T., Canada.
7	Archean-age tonalite from Slave Province
8	Mesoproterozoic gabbro from the East Arm of Great Slave Lake.
9	Paleoproterozoic massive flow-basalt from Et Then Formation, East Arm of Great Slave Lake.
10	Coarse, reddish-pink Dubawnt sandstone, Keewatin.

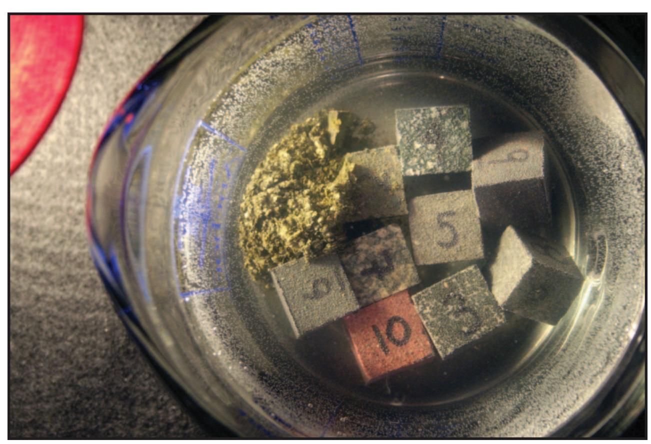
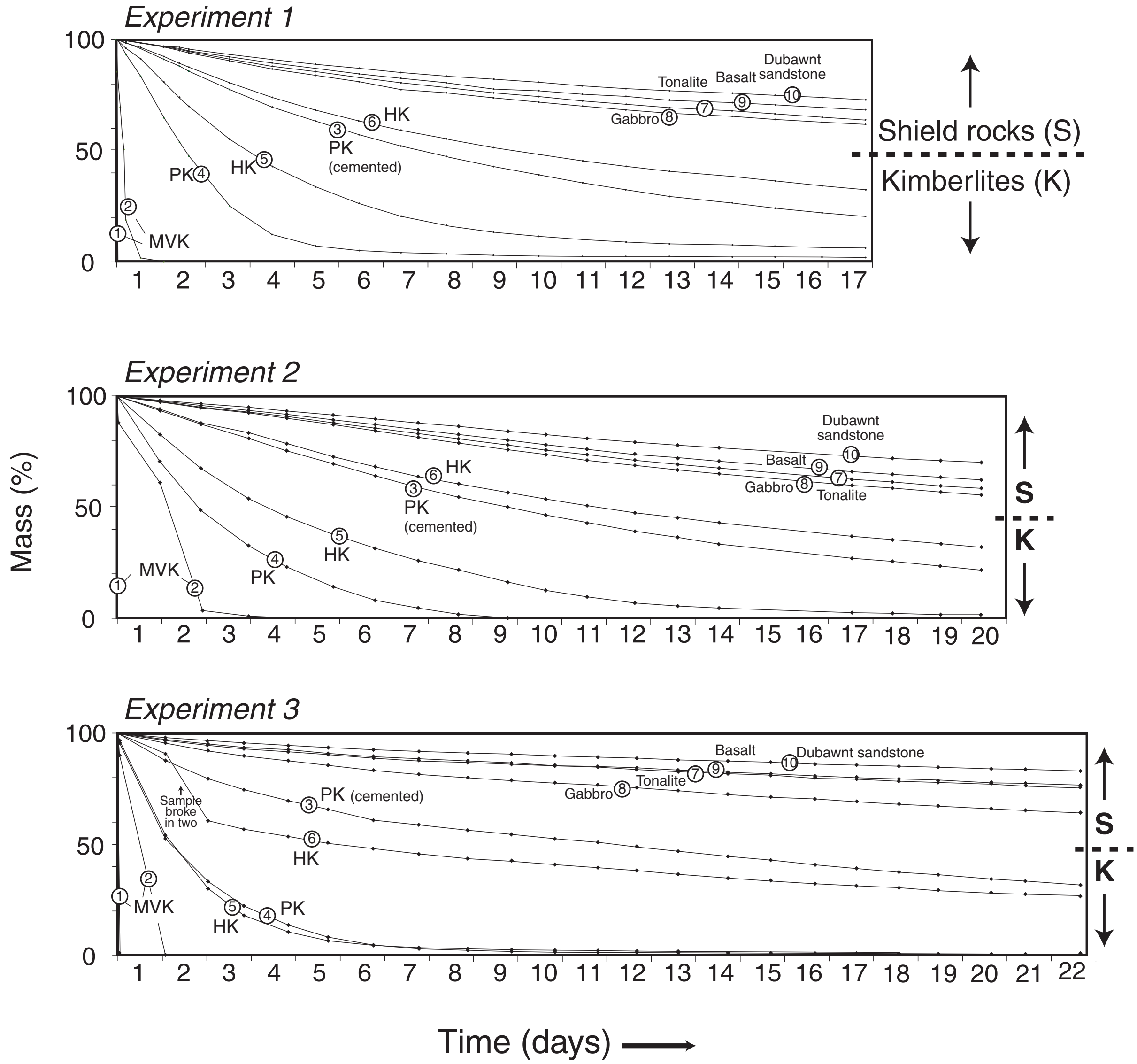


Figure 5. Freshly cut cubes after eight hours of soaking. Note that Sample 1, a massive volcaniclastic kimberlite from Ekati, has disaggregated completely. Sample 2, the other massive volcaniclastic kimberlite sample, has started to disaggregate (not visible). The other samples did not disaggregate during soaking. Photograph by D.I. Cummings. 2011-024



CLASTS

① Tuffisitic kimberlite from diatreme zone of Fox mine, Ekati, NWT.

② Tuffisitic kimberlite from diatreme zone of Premier-Cullinan mine, South Africa.

③ Pyroclastic kimberlite from crater zone of 175 body, Fort à la Corne, SK.

④ Olivine crystal tuff from crater zone of Star body, Fort à la Corne, SK.

⑤ Hypabyssal kimberlite from root zone of Peddie body, New Liskeard, ON.

⑥ Hypabyssal kimberlite from root zone of Mark body, Ekati, NWT.

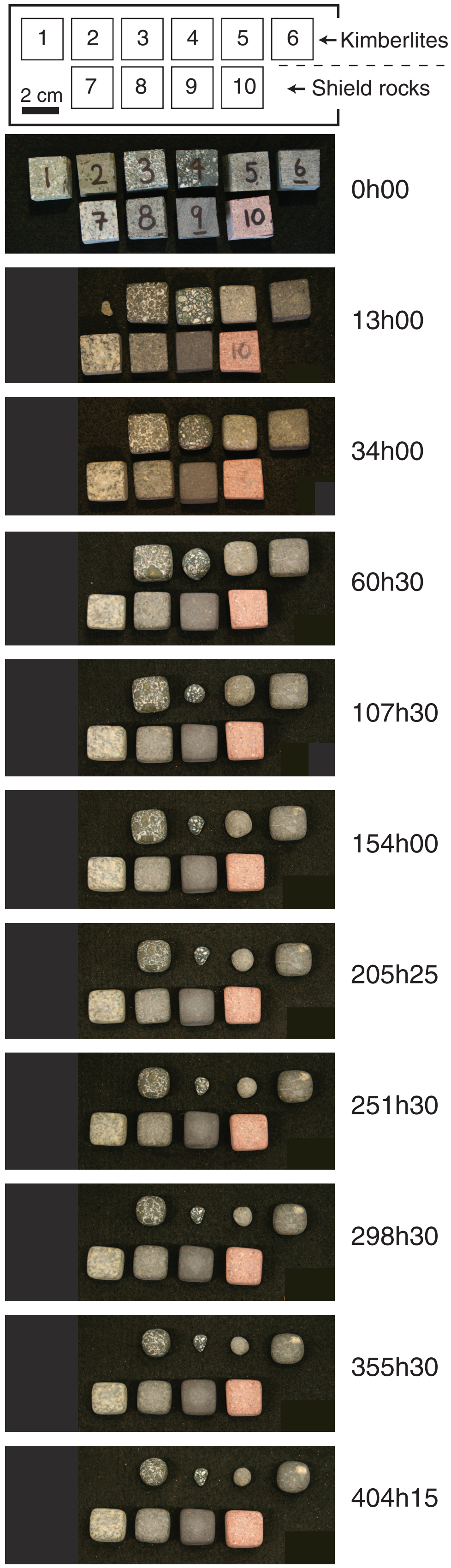
⑦ Tonalite. Slave Province, Archean.

⑧ Gabbro. East Arm, Mesoproterozoic.

⑨ Massive flow basalt. East Arm, Et Then Fm, Paleoproterozoic.

⑩ Reddish-pink coarse Dubawnt sandstone, Keewatin

Figure 6. Plots of mass loss versus time. Dots on curves represent times when cubes were extracted and weighed. The curves for Sample 1 are difficult to plot at this scale because the cubes disaggregated so quickly (between 30 minutes and 1 hour). MVK = massive volcaniclastic kimberlite; PK = pyroclastic kimberlite; HK = hypabyssal kimberlite.



4. Abrasion rates decreased with time for all lithologies (Fig. 6). It is unclear if this applies to the massive VK cubes because they lost mass so rapidly

5. Abrasion rates became low, commonly approaching zero, as clast diameters fell below about 0.75 cm, which is close to the transition from pebbles to granules (Fig. 6). This did not apply to massive VK samples, which disaggregated rapidly and completely into sand and mud.

In addition to these common trends, several differences were observed between the three experiments. In the experiments that used abrasive (experiments 1 and 2), the Canadian Shield clasts (Samples 7 to 10) and the two hardest kimberlite clasts, Sample 3 (PK) and 6 (HK), abraded faster than in Experiment 3, which did not use abrasive (*see* Figure 6). The moderately hard kimberlite clasts, Sample 4 (PK) and 5 (HK), exhibited the opposite trend; they abraded faster in Experiment 3 (Fig. 6). The muddy water in Experiment 1 had little effect on abrasion rates when compared against the clear-water results of Experiment 2 (Fig. 6).

DISCUSSION

Given the results, kimberlite clasts should lose mass and decrease in size faster than shield clasts as they are transported across the Earth's surface, provided that clast abrasion accompanies transport, which may exclude, for example, situations involving significant supra- or englacial transport (e.g. Stalker, 1956; Jackson, 1993) or suspension-dominated transport of finer clastic particles in dilute eolian, fluvial, or glaciofluvial flows (e.g. Kuenen, 1959; Tsoar and Pye, 1987). When abrasion does occur, downflow fining rates should vary as a function of the kimberlite rock type (VK, HK) being eroded and transported. The experiments show that massive VK in particular can break down almost immediately into sand-sized particles (including indicator minerals) and mud-sized particles, a phenomenon that may contribute to the high signal-to-noise ratio observed at the heads of some kimberlite dispersal trains (e.g. Averill, 2001). In the experiments, the kimberlite clasts that proved most resistant to abrasion were derived from lower portions of kimberlite pipes, cemented samples notwithstanding. It seems possible, therefore, that kimberlite pipes will commonly yield clasts that are more resistant to abrasion as they are progressively exposed and eroded (Fig. 8).

Figure 7. Photographic record of clast abrasion, Experiment 1. Experiments 2 and 3 display similar trends. Numbers marked on clasts at time = 0h00 are sample numbers. *See* Table 1 and Figure 4 for sample details. Photograph by T. Kalkowski. 2011-023

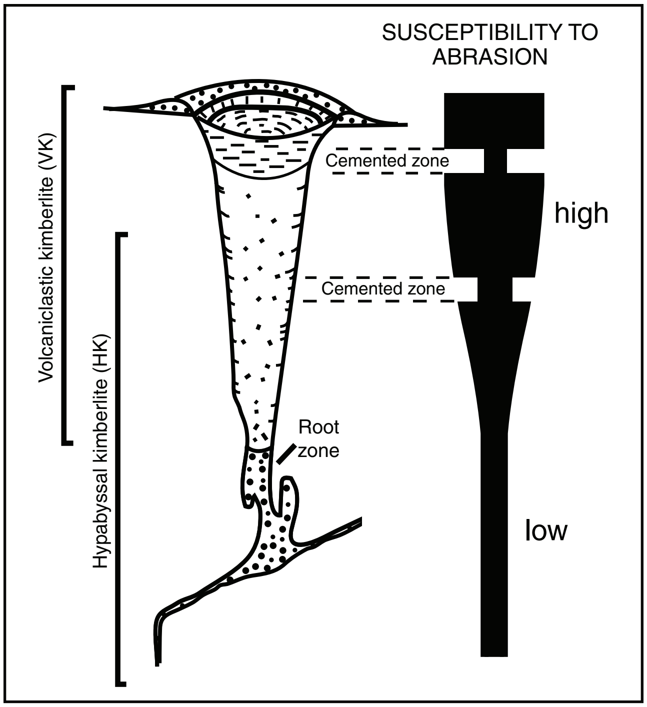


Figure 8. Conceptual model of kimberlite abrasion. Cartoon *modified from* Kjarsgaard (2007).

Another observation that has exploration significance is that the clasts lost mass and became rounded rapidly at the start of the experiments, and that abrasion rates decreased exponentially as the experiments progressed. Exponentially decreasing abrasion rates are typical of clast-abrasion experiments (e.g. Lewin and Brewer, 2002). They are generally attributed to two inter-linked phenomena, the rapid removal of sharp edges and corners, and the reduced ability for rounded clasts to abrade each other (Lewin and Brewer, 2002). Because of this exponential trend, particularly large, angular kimberlite gravel clasts may be that much more likely to be located closer to the source than smaller, rounded kimberlite clasts, provided all other things (e.g. transport process) remain equal.

One puzzling result was the increased abrasion rate for moderately hard kimberlite clasts that was observed in the experiment that did not use silicon carbide abrasive (Experiment 3). This result is especially puzzling since abrasion rates for the shield clasts and the harder kimberlite samples decreased in the same experiment, as might be expected. We have no good explanation for this observation. It is possible that Samples 4 and 5 in Experiment 3 were anomalously soft and that supplemental experiments would reveal a different trend. Irrespective, this observation is interpreted to be of minor consequence: the same general trends — kimberlite samples abraded faster than shield samples, and VK samples abraded faster than HK samples — are observed in all three experiments.

CONCLUSIONS

We draw the following conclusions from the experimental results.

1. The kimberlite pebbles abraded 3 to 3500 times faster than the shield clasts. As such, in situations where abrasion accompanies transport, kimberlites might be expected to commonly yield dispersal trains that fine downflow faster, and potentially much faster, than dispersal trains composed of typical shield clasts.
2. Abrasion rates for the kimberlite pebbles in all experiments decreased exponentially with time. Kimberlite dispersal trains may therefore have a tendency to fine exponentially downflow when abrasion accompanies transport.
3. Abrasion rates varied strongly as a function of kimberlite lithology. Softer lithologies, such as the VK samples in this study, may therefore yield dispersal trains that fine downflow orders of magnitude faster than dispersal trains sourced from more resistant lithologies, such as the HK or cemented VK samples in this study.
4. Because VK is typically prevalent near the top of kimberlite pipes and HK near the base, kimberlite pipes may yield progressively more resistant clasts as they are eroded over time. Carbonate cementation of void space in fragmental kimberlite may reverse this trend by rendering what might have been an otherwise-soft rock type in the upper part of a kimberlite pipe into a more resistant lithology.

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