Journal: Solid Earth
Title: The Morphology and Surface Features of Olivine in Kimberlite Lava: Implications for Ascent and Emplacement Mechanisms
Author(s): T.J Jones et al.
MS No.: se-2013-72
MS Type: Research Article
Topical Editor: Mike Heap

Point-by-Point Response to Referee Comments

Reviewer comments are in standard typeface. Our responses are in **bold**.

A) Summary Comments from Editor:

Page 2284 Line 8: "Scanning electron microscopy" **Corrected**

Page 2285 Line 15: You should add "(SEM)" **Corrected**

Page 2285 Line 19: Why these lavas exactly? Are they fresh? Are they representative of kimberlite lavas worldwide? I would add a short sentence here explaining your choice. **In the text we mention that these deposits are fresh and young. We have emphasized this point to make it clearer that, in our opinion, the Igwisi Hills kimberlites offer unique opportunity for this type of study.**

Page 2286 Line 18: "rimmed" **Corrected**

Page 2288 Line 10: EDS? **Now defined - Energy Dispersive X-ray Spectroscopy**

Page 2290 Line 6: I would state upfront that these analyses are 2D. **This is now clearly stated within the results section.**

Page 2291 Section 5.2: How many olivine crystals did you inspect? **That was a big oversight. We have now added this information to the sample suite description.**

Page 2292 Line 25: I would change "having" to "with". **Changed as suggested.**

Page 2293 Line 3: What do you refer to by "x-axis"? **This text is rewritten to read "with increasing distance along the x-axis".**

Page 2293 Line 11: Did you not just say they were 50 microns. **Yes this is a mistake, we now refer to sub figure C not B. These semi-spherical pits can measure 10-25 microns, they are variable in size. The text is modified to make this point and to ensure clarity.**

Page 2293 Line 23: How do you know they have identical chemistry? **We have performed EDS analysis on the SEM to estimate the compositions of the flakey surfaces of the olivine grains. The "flakes" have compositions indistinguishable from the pitted areas of olivine. The text is now modified to clearly make the point that we have done work to establish this compositional homogeneity (at least) semiquantitatively.**

Page 2293 Line 26: I would remove "themselves" **Agreed and removed.**

Page 2294 Line 23: Did you consider thermal cooling cracks?

We predict that stresses induced by decompression to be much greater than thermal. However if thermal exfoliation was to play a role its appearance is likely to be comparable. In addition we now mention the importance that temperature may have in crack formation. This is done by drawing on a few key points from the work of (Heap et al., 2013). The likely reduction in tensile strength is considered at elevated temperatures and its role in aiding the decompression cracking observed. Thank you for bringing this poorly explained consideration to our attention.

Page 2296 Line 15 (also Page 2297 Line 11): There is an important distinction here. Are these features unique to the IHV lavas? Or is their observation in kimberlite lavas unique?

They are unique to kimberlitic systems, this is now stated. The second concern is addressed by revising the text slightly (page 2297 Line 11) and we hope it is now self-explanatory.

Page 2296 Line 26: Was there any evidence for collision-induced fracturing?

The observed (sub-)hemispherical cavities are related to impact/collisions. Unfortunately we have no way of determining if through going fracturing occurs by collision. This other style of fracturing could be resultant from a variety of processes (e.g. bursting of melt inclusions, fragmentation on emplacement, or more likely sealed/healed tension cracks which are comparable fractures observed in the updated Figure 3).

<u>B) Reviewer #1 Comments:</u>

Point 1: I am wondering a little bit about the volume proportions of the mantle material in the model. If a (pyrope) garnet-bearing source is envisaged as the source of the mantle debris (as stated at the end of page 2286), you would expect roughly 60% being olivine and the remaining 40% divided between Cpx, Opx and Grt. If, this is the case why are not any of these minerals present in the IH rocks? The magma ascent model applied here assumes, building on the experiments of Russell et al. (2012), that Opx breaks down and lowers the overall solubility of CO2 in the "hybrid" melt, which actually propels the ascent of the kimberlite. So in this case, the absence of Opx in the IH kimberlite is not a major problem, but why are there no mantle Cpx and Grt present at IH? Would you not expect these mineral phases to experience the same amount of differential stress and expansion during decompression as the olivines do, and subsequently also produce similar flaking/mechanical abrasion en route to the surface? In other words, what makes olivines the unique mantle phase to be preserved in this process at Igwisi Hills?

Firstly, many peridotites from the cratonic mantle lithosphere have higher olivine contents than 60%. Studies have used both image analysis techniques and bulk whole rock compositions to estimate mineral modes in the cratonic mantle (Kopylova and Russell, 2000). Results show that cratonic mantle has modal olivine concentrations of >70%. Secondly, orthopyroxene modal proportions are ~10-30% (Figure 9;Kopylova and Russell, 2000) but as mentioned above this proportion could well be assimilated during ascent.

Secondly, garnet, orthopyroxene and clinopyroxene are all present within the Igwisi Hills lava as described by (Dawson, 1994; Reid et al., 1975) however they are in minor abundance relative to olivine. This apparent enrichment in olivine, however, is not unique to Igwisi Hills; rather it is an enigmatic, long-lived, query posed by most kimberlite deposits. It can also be partially attributed to post emplacement

accumulation- this is now also stated in the revised text. We do not attempt to predict the source exactly, we simply assume peridotite as the source material – this could be a dunite as proposed by Arndt et al., 2010. Our model simply suggests a mechanism in which a particle laden cargo ascends to the surface within a kimberlitic fluid. Therefore olivine is considered after entrainment into the kimberlitic fluid.

Point 2: When reading the manuscript, the text simply states that the lower section of the kimberlitic pahoehoe flow at Igwisi Hills contains up to 45 vol.% ellipsoidal-shaped olivine crystals (line 4, page 2288 in the manuscript). In the paper by Brown et al. (2012) high proportions of 26 vol.% is reported to occur just above the base of this lava (Fig. 7 in Brown et al., 2012), and a similar value is also given for the digitized slab in the caption to Figure 3 (i.e., 27 vol.%, page 2305), but not really in the text. Why this big discrepancy in the reported olivine content?

We thank you for pointing this out. This is a typing mistake. You are correct; the appropriate value from Brown et al., 2012 is now added to the manuscript.

Point 3: Have the CSD data been stereologically corrected? And if so, why is the sorting good (_'=0.595; Line 11, page 2290) whereas the olivines are described to range in size from 1-10 mm (line 4, page 2288). To me, a variation in size between 1-10 mm do not "reflect a relatively narrow range of olivine sizes in the cratonic mantle lithosphere" as stated in lines 12-14, page 2290. I think this needs some clarifications in the text.

All these analyses were conducted in 2D and limited to the large xenocrystic ellipsoids (this is population which we analysed by all techniques). Our sorting classification is based on pyroclastic sorting descriptors. A comparison to the sedimentary classification is now included in addition. The sedimentary descriptor requires a much lower graphical standard deviation to be considered 'well sorted' in comparison to the pyroclastic descriptor (Cas and Wright, 1987). Well-sorted sedimentary deposits are <u>*very much better sorted*</u> than well-sorted pyroclastic deposits. We hope this clarification addresses these concerns.

Point 4: In a simple back of the envelope attempt to calculate the total olivine content within the lava flow (also including the vesicular flow top in Fig. 7; Brown et al. 2012) I come up with a value in the range of 10 to 14% (in 2D). However, it is also stated that 25-45% of the primary olivine is abraded away by mechanical abrasion/collisions during ascent. This indicates that there may have been a input of just under 20% of mantle olivine into the ascending magma (pre-abrasion) and assuming that roughly 60% of the mantle material is composed of olivine then this should represent an approximate mantle fraction of 0.3-0.4 being incorporated into the ascending magma. These values makes sense to me, as higher fractions of mantle material will be very difficult to carry to the surface. Therefore, I also think that the statement of 45 vol.% olivine crystals in the lower parts of the lava flow needs to be clarified in the text and also to give an estimate of total olivine content (see comment above).

This value of 45% is incorrect, as addressed above. Our value of 25-45% abrasion has also been revised in light of previous experimental studies (Afanas'ev et al., 2008). This is fully addressed in the comments of reviewer #2.

Point 5: I am not sure about the timescales of olivine recrystallization around the edges of larger grains (as seen in Fig. 2), could this perhaps also contribute to the flaky appearance in the IH olivines and make them more susceptible to mechanical abrasion?

Previous studies suggest that olivine crystallisation does not produce flaked textures (Boudier, 1991). Crystallisation textures are homogeneous, unstrained and sharp. We now include this reference in our revised manuscript.

Point 6: Finally, in line 15 on page 2297 there are some spelling errors regarding the rock types and it should read (basalt, basanite, nephelinite).

Thank you, this is now corrected.

C) Reviewer #2 Comments:

Point 1: Scholarship.

However, had the approach been more general, and had the authors made better use of recent literature, the project could have been far more fruitful.

Firstly, we would like to apologise for our lack of scholarship in our original submission as exemplified by our scanty review of the literature. We have now revised the text substantially to be much more inclusive and exhaustive in our review of the pertinent literature. It does not change our interpretation but it has greatly helped us to clarify our arguments and to perhaps increase the potential impact of this manuscript. Our literature review is exemplified by inclusion of a table that summarises literature relevant to our study.

Point 2: Olivine Composition

It would have been greatly improved by the incorporation of information about the compositions of the olivines. A one-day session on a microprobe would have been extremely instructive; for example, it would have allowed the authors to provide more quantitative information than "(the composition of the IHV olivine crystal is) : : : close to the forsterite end member of the olivine solid solution".

The actual compositions of the Igwisi Hills olivines and the style and magnitude of their chemical zoning is reported by (Dawson, 1994) and (Reid et al., 1975). We have now included these observations in our paper to expand the description of the Igwisi Hills olivine. We do not report our own analyses, the chemical compositions of the olivine is somewhat peripheral to the model we are developing.

Microprobe analyses would probably have revealed the presence of rims of Fe-rich olivine that crystallized from the kimberlite magma, as recognized by Brett et al. (2008), Kamenetsky et al. (2008), Arndt et al. (2010) and Pilbeam et al. (2013). In a recent paper, we illustrated and described morphological and chemical features that provide very useful information about the way olivine behaves during its transport in kimberlites (Arndt et al. 2010). Deformation structures and grain boundaries within multigrain olivine "nodules" or "ellipsoids" reveal the following features: that the material entrained into the kimberlite was dunite, not peridotite; that euhedral grains (tablets) within these dunite xenoliths recrystallized during ascent of the kimberlite; that Fe-rich olivine rims crystallized from kimberlite magma during ascent; and that the rounded borders of the ellipsoids cut indiscriminately across all these olivine morphologies. Key observations such as the partial removal of both the kimberlite-derived rims and the margins of olivine tablets indicate clearly that abrasion was the main mechanism that produced the rounded shapes. This conclusion agrees with that of the authors of the present manuscript. If an inspection of the outer surfaces of Fe-rich rims showed textures indicative of abrasion, this would clearly rule out chemical abrasion because the olivine of the rims was clearly in equilibrium with the kimberlite.

In the revised manuscript we now include a section and table that summarises key findings by other scientists that are relevant to our study including, but not limited to, those mentioned in this comment. We understand that core/rim chemistry of the olivine may provide evidence that validates the timing and dominance of abrasion as the main shaping mechanism. We now include a comprehensive review of core and rim kimberlitic olivine observations (Table 1). Building on this we describe the core/rim chemistry of the IH lava olivine used in this study. Two previous papers (1) Dawson (1994) and (2) Reid et al., 1975 examine the geochemistry of the IH lavas in detail. Both studies examine the forsterite component and the core to rim geochemical profiles within these olivines. Given that this published data already exists we use values and observations from these papers to support our sample characterisation.

Point 3: Mineral Proportions

As anonymous reviewer #1 points out, the proportions of minerals observed in kimberlites are not easily reconciled with the hypothesis that the olivine grains were derived from four-phase peridotite: relicts of opx, cpx or gt are rare to absent in kimberlites. Arndt et al (2010) argued that these phases were removed during metasomatism in the lithosphere, and that the entrainment of xenoliths of dunite, not peridotite, explains the abundance of olivine and the absence of the other minerals in most kimberlites. The authors could make a very useful contribution if they addressed directly the question of how opx, cpx or gt could be removed during transport in kimberlite. These minerals make up about 50% of normal mantle peridotite – if they were removed during transport, how did the remaining olivine grains aggregate to form the large and commonly multigrain ellipsoids observed in kimberlites worldwide? It would be very interesting to see a quantitative comparison of grainsize in peridotite xenoliths, where the olivine grains are rarely larger than 4 mm, with the seemingly larger grains illustrated in Figs 1 and 2.

As mentioned this query is partially addressed in comments by reviewer #1. Our model sorts to explain the transport of xenocrystic olivine cargo to the surface. We state the source of xenocrystic material to be mantle peridotite; this is open to a range of compositions including dunite as proposed by (Arndt et al., 2010). Both garnet and chrome diopside have been identified in the lavas from the Igwisi Hills (Dawson, 1994). The extremely rare nature of orthopyroxene in these rocks can be explained by its instability in kimberlite melts. It is proposed that orthopyroxene is assimilated during ascent (e.g. Russell et al., 2012).

Point 4: Alteration & Age.

Some other aspects of the manuscript warrant discussion: Page 2285, line 1: the degree of alteration can be independent of age: the Proterozoic Kangamuit (Majuagaa) kimberlite is as well preserved as the 10 ka Igwisi Hills kimberlite.

This is correct, however, in a general sense age can be linked to degree of alteration. Younger volcanic rocks will always have a higher probability of being fresh and unaltered. The phrasing of the sentence has been changed to account for this.

<u>Other, more minor comments:</u>

Page 2287, line 25: the subgrains illustrated in Fig 2c are rather like the recrystallized grains described by Arndt et al. It is not clear what is meant by the phrase "The peripheral olivine grains are randomly oriented but still retain the overall rounded shape, suggesting that recrystallization post-dates and conforms to the rounded structure". A simple explanation of these textures is that abrasion has removed the outer portions of both lithosphere-derived and recrystallized olivine grains.

A new figure of microphotographs (Figure 3) has now been inserted with an associated description. Close ups of the grain boundary show increasingly fine grained olivine recrystallization. It is discussed that removal of these small grains may occur as part of the abrasion process.

Page 2289. It is surprising that no mention is made here of the work of Holden et al (2008). As reviewer #1 points out, the conclusion that the grains are very well sorted is surprising. First, the sorting coefficient is in fact rather large; second, the results have been biased by the exclusion of smaller grains by the manual method that was used to outline grain boundaries. Why wasn't an automatic image analysis technique like that of Holden et al used?

Image analysis was only conducted on the large xenocrystic ellipsoid grains, as this was the population analysed by the other methods in this study. An image analysis technique like the one used in Holden et al., 2008 was not used as we only digitalize a single slab. If we were to be analysing the population and sorting of olivine grains across a suite of lava slabs then this approach would have been appropriate.

Page 2291. The quality of Figure 6c is not high enough to observe that the layering exists below the surface.

This can now also be observed in Figure 3 for example.

It is not clear why the hemispherical structures are ascribed to impact. They are very small (<50 microns) and it is not evident that such structures would result from impacts of mm-sized olivine grains. In this context it would be interesting to see a more detailed exploration of erosion mechanisms and intensities in the kimberlite system where olivine grains are transported within a relatively viscous fluid. Some information might come from comparison with better-understood situations such as abrasion of cobbles or sand in fluvial or eolian settings. Intuitively it would seem that inertial forces of mm-sized olivine grains within a silicate liquid would be small and that abrasion would occur mainly in zones of shearing where olivine grains were brought into contact by differential movement of the fluid.

Within the discussion we now also make reference to (1) (McCandless, 1990) who performs experimental studies on kimberlitic garnet in order to model abrasion and transport processes in fluvial systems. His observations and figures are in agreement with what we interpret to be generated by abrasion. (2) (Afanas'ev et al., 2008) who again perform experimental studies on kimberlite material. We compare external morphologies of olivine and use their experimental data to estimate a percentage mass loss of the IH olivine- see later comment also.

Do such zones exist in the kimberlite conduits?

We believe that this is unlikely, or at least trivial in comparison to the process which we describe. Current literature shows that by flow differentiation xenocrysts are removed from regions proximal to the wall rock. A aphanitic contact is preserved with the wall rock where the largest xenocrysts have been removed (e.g. Price et al., 2000).

Page 2292. Do data exist to show that the flakes have the same "chemistry" as the surrounding fresh olivine?

SEM coupled Energy Dispersive X-ray Spectroscopy analysis shows no measurable differences in composition between the freshly exposed olivine and the flakes.

Page 2293. It would be interesting to try to relate the theory of decompression-related flaking at the surface of olivine grains with the reworking of peridotite (removal of px and garnet, aggregation of olivine grains) that is assumed to take place during transport to the surface.

We believe that this is truly interesting however, well beyond the scope of this current manuscript.

Page 2294. The discussion of abrasion is very qualitative. More explanation is needed to explain how the figure of 25-45% volume loss was obtained. Comparison to erosion in fluvial systems would be interesting in this context. The experiments in which the surfaces were etched with HF seem to provide only a very crude approximation of reaction of olivine with silicate liquid. Other observations argue far more strongly for mechanical abrasion.

We have now sought to make our description of abrasion more quantifiable. Using experimental studies on kimberlitic minerals performed by (Afanas'ev et al., 2008) coupled with our morphological observations we have estimated the percentage mass loss attributed to abrasion during ascent. This is represented in the discussion and a new figure (Figure 9 in the revised manuscript).

Page 2296. What is meant by the phrase “decompression makes the olivine more susceptible for abrasion”? More susceptible than what? The key observation is that olivine is far more abundant in kimberlites that might be expected if the source was mantle peridotite. A mechanism must be sought to explain the persistence of olivine a system in which other minerals are supposed to be selectively removed.

This sentence has now been changed. We hope that it is now clear that decompression cracking of the olivine exterior makes the edges weak – therefore more susceptible than a freshly crystalized grain. Secondly, our model is sought to prove a particle laden turbulent ascent of olivine within kimberlites. We never attempt to define the starting composition. “Mantle peridotite” could refer to dunites as proposed by Arndt et al., 2010

References cited in response:

Afanas'ev, V. P., Nikolenko, E. I., Tychkov, N. S., Titov, A. T., Tolstov, A. V., Kornilova, V. P., and Sobolev, N. V., 2008, Mechanical abrasion of kimberlite indicator minerals: experimental investigations: Russian Geology and Geophysics, v. 49, no. 2, p. 91-97.

Arndt, N. T., Guitreau, M., Boullier, A.-M., Le Roex, A., Tommasi, A., Cordier, P., and Sobolev, A., 2010, Olivine, and the Origin of Kimberlite: Journal of Petrology, v. 51, no. 3, p. 573-602.

Boudier, F., 1991, Olivine xenocrysts in picritic magmas: Contributions to Mineralogy and Petrology, v. 109, no. 1, p. 114-123.

Cas, R. A., and Wright, J. V., 1987, Volcanic successions, modern and ancient: A geological approach to processes, products, and successions, Allen & Unwin.

Dawson, J., 1994, Quaternary kimberlitic volcanism on the Tanzania Craton: Contributions to Mineralogy and Petrology, v. 116, no. 4, p. 473-485.

Heap, M., Mollo, S., Vinciguerra, S., Lavallée, Y., Hess, K.-U., Dingwell, D. B., Baud, P., and Iezzi, G., 2013, Thermal weakening of the carbonate basement under Mt. Etna volcano (Italy): implications for volcano instability: Journal of Volcanology and Geothermal Research, v. 250, p. 42-60.

Kopylova, M. G., and Russell, J. K., 2000, Chemical stratification of cratonic lithosphere: constraints from the Northern Slave craton, Canada: Earth and Planetary Science Letters, v. 181, no. 1–2, p. 71-87.
McCandless, T. E., 1990, Kimberlite xenocryst wear in high-energy fluvial systems: experimental studies: Journal of Geochemical Exploration, v. 37, no. 3, p. 323-331.
Price, S., Russell, J., and Kopylova, M., 2000, Primitive magma from the Jericho Pipe, NWT, Canada: constraints on primary kimberlite melt chemistry: Journal of Petrology, v. 41, no. 6, p. 789-808.
Reid, A. M., Donaldson, C., Dawson, J., Brown, R., and Ridley, W., 1975, The Igwisi Hills extrusive "kimberlites": Physics and Chemistry of the Earth, v. 9, p. 199-218.
Russell, J. K., Porritt, L. A., Lavallée, Y., and Dingwell, D. B., 2012, Kimberlite ascent by assimilation-fuelled buoyancy: Nature, v. 481, no. 7381, p. 352-356.