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COMMINUTION OF INDICATOR MINERALS IN A TUMBLING MILL: IMPLICATIONS FOR MINERAL EXPLORATION

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2014

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doi:10.4095/293467

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Recommended citation

Cummings, D.I., Kjarsgaard, B.A., Russell, H.A.J., and Sharpe, D.R., 2014. Comminution of kimberlite indicator minerals in a tumbling mill: Implications for mineral exploration; Geological Survey of Canada, Open File 7111. doi:10.4095/293467

Publications in this series have not been edited; they are released as submitted by the authors.

ABSTRACT

Heavy mineral dispersal trains are commonly used during mineral exploration to locate ore bodies buried at depth. Heavy minerals tend to physically break down (comminute) as they are transported away from their bedrock sources, causing them to become smaller, less frequent and commonly rounder. The size, roundness and concentration (number) of heavy mineral grains are therefore commonly used as indications of proximity to source. However, few studies have investigated the rate at which different heavy minerals break down during transport. To provide quantitative insight into this, we studied the comminution of several heavy minerals used in diamond exploration, termed *kimberlite indicator minerals* (KIMs), in a tumbling mill. In the experiment, pyrope garnet grains lost mass the fastest, followed by chrome diopside grains, which generally lost mass much slower, and, finally, ilmenite grains, which hardly lost any mass at all. The pyrope grains lost mass the fastest because each grain broke into tens to hundreds of angular fragments, producing abundant sand-sized particles, in addition to abundant mud (i.e. silt and clay). By contrast, the chrome diopside and ilmenite grains remained relatively intact and lost mass primarily by edge rounding, which produced a comparatively small amount of mud and little to no sand. These results suggest that in situations where grain comminution occurs during transport, the sand and gravel (>0.063 mm) and mud (<0.063 mm) fractions of kimberlite dispersal trains have the potential to continuously change in composition downflow—specifically the mud and finer sand fractions may become progressively enriched in pyrope garnet fragments relative to fragments of other indicator minerals moving away from the source.

1. INTRODUCTION

An *indicator mineral* is a sediment grain, typically "heavy" (i.e., heavier than quartz), sand-sized and monomineralic, whose provenance can be linked to a distinct bedrock source. In most cases, indicator minerals, in addition to gravel- and/or mud-sized particles derived from the same bedrock source, are displaced downflow one or more times by the action of wind, water, glacier ice and/or slope processes, generating distinctive trails of sediment known as *dispersal trains*. Indicator minerals break down (comminute) during transport as they contact each other or the bed. This, along with dilution and/or selective sorting, tends to cause a decrease in indicator mineral frequency and size, and commonly an increase in indicator mineral roundness, downflow in dispersal trains (e.g., Sternberg, 1875; Mosig, 1980). Mineral exploration companies exploit this to find ore bodies: the larger, more numerous, and more angular the indicator minerals, the closer the ore body source.

Since the pioneering work of Daubrée (1879), many studies have investigated clast comminution in controlled laboratory settings to gain insight into the relationship between transport distance, grain size and grain roundness. Most of these studies have focused on gravel-sized rock fragments, and most have used tumbling mills (Table 1). Only several have focused on sand-sized grains or on indicator minerals commonly used in mineral exploration. Using a tumbling mill, Alling (1944) found that medium sand sized grains of quartz, microcline, tourmaline and garnet comminuted in that order. Kuenen (1959) used a circular flume to study the comminution of sand sized quartz and carbonate grains in flowing water. He found that their masses decreased by only several percent over transport distances of hundreds of kilometers. McCandless et al. (1990) performed a tumbling mill experiment to study surface features produced on kimberlite indicator minerals (KIMs), which are used to locate diamondiferous kimberlites. These authors did not report comminution rates. Afanas'ev et al. (2008) used an ultrasonic rock polisher to study KIM comminution rates. In their single experimental run, they found that apatite lost mass the fastest, followed by picroilmenite, olivine, pyrope garnet and finally diamond.

In this paper, we report the results of an experimental study conducted to gain further insight into KIM comminution rates and styles. We used a tumbling mill, the device most commonly used in comminution studies (Table 1). Three identical experiments were run, which allowed us to assess result repeatability. The KIM species we used are those most common to kimberlites in the Northwest Territories, home to the Lac de Gras kimberlite field and several active diamond mines.

2. MATERIALS AND METHODS

The tumbling experiment was conducted between January and March 2012. Five different KIM species were used: pyrope garnet with kelyphite rinds, ilmenite, chrome diopside (clinopyroxene), chromite, and olivine (Table 2). Initially, the garnets were pebble sized and round; the ilmenites were pebble sized and subround; the chrome diopsides were

pebble sized and subround to subangular; the chromites were medium sand sized and angular to subangular; and the olivines were granule sized and angular to subangular (Table 3). These KIM species are known to have distinctly different average physical and chemical properties (Table 3). Cleavage is well developed in chrome diopside, whereas it is lacking in ilmenite and pyrope garnet. Pyrope garnets with kelyphite rinds tend to be fractured internally and have multiple inclusions, the result of chemical and physical disequilibrium (e.g., rapid decompression) experienced during kimberlite emplacement (Garvie and Robinson, 1984). The kelyphite is generally microcrystalline, concentrically layered, and unfractured, and it tends to be separated from the underlying fractured garnet by a sharp contact (Garvie and Robinson, 1984).

Table 1. Devices and grain sizes used in previous clast comminution experiments (in part from Lewin and Brewer, 2002).

Study	Device used	Clast size investigated
Daubrée, 1879	Tumbling mill (iron)	Gravel
Wentworth, 1919	Tumbling mill (wood)	Gravel
Marshall, 1927	Tumbling mill (iron)	Gravel
Cozzens, 1931	Tumbling mill (wood)	Gravel
Wentworth, 1931	Tumbling mill (wood)	Gravel
Thiel, 1940	Tumbling mill (steel)	Coarse sand
Krumbein, 1941	Tumbling mill (wood)	Gravel
Alling, 1944	Glass	Medium sand
Kuenen, 1956	Circular flume	Gravel
Kuenen 1959	Circular flume	Sand
Abbott and Peterson 1978	Tumbling mill (rubber)	Gravel
Adams, 1978	Tumbling mill (tin)	Gravel
Haldorsen, 1981	Tumbling mill	Gravel
Bigelow, 1982	Tumbling mill (rubber)	Gravel
McCandless et al., 1990	Tumbling mill	Sand-sized heavy minerals*
Kodama, 1992	Tumbling mill (rubber with vanes)	Gravel
Jones and Humphrey, 1997	Tumbling mill (plastic with vanes)	Gravel
Lewin and Brewer, 2002	Tumbling mill (resin)	Gravel
Afanas'ev et al., 2008	Ultrasonic rock polisher	Sand-sized heavy minerals
Cummings et al., 2011	Tumbling mill (rubber)	Gravel

*Investigated surface features on heavy minerals, not comminution rates

A three-barrel Lortone tumbling mill was used in the experiment (Fig. 1A). This allowed three replicate experiments to be run simultaneously. The tumbling mill barrels were lined with rubber and had internal diameters of 14 cm.

At the start of the experiment, one grain of each KIM species was introduced into each barrel, for a total of five KIM grains per barrel, along with ~425 g of stainless steel shot (Fig. 1B) and enough tap water to cover the contents. The tumbling mill was then turned on and run overnight. The next day, the barrels were opened, the mud fraction (<0.063 mm) was sieved and discarded, and the sand and gravel sized KIM fragments (>0.063 mm) were

picked, grouped, weighed, and photographed (Appendices). The KIM fragments and the steel shot were then reintroduced back into their respective barrels, along with enough water to bring the weight of the barrels back to what it was initially, and the tumbling mill was restarted. This process was repeated 26 times, for an average experimental run time of 17.69 hours. The KIMs were also photographed using a binocular microscope at seven time periods (0, 77, 149.5, 225, 282.5, 389, and 460 hours). In total, the tumbling mill ran for 460 hours.

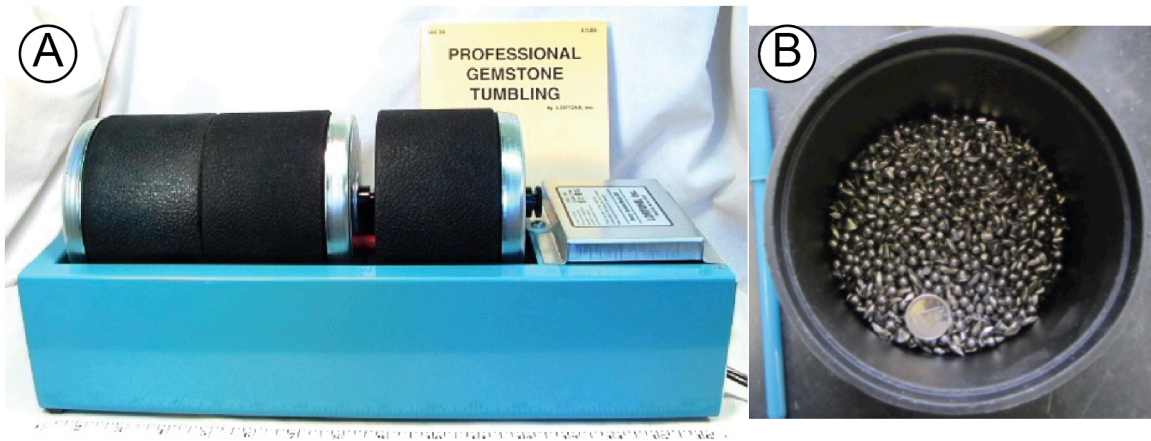


Figure 1. A) The Lortone three-barrel tumbling mill used in the experiment. The barrels have an inner diameter of 14 cm and are lined with rubber. B) Stainless steel shot used in the experiment. Coin for scale is 18 mm in diameter.

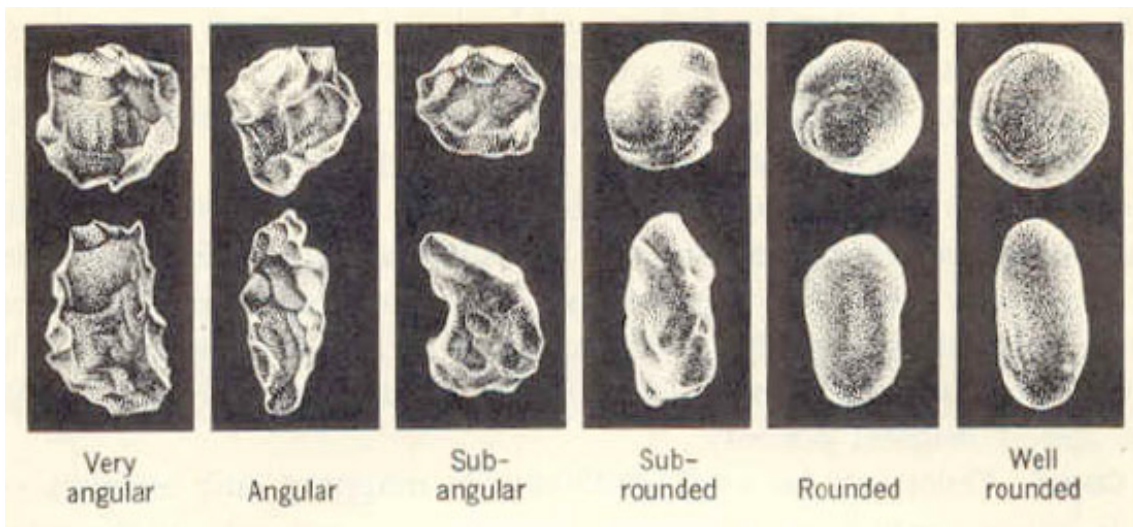


Figure 2. Illustrative scale of grain roundness (from Powers, 1953).

Table 2 Initial size, mass and roundness of kimberlite indicator mineral grains used in the experiment

Kimberlite indicator mineral	Barrel	Grain size (mm)	Mass (g)	Roundness	Source
Pyrope garnet with kelyphite rinds	A	9.3	0.9882	Round	Point Lake pipe, Lac de Gras, Northwest Territories
	B	10.7	1.257	Round	
	C	9.1	0.9047	Round	
Ilmenite	A	5.8	0.13	Subround	Roberts-Victor kimberlite, South Africa
	B	4.2	0.0877	Subround	
	C	4.4	0.1021	Subround	
Chrome diopside	A	10.2	0.555	Subangular	Point Lake pipe, Lac de Gras, Northwest Territories
	B	10.3	0.6233	Angular	
	C	11.1	0.7895	Subangular	
Chromite	A	0.5	Not measured	Subangular	Nord kimberlite, Somerset Island, Nunavut
	B	0.9	0.0011	Subangular	
	C	0.6	Not measured	Subrounded	
Olivine	A	2.9	0.0181	Angular	Nord kimberlite, Somerset Island, Nunavut
	B	2.5	0.0146	Subangular	
	C	2.3	0.0102	Angular	

Table 3. General mineralogical characteristics of the kimberlite indicator minerals used in the experiment.

Kimberlite indicator mineral	Density (g/cm³)	Mohs hardness	Cleavage	Fracture	Comments
Pyrope garnet	3.5 to 4.3	6.5 to 8.0	None. May exhibit <u>parting</u> .	<u>Conchoidal</u> to uneven	Extensively fractured when sourced from kimberlites
Ilmenite	4.7 to 4.8	5.5 to 6.0	None	None	
Chrome diopside	3.2 to 3.5	5.5 to 6.5	Well developed	Irregular to uneven, conchoidal	
Chromite	4.5 to 4.8	5.5	None. May exhibit parting	Uneven	
Olivine	3.27 to 3.37	6.5 to 7.0	Poorly developed	Conchoidal	Brittle

3. RESULTS

Data for two of the five KIMs investigated, chromite and olivine, proved unusable. The sand sized chromite grains were too small to weigh accurately, and the olivine grains became coated with particles from the rubber-lined barrels, causing them to become darker and, in some cases, heavier with time. By contrast, the ilmenite, chrome diopside and pyrope garnet grains were heavy enough to weigh accurately and did not become coated with rubber particles from the barrels.

Comminution rates were different for the different KIMs. The garnet grains lost mass the fastest, followed by chrome diopside, and then ilmenite (Fig. 3). Two distinct end-member comminution styles were observed: surface abrasion, which rounded KIM grains and produced mud, and grain breakage, which rendered KIM grains more angular and produced granules and sand (Fig. 4).

The ilmenite grains lost between 4 and 6% of their masses to the mud fraction over the course of the experiment. Mass loss was commonly small and difficult to detect during the daily measurements. Mass loss occurred primarily by surface abrasion, which rounded the edges of the grains and produced mud (Fig. 5). Grain breakage was rare: isolated sand grains were observed at 97.5 and 263 hours in Barrels C and A, respectively, and a sand grain was present in Barrel B from 225 hours onward until the end of the experiment.

The chrome diopside grains lost between 11 and 52% (average 25%) of their masses to the mud fraction over the course of the experiment. Grains in Barrel A and B lost 12 and

11% of their masses at similar rates (Fig. 3). They lost mass primarily by surface abrasion, which rounded the edges of the grains and produced mud, although the grain in Barrel B also shed a small number of sand grains. By contrast, the grain in Barrel C shed multiple granules and coarse sand grains (Fig. 5). It lost mass more rapidly than grains in Barrels A and B, and had decreased by 52% of its original mass by the end of the experiment.

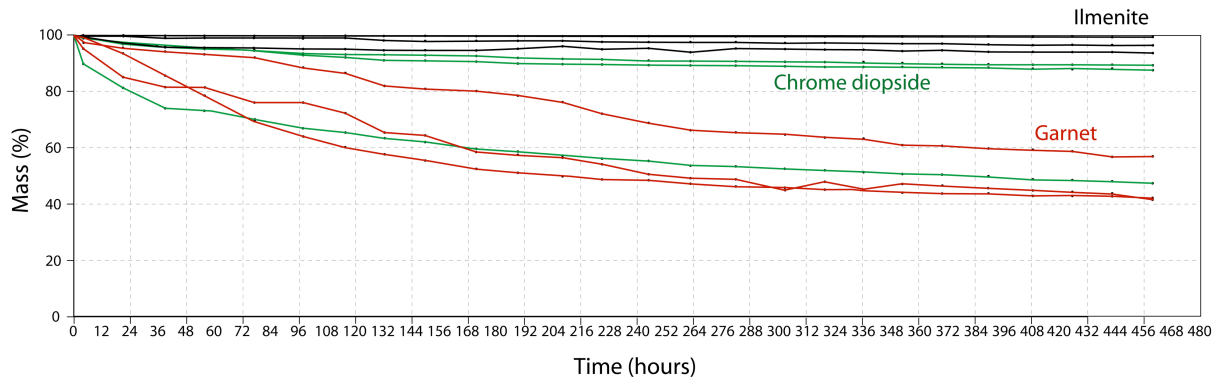
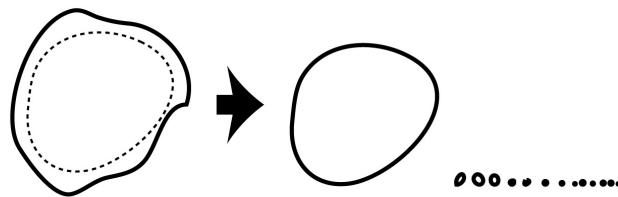


Figure 3. Plot of percentage mass loss to the mud (<0.063 mm) fraction versus time for grains of three mineral species.

Surface abrasion



Grain breakage

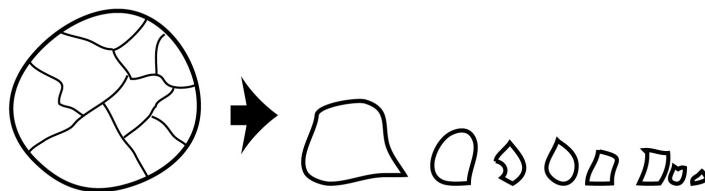


Figure 4. The two end-member comminution styles observed in the experiment: surface abrasion, which rounded grains and produced mud, and grain breakage along pre-existing internal weaknesses (e.g., fractures, cleavage planes), which rendered grains more angular and produced sand and granules. Figure adapted in part from Kelly and Spottiswood (1982).

The pyrope garnet grains broke down faster and differently than the ilmenite and chrome diopside grains. They lost between 43 and 58% (average 53%) of their masses to the mud fraction over the course of the experiment (Fig. 3). They comminuted in two

distinct stages (Figs. 5, 6). First, mass loss occurred entirely by surface abrasion, which produced mud at a rapid rate. Second, after a day or two, the grains started to break apart rapidly, yielding multiple granules and tens to hundreds of smaller, angular sand grains in addition to abundant mud.

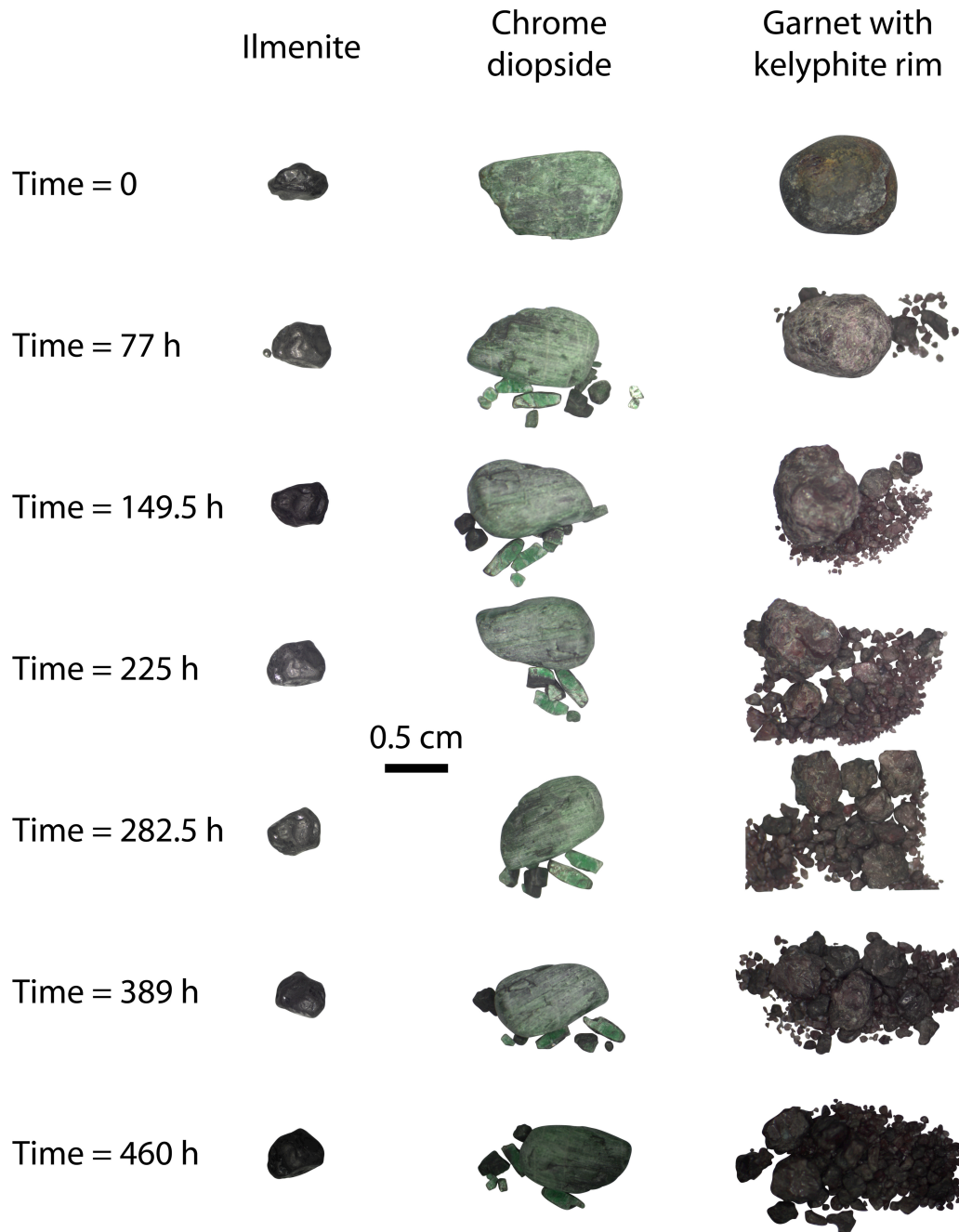


Figure 5. Binocular microscope photographs showing the different comminution styles of the ilmenite, chrome diopside and pyrope garnet grains (>0.063 mm fraction, Barrel C).

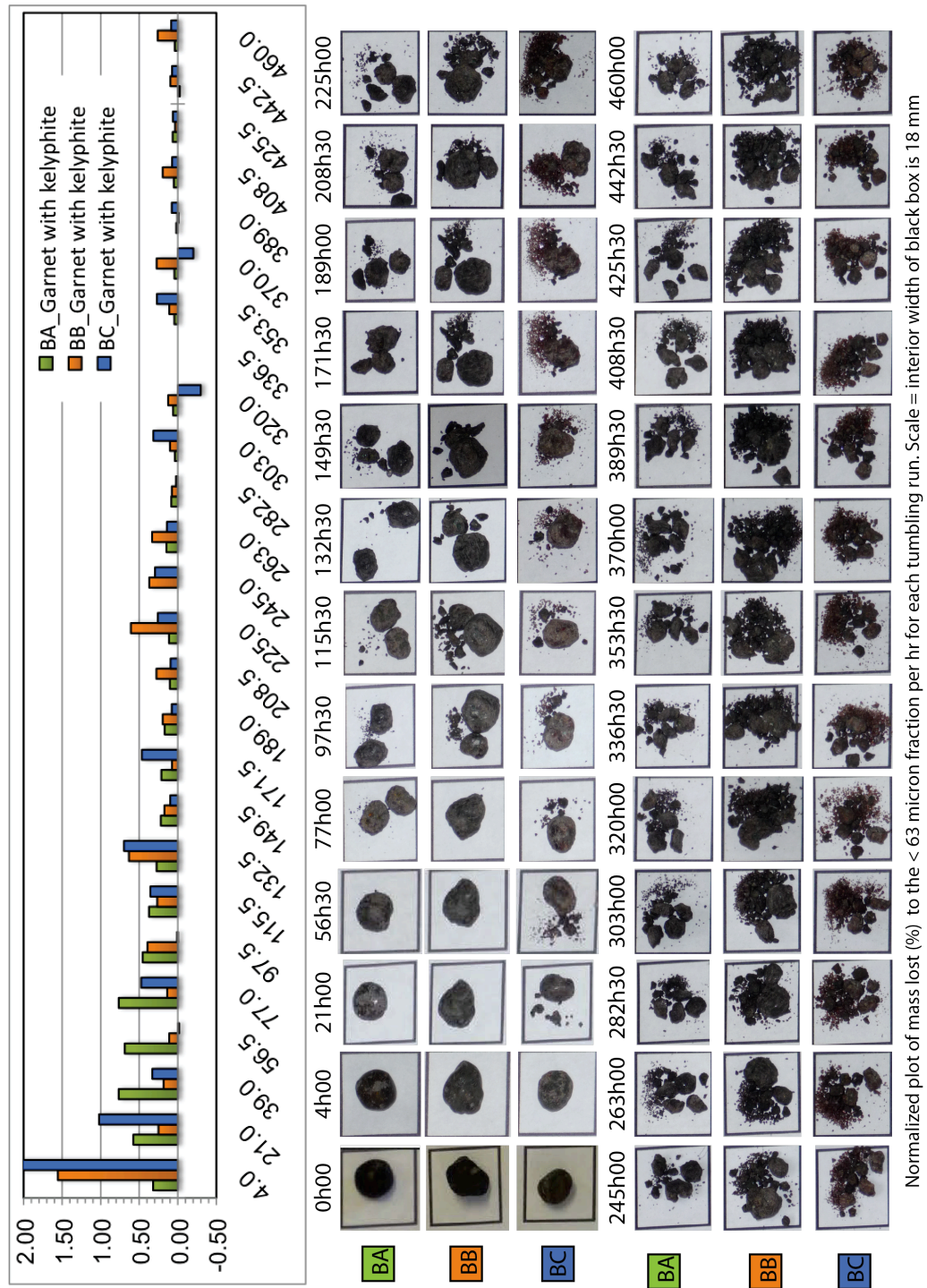


Figure 6. Comparison of comminution rates (A) and comminution styles (B) of the pyrope garnet grains in Barrels A, B and C. The graph in (A) depicts the amount of mass "lost" from the sand and gravel fraction to the mud fraction over time. Mass loss is given in percent of the initial grain mass at start of experiment normalized per hour of tumbling. Letters refer to barrels. In (B), the photographs show the evolution of the sand and gravel (>0.063 mm) fraction over the course of the experiment. Letters refer to barrels. For scale, the width of the boxes is 1.8 cm.

4. DISCUSSION

The different comminution styles and the different comminution rates observed in the experiment relate primarily to the different physical properties of the KIM species, a conclusion supported by earlier comminution studies (e.g. Alling, 1950; Cozzens, 1931). A relative lack of internal weaknesses in the ilmenite grains likely limited sand production and contributed to their low rates of mass loss. When the chrome diopside grains broke, they appeared to do so along cleavage planes, given the elongate shape of many of the sand and granule fragments produced. The rapid, two-stage comminution of the garnets is tentatively interpreted to reflect initial removal of the soft, microcrystalline kelyphite by surface abrasion, which produced mud rapidly, followed by breakage of the highly fractured internal parts of the grains, which produced sand and granules rapidly, in addition to mud. Continued high rates of mud production following kelyphite removal may have actually been related to commencement of sand and granule production, given that breakage would have increased surface area to volume ratios, which in turn would have increased the potential for continued surface abrasion and "loss" of mass to the mud fraction.

The experimental results have several implications for mineral exploration. One of these relates to the use of KIM abundance as an indicator for proximity to source. Kimberlite indicator minerals are typically picked and counted from a portion of the sand fraction, commonly somewhere in the medium to coarse sand range, but also sometimes from the finer sand range (Averill, 2001). If larger pyrope garnets, such as those analyzed in the experiment, were present in the kimberlite source rock, break down of these grains at the head of the dispersal train could flood the sand fraction with garnet fragments. This could potentially lead to an *increase* in the number of garnet and total KIM fragments moving downflow, with a commensurate increase in angularity of garnet grains (Fig. 7). In situations where this occurs, the total mass of KIM fragments in the sand and gravel fraction might serve as a better proxy for transport distance than KIM counts, given that it should always decrease downflow in dispersal trains due to some combination of comminution, dilution and/or selective sorting (Cummings et al., 2011).

Another implication of the experimental results relates to provenance interpretation. When working on broad dispersal plumes composed of multiple dispersal trains sourced from multiple kimberlites, caution must be exercised when attempting to "fingerprint" (i.e., correlate) a given dispersal train back to its parental kimberlite source. If comminution occurred during transport, the ratio of KIM mineral species in the dispersal train may have changed downflow (Fig. 8). In the extreme, the dispersal train could exhibit KIM assemblages more closely resembling those of an adjacent, unrelated kimberlite than the actual parent kimberlite, which could lead to false correlation. As with all geological problems, a weight-of-evidence approach should therefore be used. The ratio of different KIM mineral species should be examined alongside other criteria (e.g., KIM chemistry; mud-fraction geochemistry; paleoflow indicators) when attempting to correlate dispersal trains and kimberlite sources.

Pyrope garnet in our experiment lost mass faster than the other KIMs investigated. By contrast, garnet lost mass the slowest in the study of Alling (1944) and was only second slowest to diamond in the study of Afanas'ev et al (2008). There may be several reasons for this. The garnet used by Alling (1944) was non-kimberlitic. It was being mined and sold as a commercial abrasive. It might be expected to be more resistant than kimberlitic garnets we used. The pyrope garnet used by Afanas'ev et al (2008) was kimberlitic, but it could have potentially been quite different than the garnets we used. They only performed one experimental run; it is unclear if their results are repeatable. Furthermore, it is suspected that the ultrasonic rock polisher they used promoted surface abrasion and dissuaded grain breakage more so than the steel-shot-charged tumbling mill we used. Further comminution experiments are required with garnets from kimberlitic and non-kimberlitic sources.

As a final note, we must emphasize caution in direct transposition of our experimental results to real world situations. Tumbling mills offer crude approximations of natural systems. For example, they are widely acknowledged to overproduce mud and underproduce sand relative to natural settings (Lewin and Brewer, 2002). Transport distances in tumbling mills are not equivalent to real world transport distances (e.g., Schumm and Stevens, 1973). What tumbling mills do provide is general insight into the *relative* rates at which different clastic particles will likely break down during transport. For inaccessible environments, such as the base of a glacier—the setting where most surficial sediment in Canada was produced—they offer some of the only quantitative insight available into clast comminution.

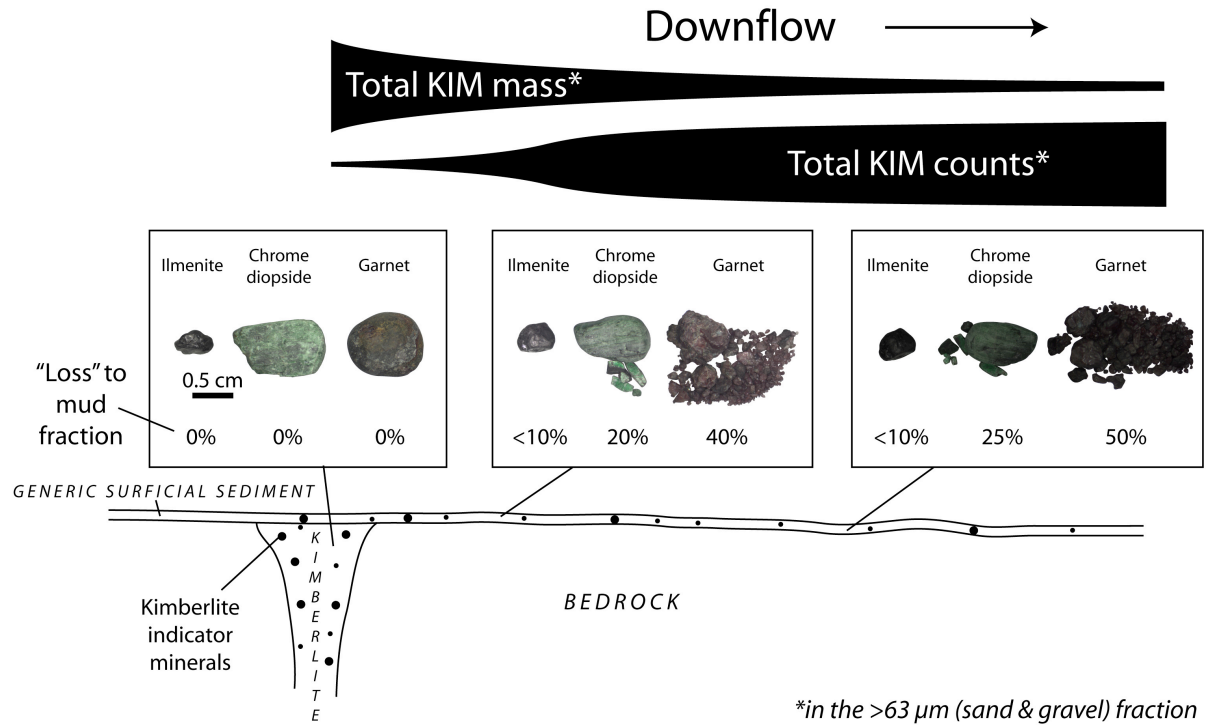


Figure 7. The head of a theoretical dispersal train produced if KIM comminution proceeded as observed in the tumbling mill experiment. Farther downflow, total KIM counts would decrease, assuming continued comminution (in addition to selective sorting and/or dilution).

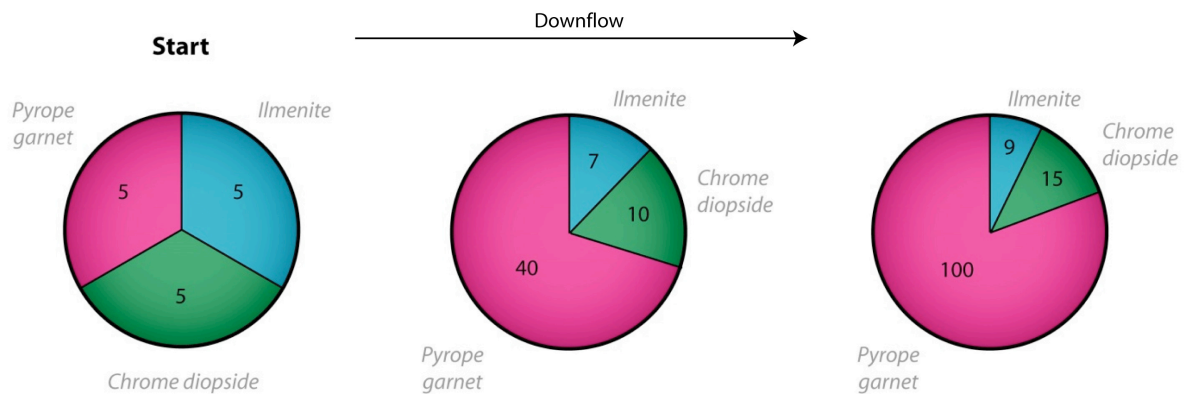


Figure 8. Downflow evolution of indicator mineral assemblages at the head of a hypothetical kimberlite dispersal train in which rapid break down of larger pyrope garnets produces abundant sand-sized grains. Farther downflow, total KIM counts would decrease, assuming continued comminution (in addition to selective sorting and/or dilution). Numbers refer to grain counts.

5. CONCLUSION

The kimberlite indicator minerals we investigated broke down at significantly different rates and by significantly different mechanisms.

Pyrope garnet grains broke down the fastest. They broke down in two stages, which produced abundant sand and granules in addition to abundant mud. The two comminution stages are interpreted to reflect removal of kelyphite by surface abrasion followed by breakage along internal weaknesses.

Ilmenite grains broke down the slowest. They lost mass primarily by surface abrasion, which produced a small amount of mud and rare sand grains. This comminution style is interpreted to reflect lack of internal weaknesses, which promoted surface abrasion as opposed to grain breakage.

Chrome diopside grains broke down at rates intermediate between those of ilmenite and garnet. They lost mass primarily by surface abrasion, which produced mud, but they also produced sand and granules. This comminution style is interpreted to reflect surface abrasion in addition to breakage along cleavage planes.

The experiments suggest that rapid break down of large pyrope garnets could flood the heads of kimberlite dispersal trains with sand sized garnet fragments, causing the number of KIMs in samples to *increase* downflow, at least initially. This could skew interpretation of proximity to source. A good alternative proxy in these situations may be the total mass of KIM fragments in the sand and gravel (>0.064 mm) fraction, which will always decrease downflow of specific point source (not necessarily the original source) liberation of indicator minerals in dispersal trains.

6. ACKNOWLEDGMENTS

This experiment would not have been possible without the dedicated laboratory assistance of A. Grenier, C. Moore, and M. Wygtergangs. A critical review by R. Knight is much appreciated. Funding for this experiment was initially provided within the Diamond project of the Geo-mapping for Energy and Minerals (GEM) Minerals Program. Analysis of the results was completed as part of the Targeted Geosciences Initiative IV (TGI-IV): Enhanced Effectiveness of Deep Exploration Program, and specifically the Methodology Project on Indicator Mineral Dispersion.

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