Discovery and Interpretations of Melt Inclusions in Kimberlitic Olivine

Comparisons to experimental and reconstructed primitive/parental kimberlite melt compositions
What Problems do Melt/Fluid Inclusions Address?

What was the composition of the primary/parental kimberlite melt?

What is the composition of the parental melt?

What is the composition of the primary (or proto-) melt?

Giuliani et al. (2023)
What Problems do Melt/Fluid Inclusions Address?

➢ Kimberlites represent complex, “hybrid rocks containing xenocrystal, primary magmatic, and hydrothermal minerals” (Mitchell et al., 2019)⁵.

**Bulk rock ≠ Kimberlite magma!**

**Mantle Contamination**
- Peridotite
- Kimberlite

**Crustal Contamination**
- Volcaniclastic Kimberlite

**Ascent & Eruption**
- Degassing of volatiles (CO₂, H₂O), magma differentiation...

**Alteration**
- Serpentine
- Ol
“Fresh” olivine is required to reconstruct an unambiguous record of different generations of inclusions entrapped in olivine.

Olivine has xenocrystic (e.g., core) and magmatic (e.g., rim, rind) components.
➢ **NO** primary melt/fluid inclusions in xenocrystic olivine cores.

➢ May contain crystal inclusions of other mantle minerals: Cr-diopside, enstatite, Cr-pyrope garnet, picroilmenite, sulphides.
Primary Crystal Inclusions in Magmatic Olivine Zones

- Olivine rims and rinds contain crystal inclusions of:
  - Spinel - Cr-spinel and MUM-TIMAC, Mg-magnetite, pleonaste
  - Phlogopite
  - Perovskite
  - Ilmenite
  - Monticellite
  - Apatite
  - Rutile

Mark kimberlite (Canda)

Kamenetsky et al., (2012)

(Udachnaya-East)
Primary Melt/Fluid Inclusions in Olivine

- Restricted to magmatic growth zones (rims, rinds).
- Extremely rare.

Mark Kimberlite (Canda) – Abersteiner et al., (2020b)
Secondary Melt/Fluid Inclusions in Olivine

- Very common.
- Clusters of inclusions are aligned along fractures and planes + cross-cut olivine zones.
- Typically interconnected by thin channels, indicating potential modification by ‘necking down’.

Udachnaya-East (Russia) - Abersteiner et al., (2018)
Pseudosecondary Melt/Fluid Inclusions in Olivine

- Entrapped if a crystal cracks and heals during formation.
- Usually occur as trails and terminate abruptly at growth zones.
- Appearance is usually difficult to distinguish from secondary inclusions.

Abersteiner et al. (2022b)

Mark kimberlite (Canada) - Abersteiner et al., (2020b)

Pseudosecondary Inclusion (PSI) trails in olivine (Udachnaya-East) Kamenetsky et al. (2008)
What’s Inside Melt/Fluid Inclusions in Olivine?

Golovin et al. (2020) – Unexposed secondary melt inclusions in olivine from a sheared garnet harzburgite xenolith (Udachnaya-East kimberlite)
Methods of analysis

**Scanning Electron Microscope**

**Raman Spectroscopy**

**LA-ICPMS**
SEM-EDS Analysis of Melt Inclusions in Olivine

Primary Melt Inclusions in Olivine

Mark Kimberlite
Abersteiner et al. (2020b)

Bultfontein Kimberlite
Giuliani et al. (2017)

SEM-EDS Analysis of Melt Inclusions in Olivine

Secondary/Pseudosecondary Melt Inclusions in Olivine

➢ Backscatter electron SEM images with point analyses and X-ray element maps on melt inclusions in kimberlitic olivine.

Example BSE SEM images of secondary/pseudosecondary melt inclusions in olivine. Daughter minerals were identified by EDS. Udachnaya-East kimberlite (Abersteiner et al., 2018).
Considerations!

➢ Instability of daughter phases in melt inclusion.

➢ Loss of fluids/volatiles upon exposure.

➢ Electron beam damage.

Decrepitation and recrystallisation of melt inclusions upon exposure to the atmosphere.
Raman Analysis of Melt/Fluid Inclusions in Olivine

- Does not require exposure of inclusions (i.e., potential loss of volatile/fluid phases).
- Requires an established database of Raman spectra.
- Most common fluid phase is CO$_2$.

LA-ICPMS Analysis of Melt/Fluid Inclusions in Olivine

- Bulk homogenisation of melt/fluid inclusions in olivine.
- Challenging to quantify due to heterogeneity of inclusions.
- Method requires further development.

Melt/fluid inclusions in olivine from a peridotite xenolith (Bultfontein)

Example LA-ICPMS ablation of melt/fluid inclusions in olivine from a peridotite xenolith (Bultfontein)

(Kamenetsky et al. 2009)
Objective: Homogenise the daughter mineral + fluid component into a melt inside the inclusion.

Immiscibility occurs during heating and cooling.

No quenched/homogeneous glass produced.

Wallace et al. (2021)

Quenched silicate glass melt inclusion in basalt (Mauna Loa, Hawaii).

~1100 – 1300 °C to homogenise

Carbonate-Chloride-Phosphate Immiscibility in melt inclusions in kimberlitic olivine.

~660 – 820°C to homogenise
Studies of Melt/Fluid Inclusions in Olivine

- Confined to locations where ‘fresh’ olivine is preserved.
- Numerous kimberlite localities of different ages and from different cratons.
- Some detailed work on melt/fluid inclusions in olivine from olivine lamproites (Abersteiner et al. 2022a) and Kaapvaal lamproites (aka orangeites; Abersteiner et al. 2024).
What’s Inside Melt/Fluid Inclusions in Olivine?

Regardless of kimberlite locality, melt/fluid inclusions in olivine are characterised by:

➢ Very heterogeneous daughter mineral assemblages.

➢ Sometimes contain shrinkage bubbles (CO\textsubscript{2}).

➢ No aqueous fluid or silicate glass found.

➢ More than >60 mineral species identified (Golovin and Kamenetsky, 2023).

### Daughter Mineral Assemblages

**Dominated by:**

- **Carbonates** (*alkali/alkali-earth-bearing Ca-Mg-Na-K-(Ba-Sr))

**Low-to-moderate amounts of:**

- **Chlorides** (*Na-, K-chlorides*)
- **Phosphates** (*e.g., apatite, alkali-bearing*)
- **Oxides** (*e.g., perovskite, Cr-Ti-Mg-Fe-Al spinel, ilmenite, rutile*)
- **Sulphates** (*alkali-bearing*)
- **Sulphides** (*Fe-Ni-, including K-Cl-bearing*)

**Low-to-rare amounts of:**

- **Silicates** (*e.g., phlogopite, tetraferriphlogopite, monticellite*)

Upper and lower estimates of silicates, chlorides and carbonates in olivine-hosted melt inclusions from kimberlites (Golovin and Kamenetsky, 2023 + references therein)
Significance of Melt/Fluid Inclusions in Olivine

- Primary + Secondary + Pseudosecondary Melt Inclusions = Same compositions
- Melt Inclusions are enriched in Na$_2$O, K$_2$O, CaO, CO$_2$ and Cl, contain low-to-moderate MgO and SiO$_2$ and depleted in H$_2$O.

The composition of melt inclusions is in stark contrast to the kimberlite bulk-rock.

Modified from Förster et al. (2019)
Insights into Primary Kimberlite Melt Compositions

- Melt/fluid inclusions suggest that the parental kimberlite melt was:
  - **Ca-Mg carbonate rich** (or even carbonatitic), with higher concentrations of **alkalis** (Na, K), **halogens** (F, Cl), **phosphorus** and **sulphur** than kimberlite bulk-rock.
  - **Low ultramafic and aluminosilicate** components and **H$_2$O-poor** compared to kimberlite bulk-rock.

- Melt Inclusions look more like carbonatites...

### Global Kimberlite Bulk Rock Averages (wt.%)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>~25-35</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>~1-3</td>
</tr>
<tr>
<td>MgO</td>
<td>~25-35</td>
</tr>
<tr>
<td>CaO</td>
<td>~12-20</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>~1-3</td>
</tr>
<tr>
<td>FeO</td>
<td>~6-10</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>~0.3-2</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>&lt;0.1-0.3</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>~0.5-2</td>
</tr>
<tr>
<td>Cl</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>F</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>~5-8</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>~8-13</td>
</tr>
</tbody>
</table>

Oldoinyo-Lengai natrocarbonatite lavas (Tanzania)
Evolution of Kimberlite Melts

➢ Assimilation of mantle silicates (e.g., orthopyroxene) by carbonate-rich melt drives CO₂ exsolution and increases the ultramafic-silicate component of kimberlite melts.

➢ Decarbonation reactions as a driver of kimberlite magma ascent?

➢ Carbonates + alkalis, halogens, P, S lost during kimberlite magma ascent + emplacement due to exsolution and alteration.
Thank you for your attention!

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References


Aragonite in MI – Evidence for Deep Entrapment?

➢ Aragonite in olivine-hosted melt inclusions in sheared peridotites.

➢ Aragonite is a high-pressure polymorph of CaCO$_3$

Golovin and Kamenetsky (2023)
Abersteiner et al. (2020a) Constraints on Deep Crustal Entrapment?

➢ Pseudosecondary melt/fluid inclusions containing CO$_2$ (Mark kimberlite, Canada).

➢ Estimated fluid densities (0.47–0.77 g/cm$^3$)

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Abersteiner et al. (2020a)
Cr-spinel hosted Melt Inclusions

Mark Kimberlite - Abersteiner et al. (2020a)

Dol/D: Dolomite, Cb: Carbonate, Ol: Olivine, Phlg: Phlogopite, Tph: Tetraferriphlogopite, aC: alkali (Na-K) carbonate, B:: Bradleyite

Koala Kimberlite – Kamenetsky et al. (2013)
Melt Inclusions in Groundmass Minerals

Perovskite