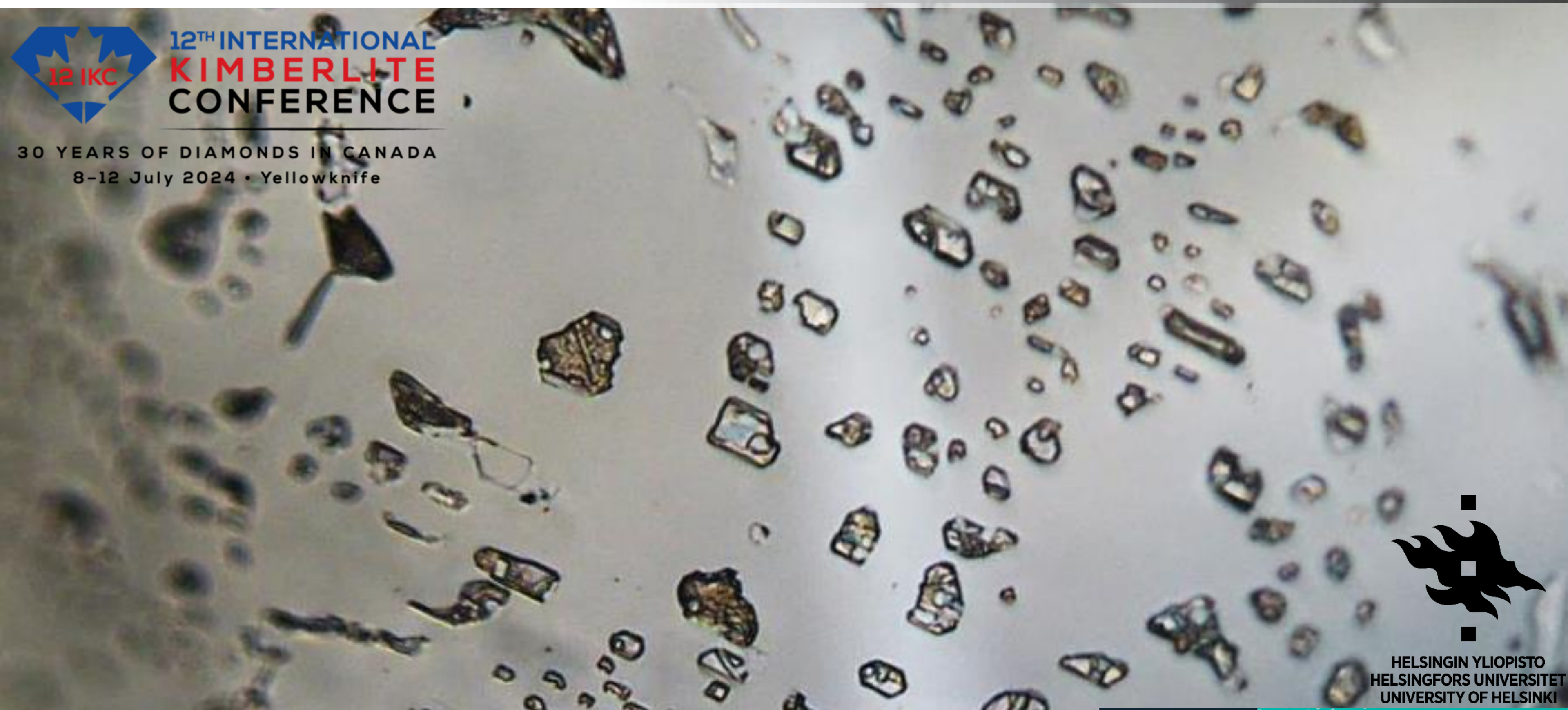
Discovery and Interpretations of Melt Inclusions in Kimberlitic Olivine

Comparisons to experimental and reconstructed primitive/parental kimberlite melt compositions



12TH INTERNATIONAL KIMBERLITE CONFERENCE
30 YEARS OF DIAMONDS IN CANADA
8-12 July 2024 • Yellowknife

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HELSINGIN YLIOPISTO
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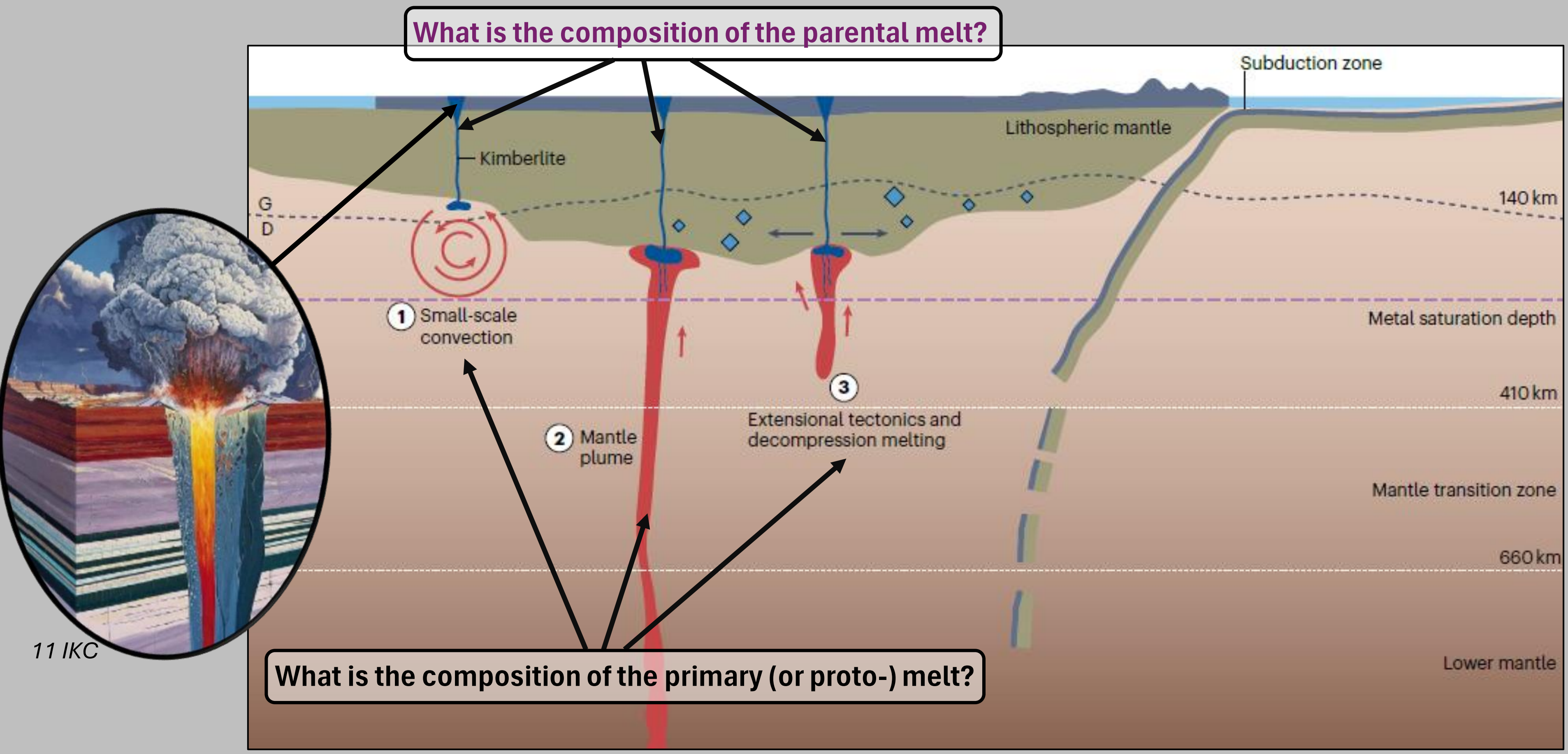
THE UNIVERSITY of ADELAIDE
Institute for Sustainability, Energy and Resources.

What Problems do Melt/Fluid Inclusions Address?

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



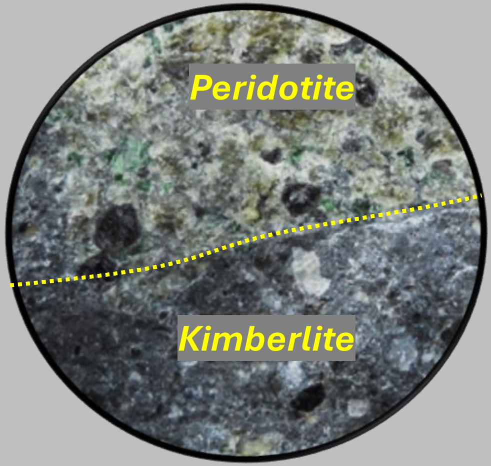
Giuliani et al. (2023)

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



Entrainment and interaction with mantle xenoliths, xenocrysts…

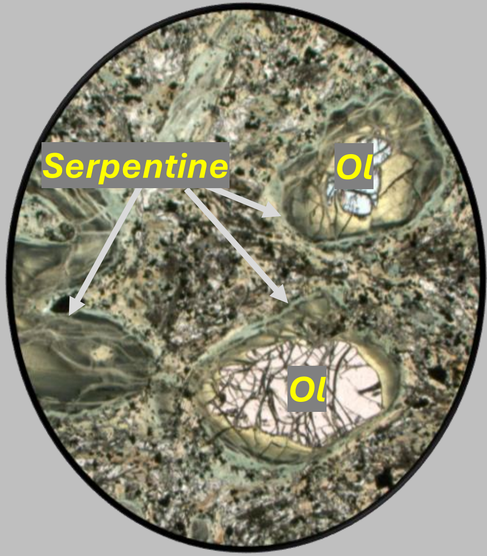
Crustal Contamination

Entrainment and interaction with crustal material…

Ascent & Eruption

Degassing of volatiles (CO_2, H_2O), magma differentiation…

Alteration

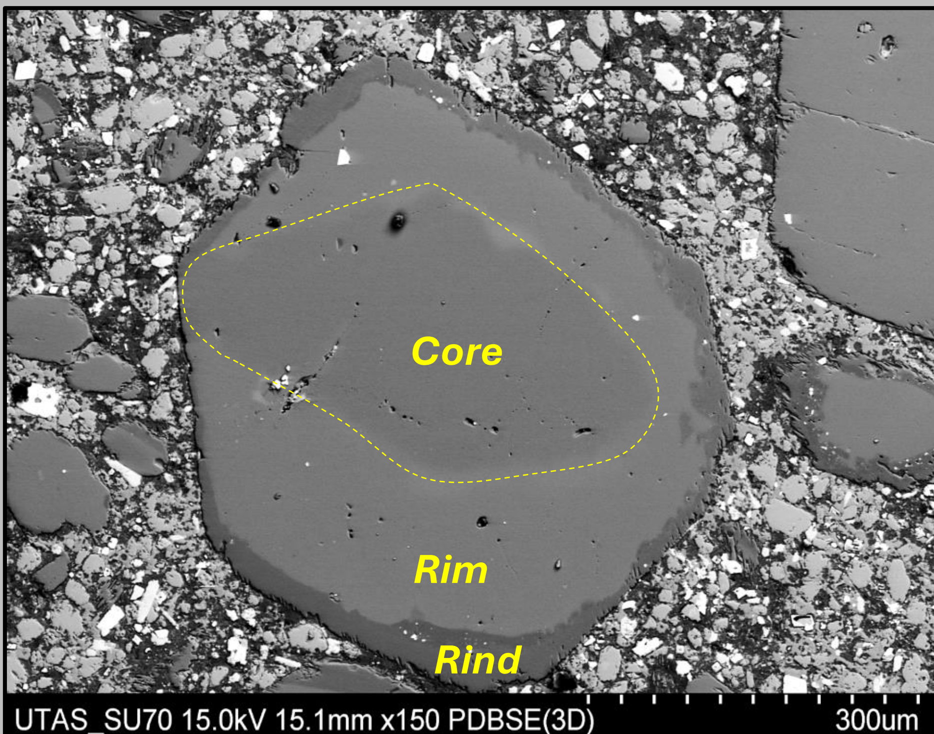


Alteration, Serpentinization…

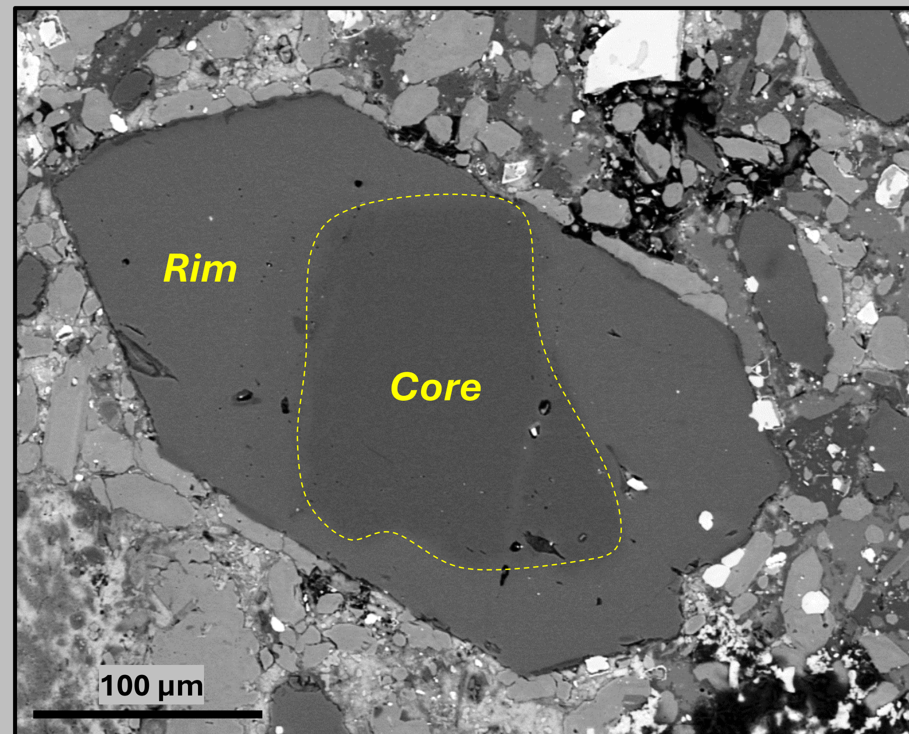
Historic Challenges

- “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.



Perfectly preserved olivine (Mark kimberlite, Canada)

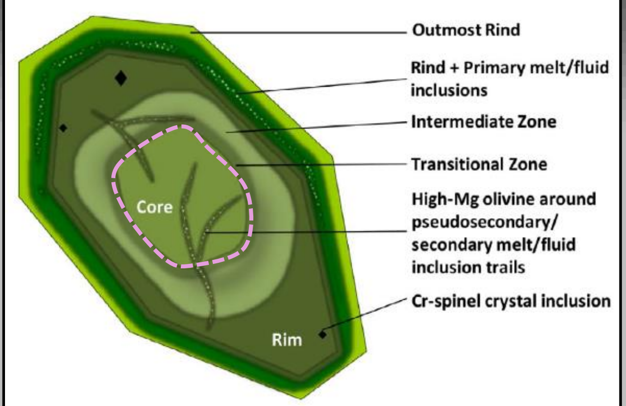


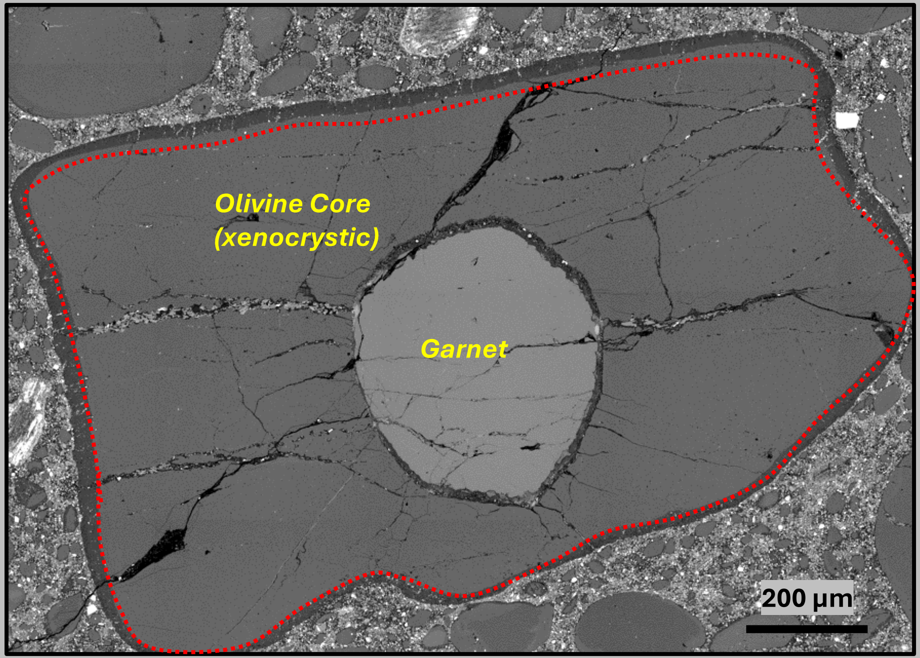
Perfectly preserved olivine (Udachnaya-East, Russia)

Primary Crystal Inclusions in Olivine Cores

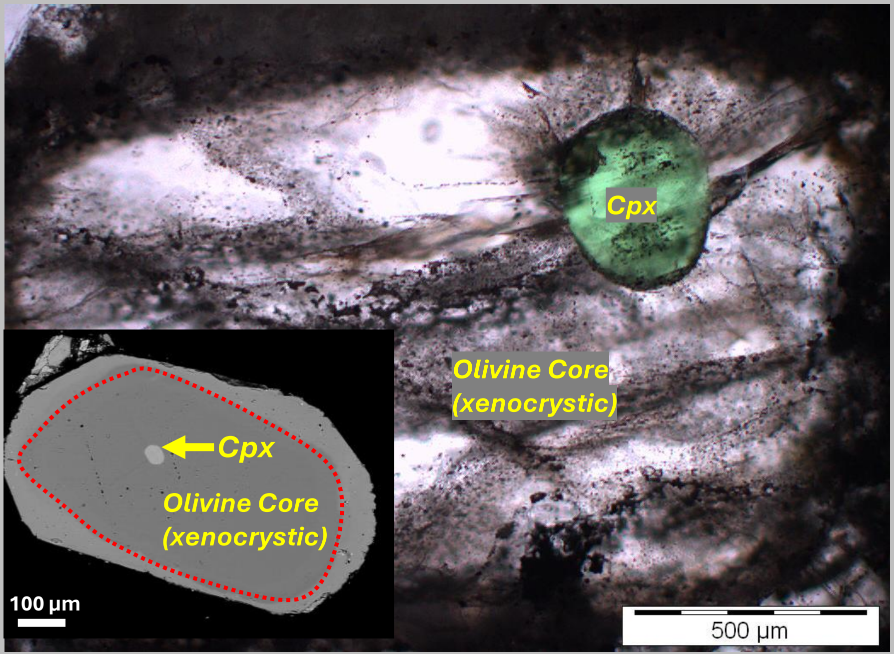
- **NO** primary melt/fluid inclusions in xenocrystic olivine cores.
- May contain crystal inclusions of other mantle minerals: Cr-diopside, enstatite, Cr-pyrope garnet, picroilmenite, sulphides.

Abersteiner et al. (2022b)





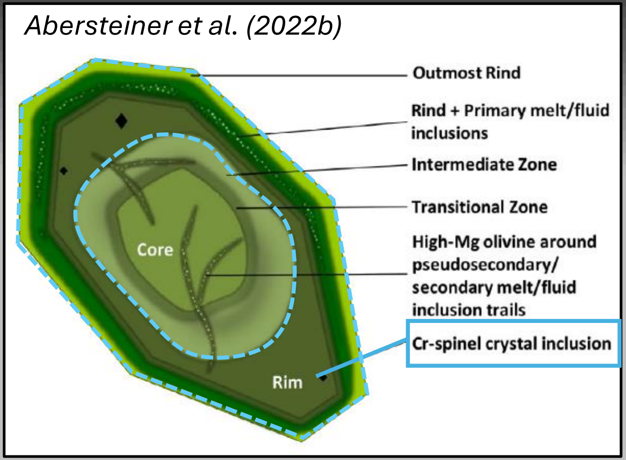
Mark kimberlite (Canda)

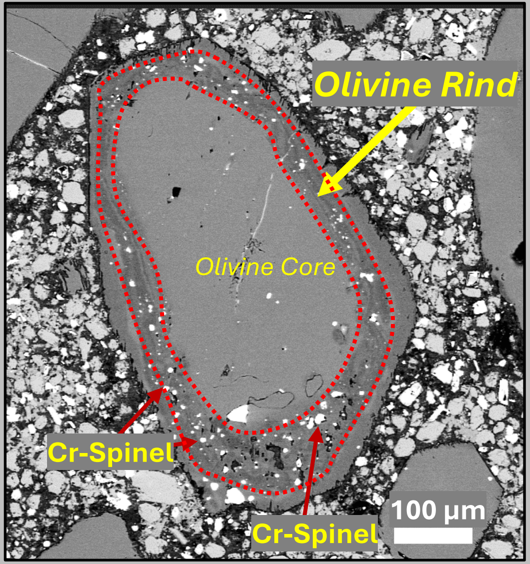


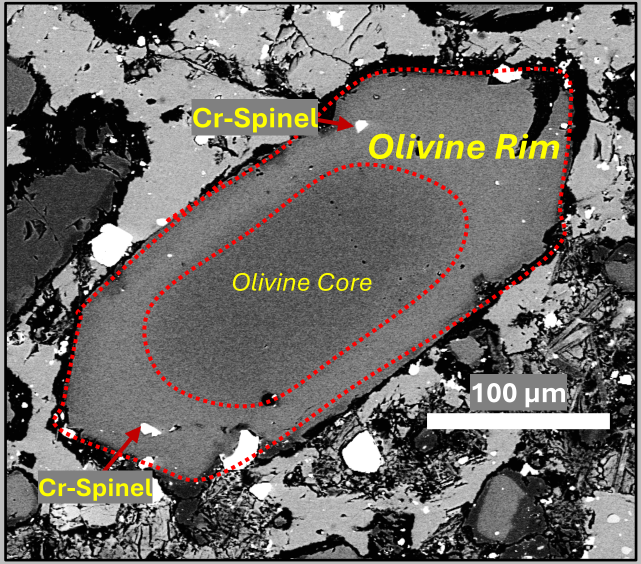
Udachnaya-East (Russia) – Kamenetsky et al. (2008)

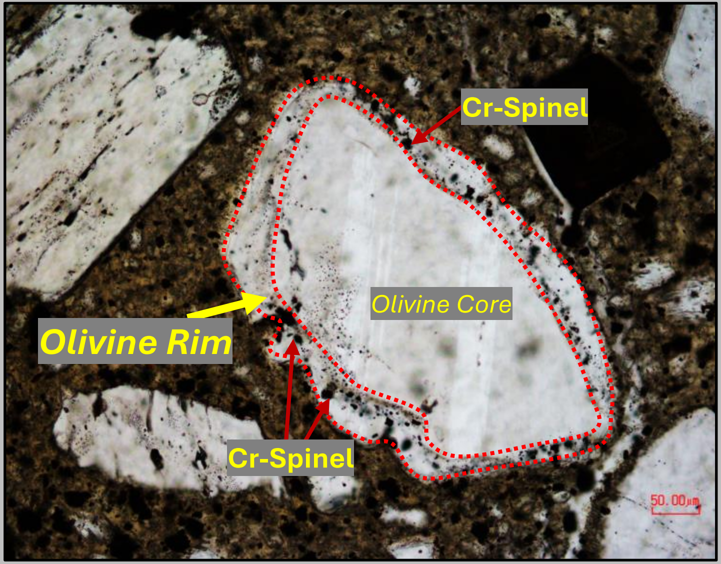
Primary Crystal Inclusions in Magmatic Olivine Zones

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



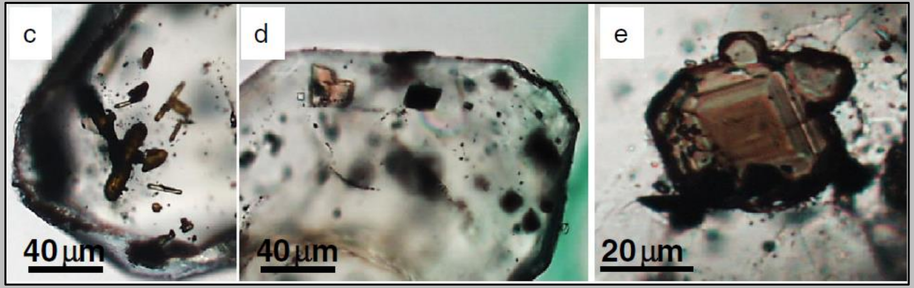






Mark kimberlite (Canda)

Mark kimberlite (Canda)



(Udachnaya-East)
Kamenetsky et al., (2012)

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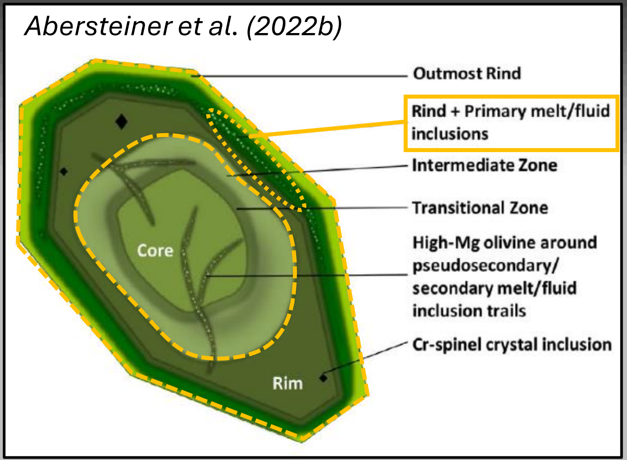
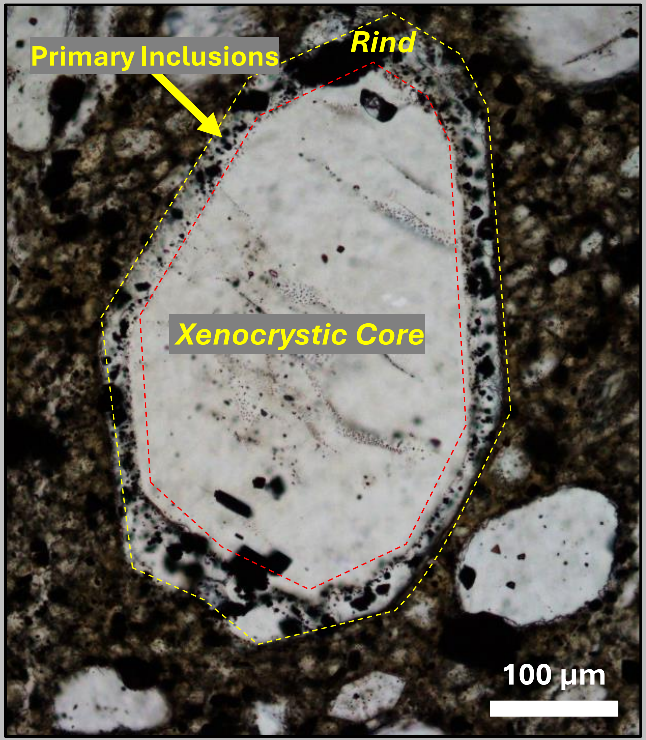
Primary Melt/Fluid Inclusions in Olivine

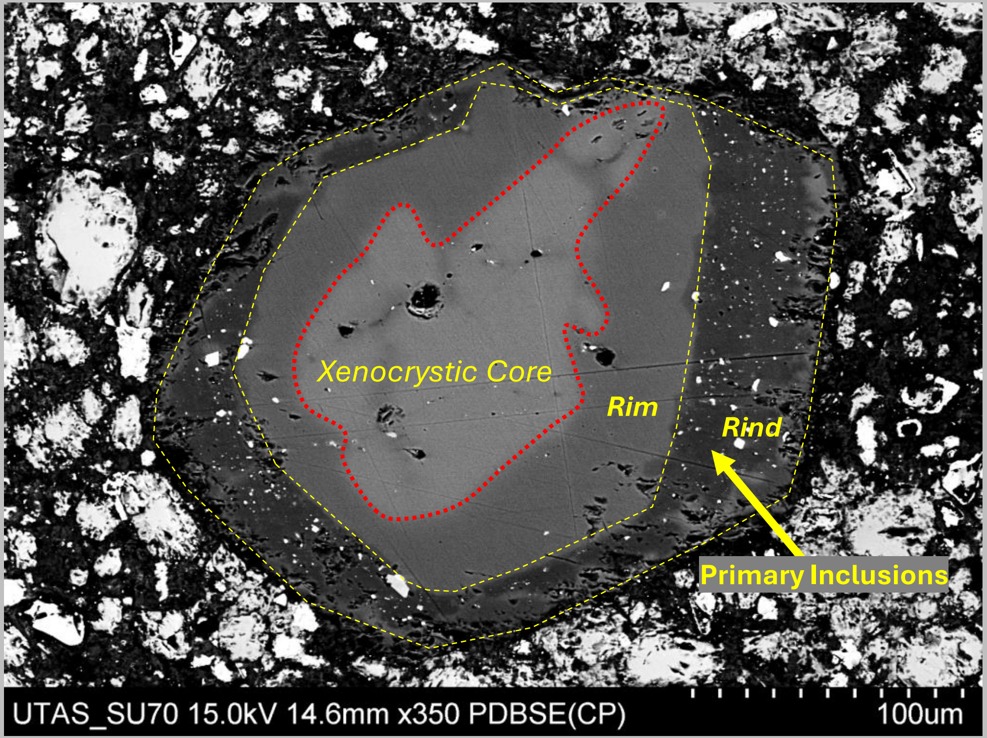
➢ Restricted to magmatic growth zones (rims, rinds).

➢ Extremely rare.



Mark kimberlite (Canda) – Abersteiner et al., (2020b)





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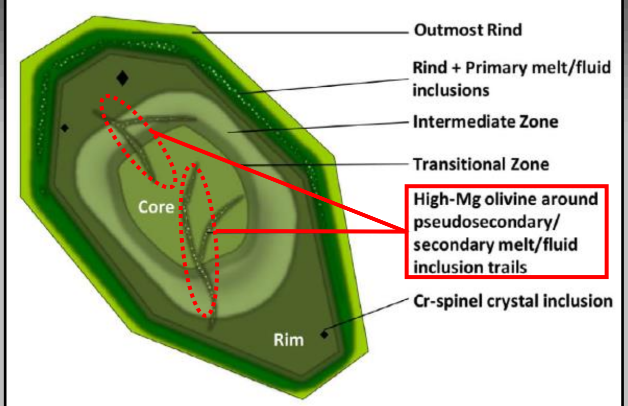
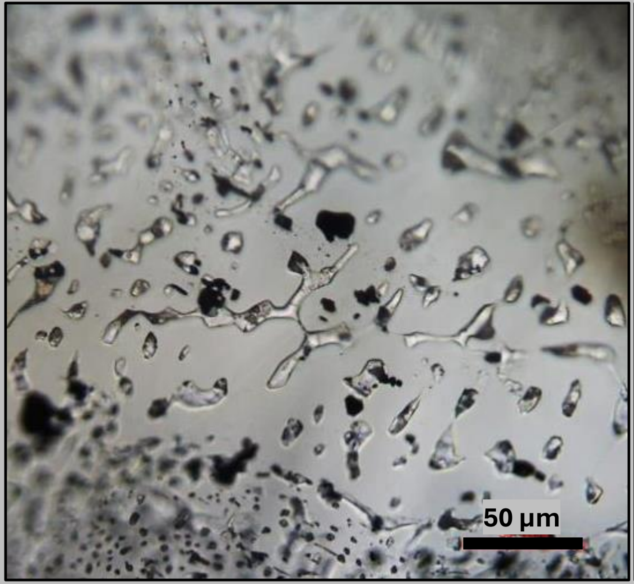
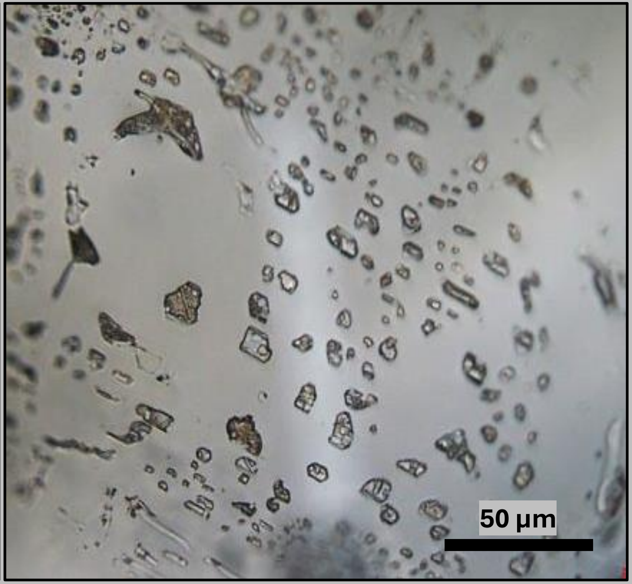
Secondary Melt/Fluid Inclusions in Olivine

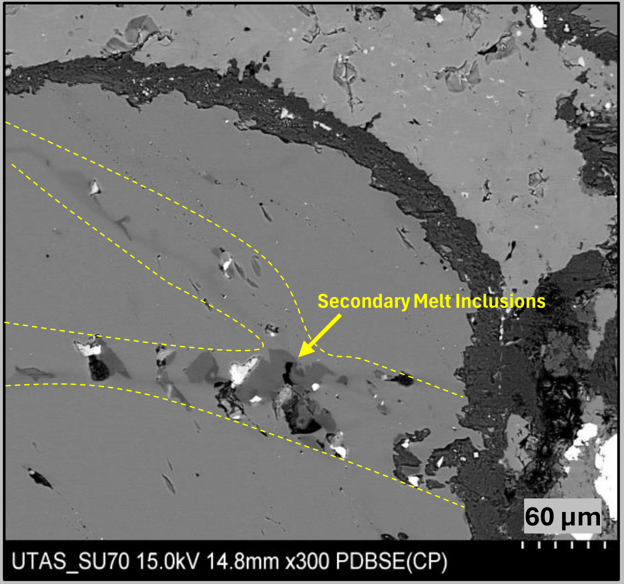
- Very common.
- Clusters of inclusions are aligned along fractures and planes + cross-cut olivine zones.
- Typically interconnected by thin channels, indicating potential modification by 'necking down'.

Abersteiner et al. (2022b)







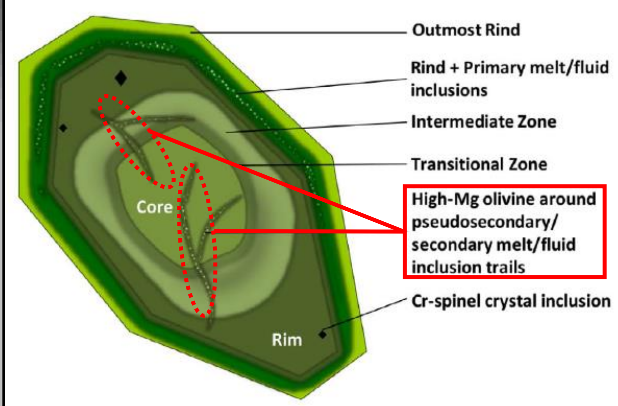


Udachnaya-East (Russia) - Abersteiner et al., (2018)

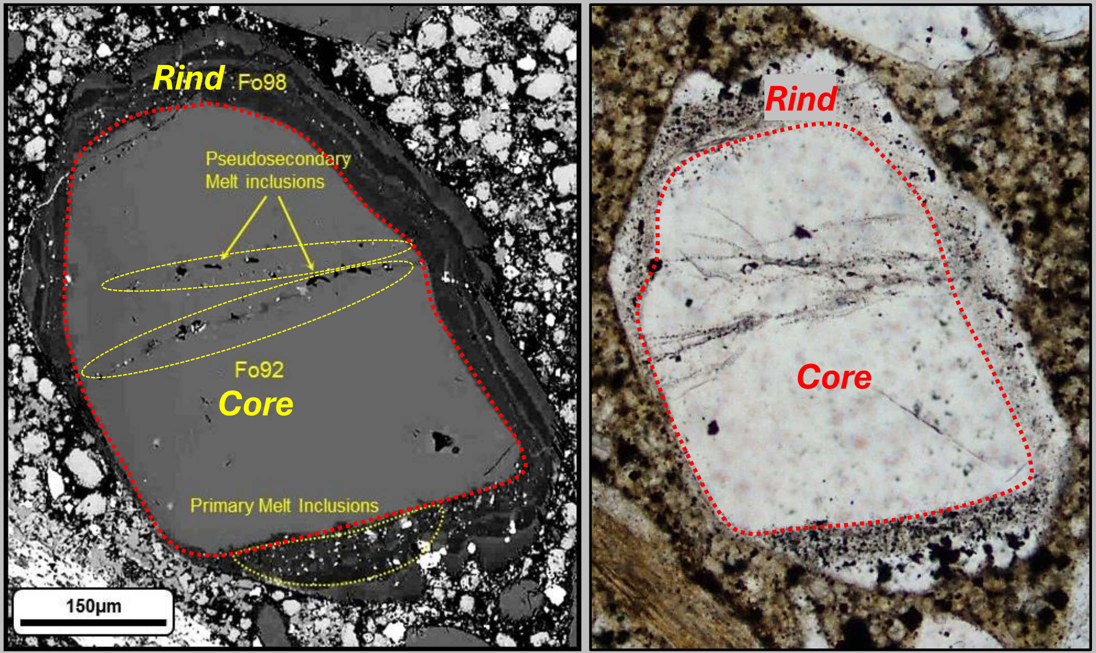
Pseudosecondary Melt/Fluid Inclusions in Olivine

- 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.

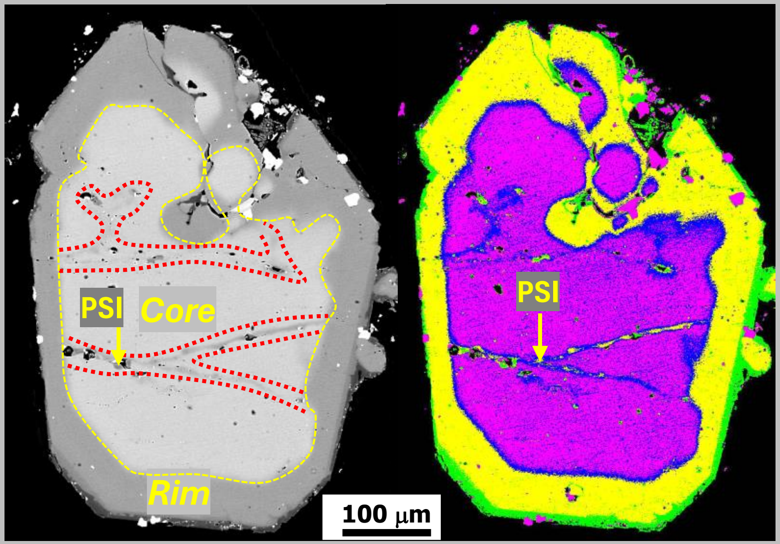
Abersteiner et al. (2022b)



PSI trails in olivine core terminate at the olivine rim boundary

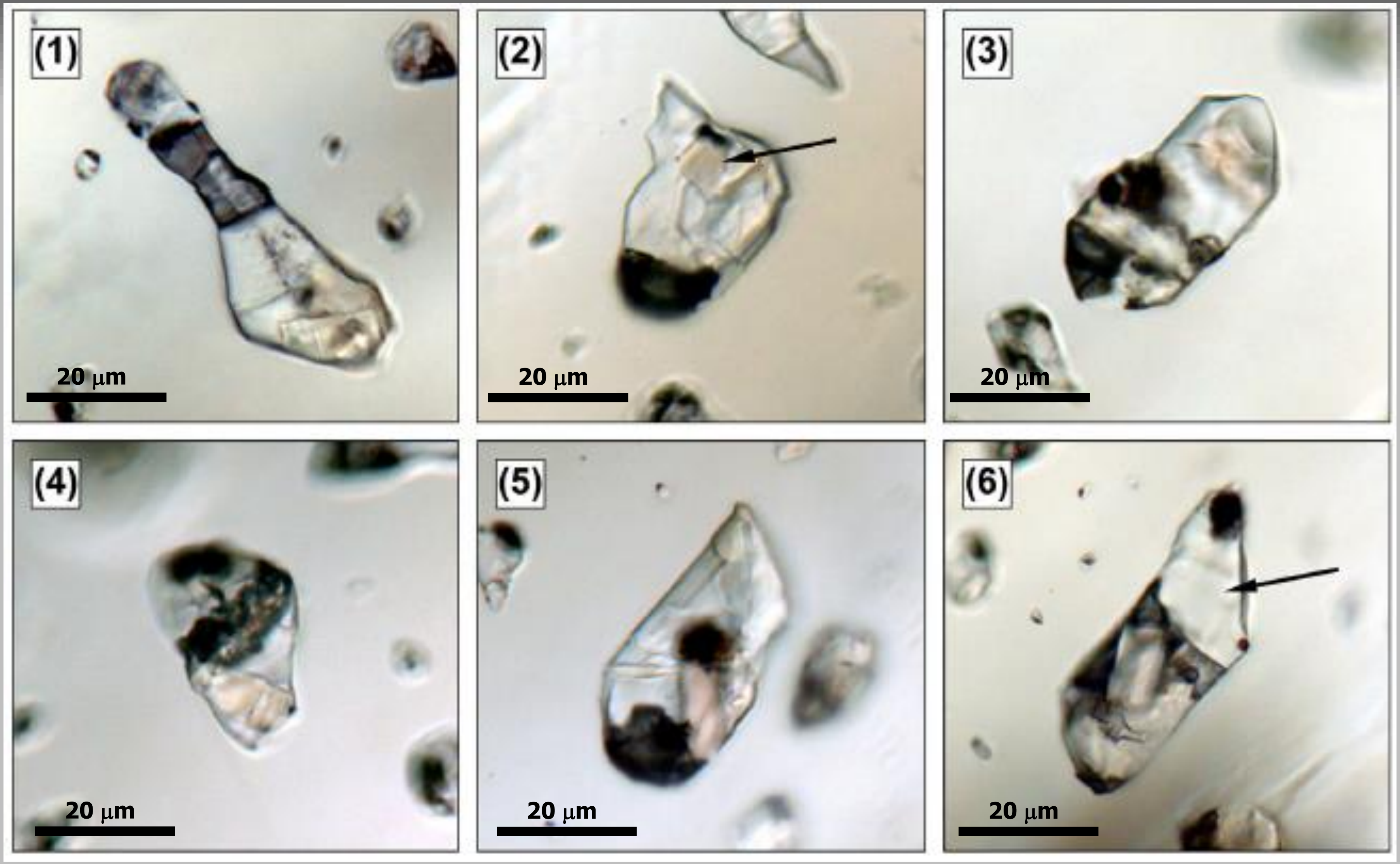


Mark kimberlite (Canada) - Abersteiner et al., (2020b)



Pseudosecondary Inclusion (PSI) trails in olivine (Udachnaya-East) Kamenetsky et al. (2008)

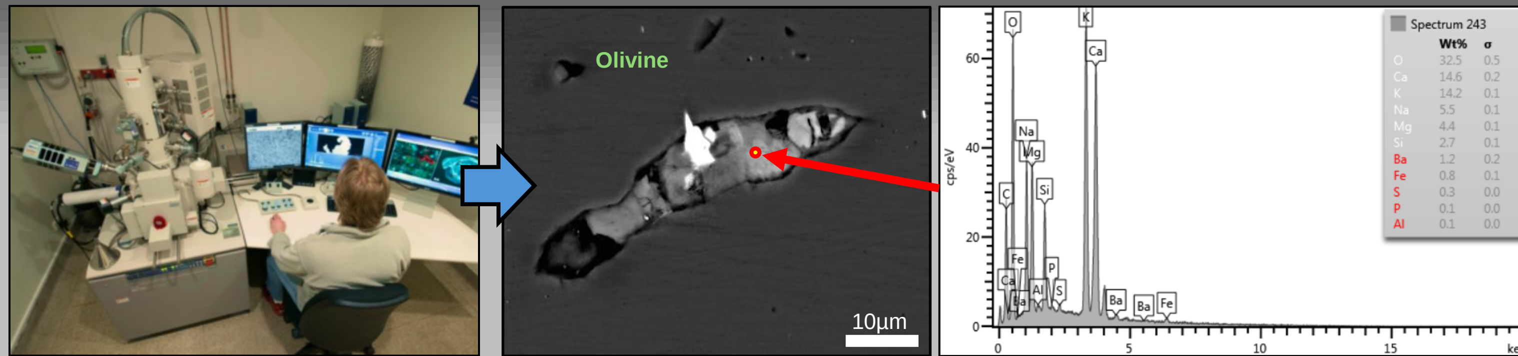
What's Inside Melt/Fluid Inclusions in Olivine?



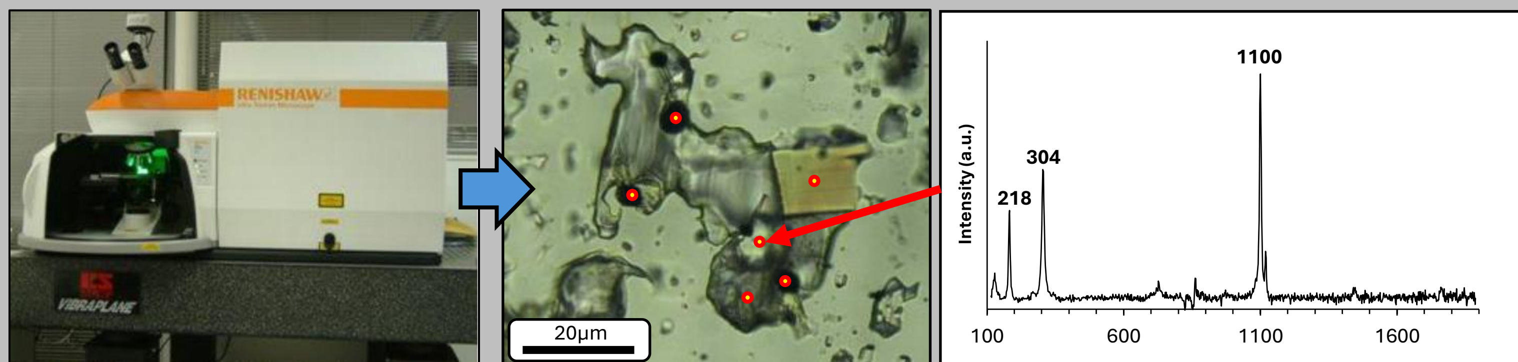
Golovin et al. (2020) – Unexposed secondary melt inclusions in olivine from a sheared garnet harzburgite xenolith (Udachnaya-East kimberlite)

Methods of analysis

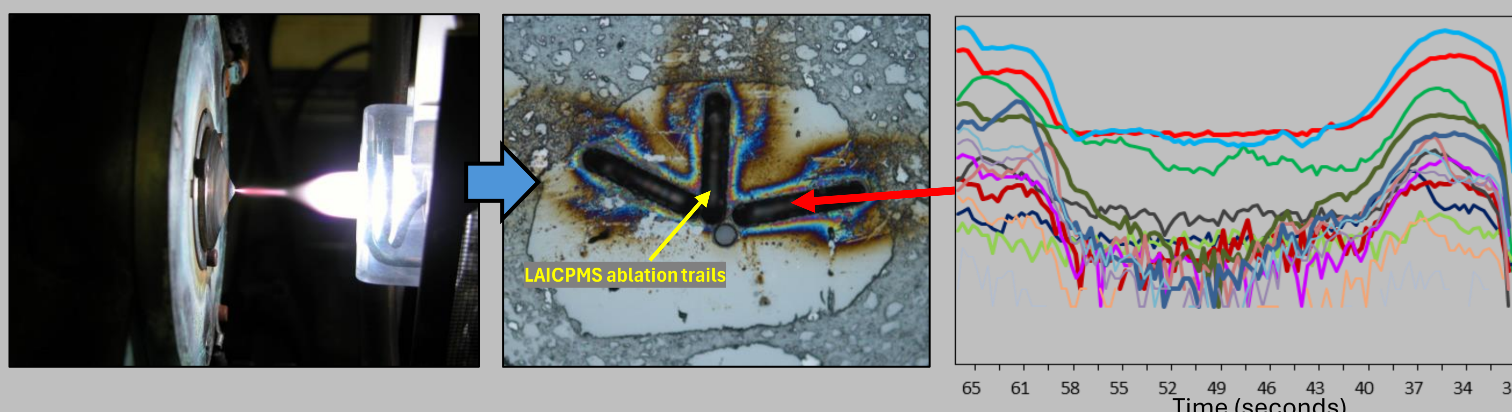
Scanning Electron Microscope



Raman Spectroscopy

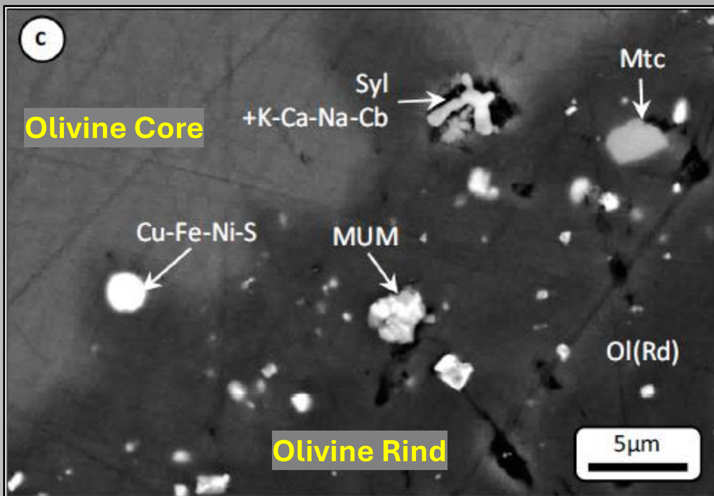


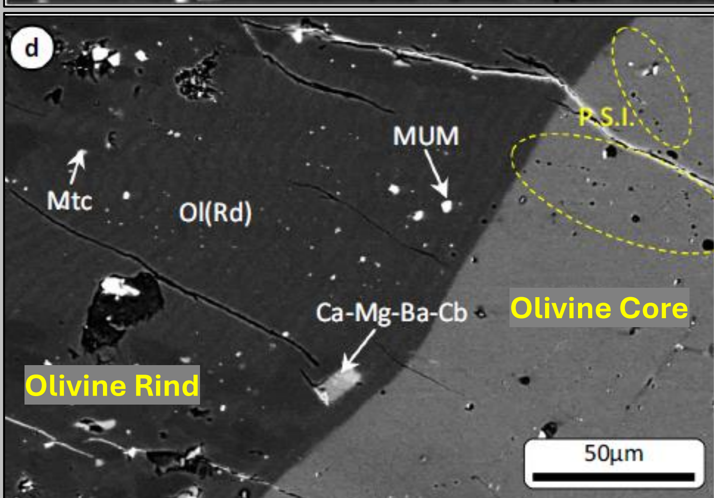
LA-ICPMS



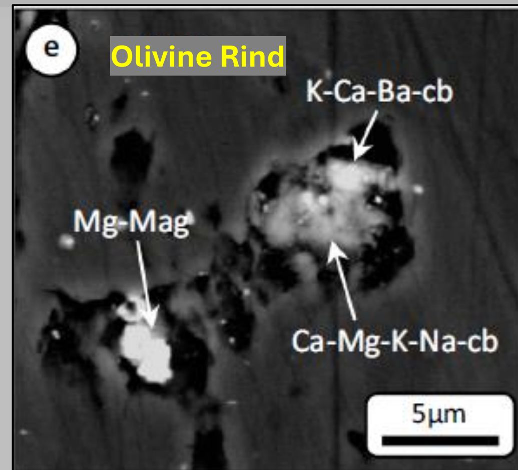
SEM-EDS Analysis of Melt Inclusions in Olivine

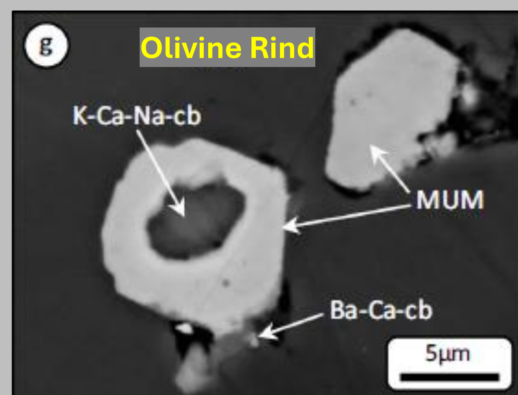
Primary Melt Inclusions in Olivine



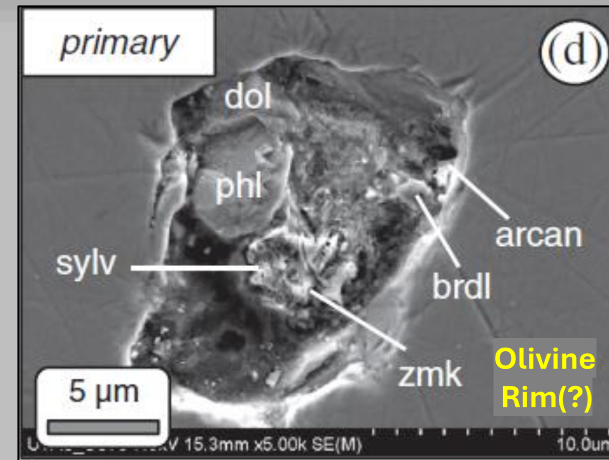


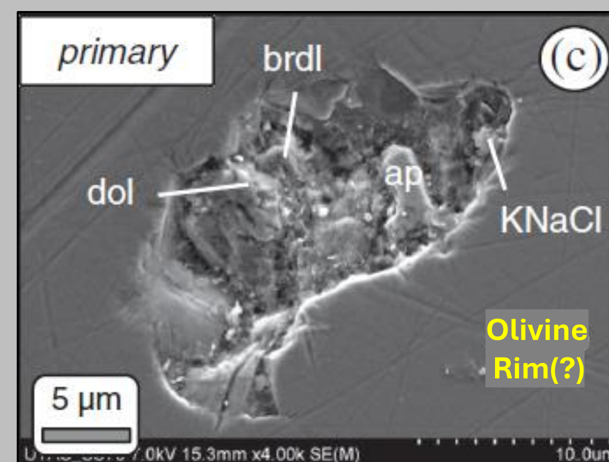
Mark kimberlite
Abersteiner et al. (2020b)





Mark kimberlite
Abersteiner et al. (2020b)





Bultfontein kimberlite
Giuliani et al. (2017)

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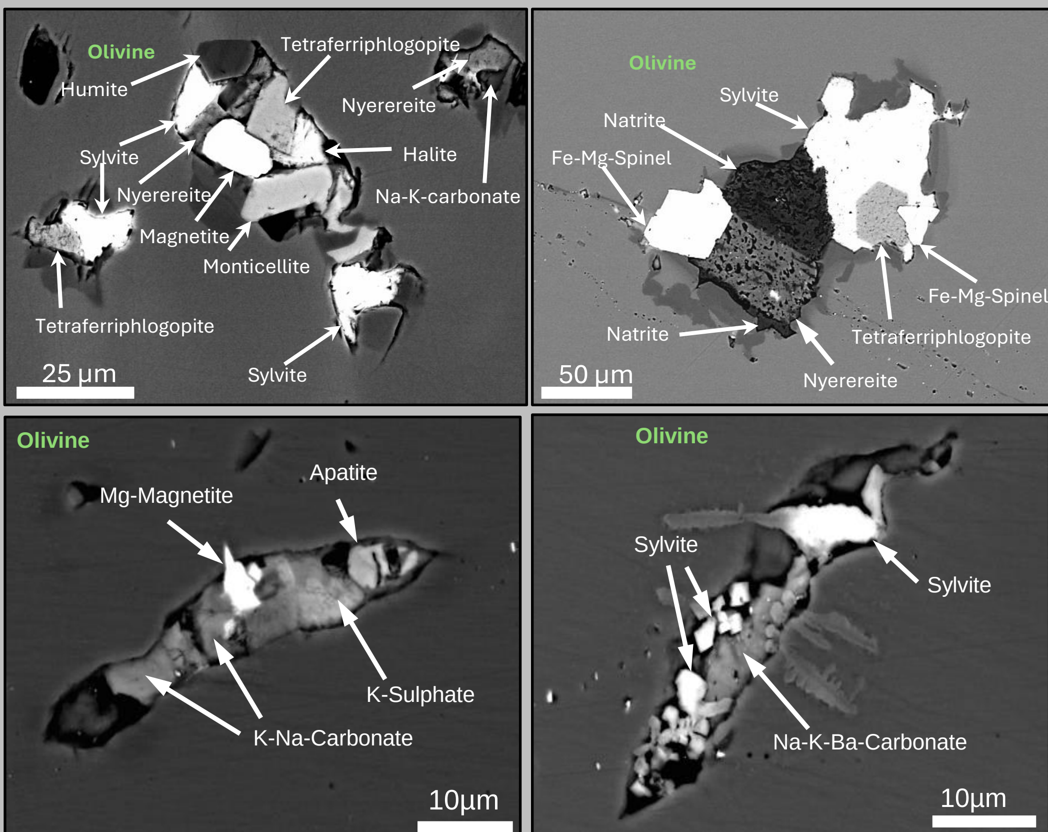
MUM: Magnesio-ulvospinel-magnetite, Mtc: Monticellite, Cb: Carbonate, Syl(v): Sylvite, S: Sulphide, Mag: Magnetite, Phl: Phlogopite, dol: dolomite, brdl: Bradleyite, Ap: Apatite, Arcan: Arcanite, Cl: Chloride

SEM-EDS Analysis of Melt Inclusions in Olivine

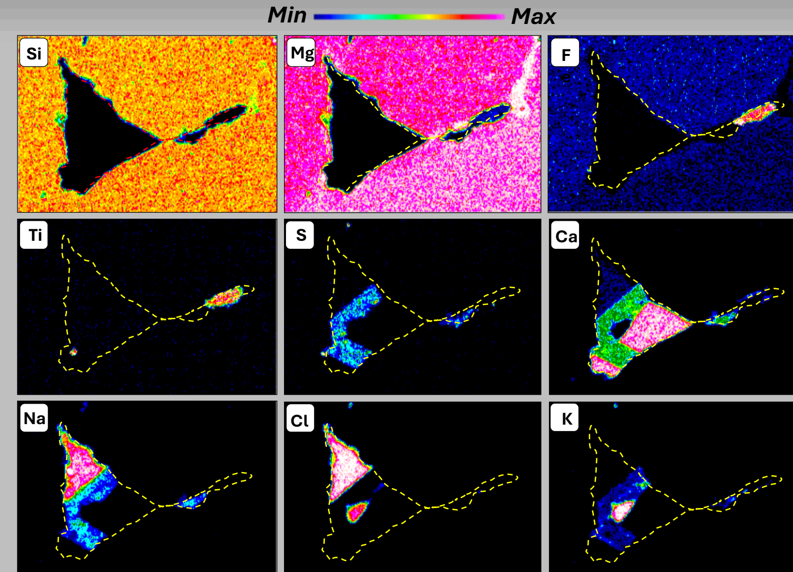
Secondary/Pseudosecondary Melt Inclusions in Olivine

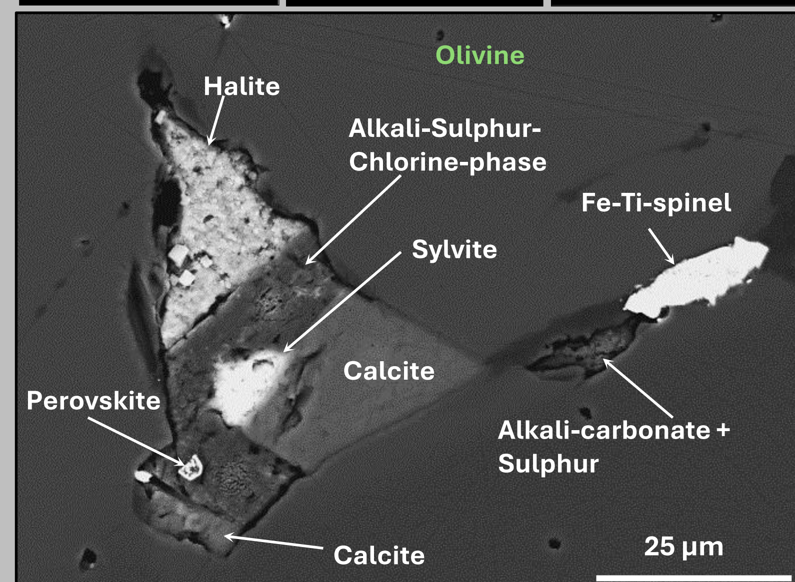
- Backscatter electron SEM images with point analyses and X-ray element maps on melt inclusions in kimberlitic olivine.



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

EDS X-ray element map





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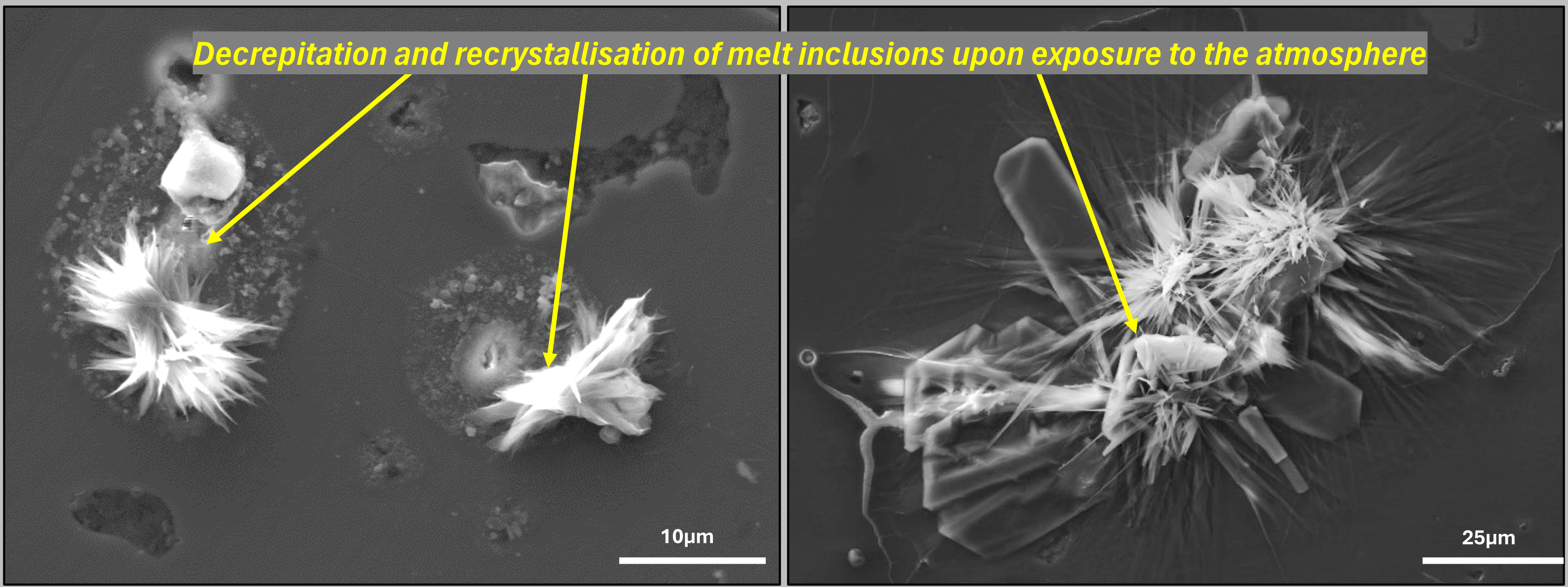
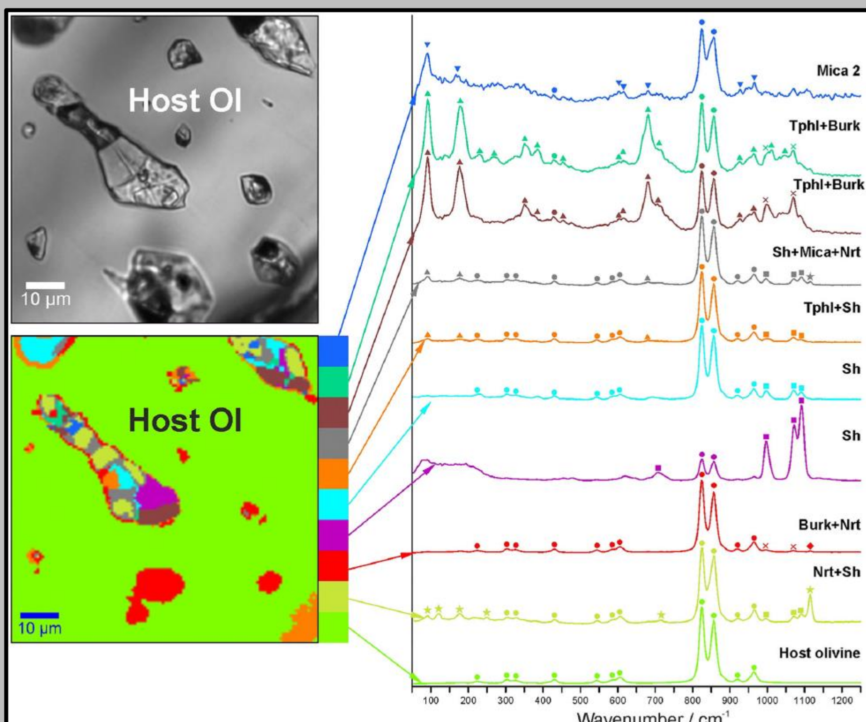
Considerations!

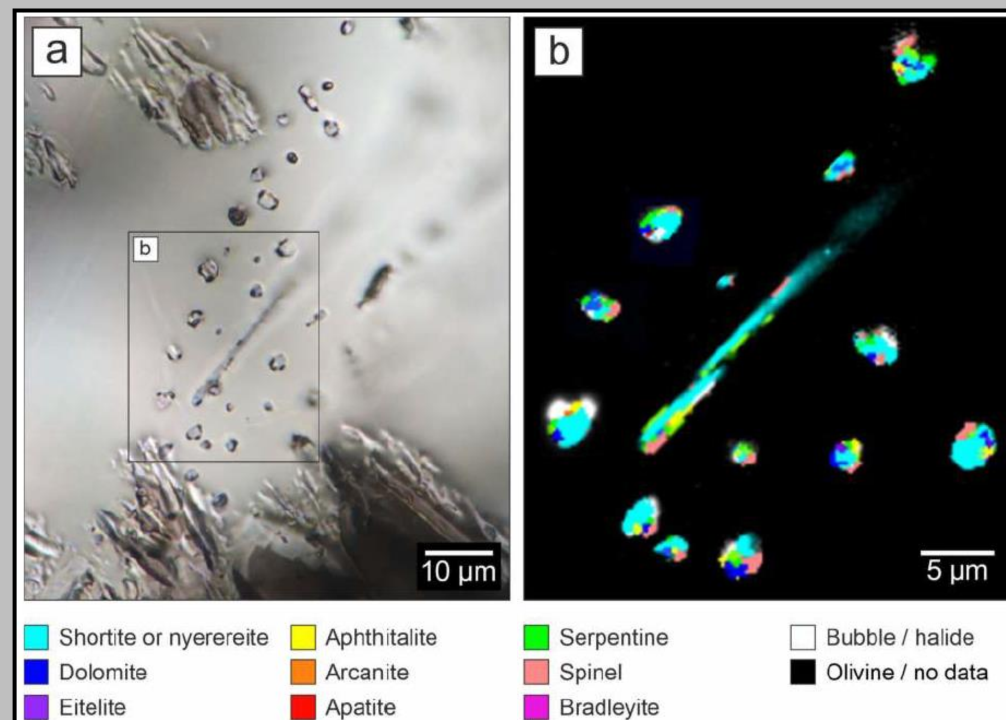
- Instability of daughter phases in melt inclusion.
- Loss of fluids/volatiles upon exposure.
- Electron beam damage.



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.

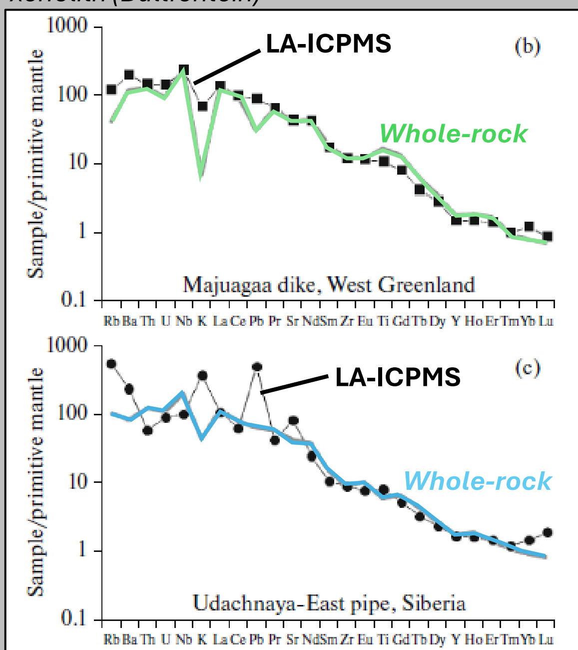




Golovin et al., (2020) – Unexposed melt inclusions in olivine from a kimberlite-hosted peridotite xenolith.

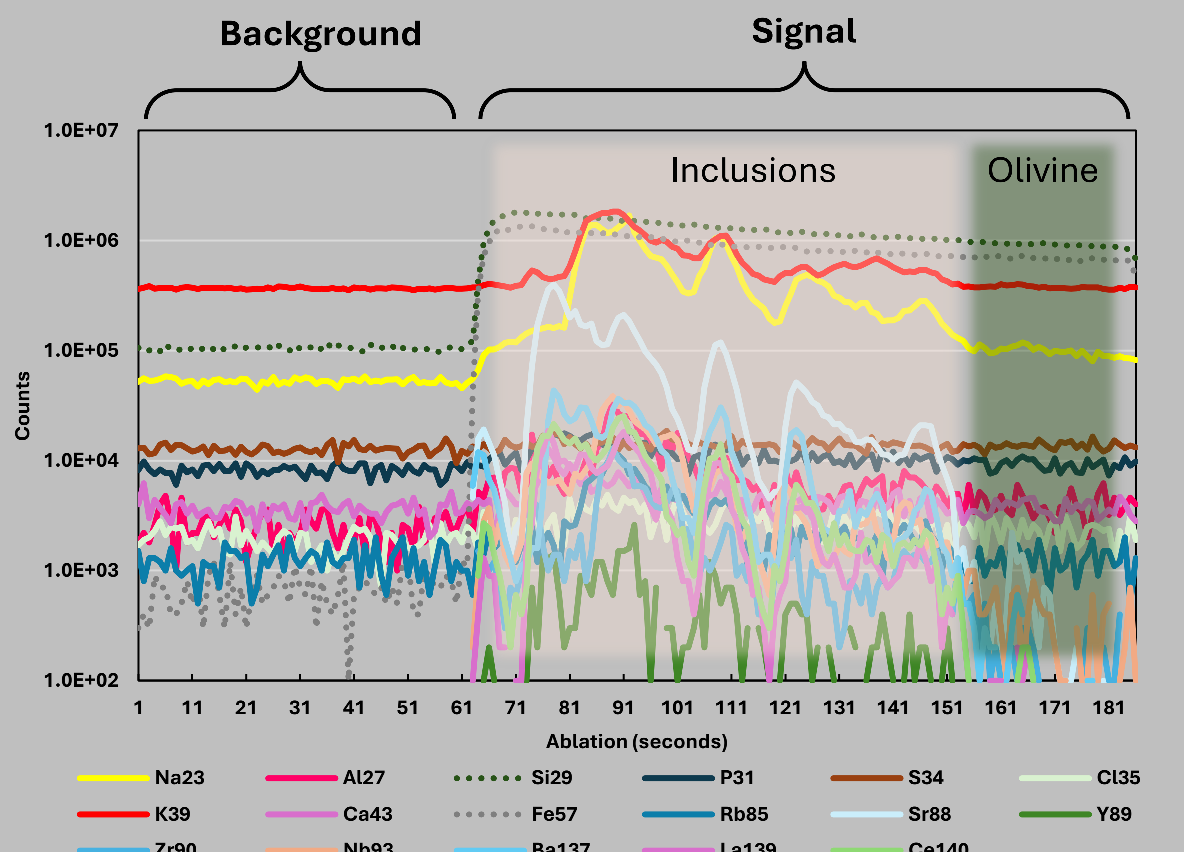
LA-ICPMS Analysis of Melt/Fluid Inclusions in Olivine

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



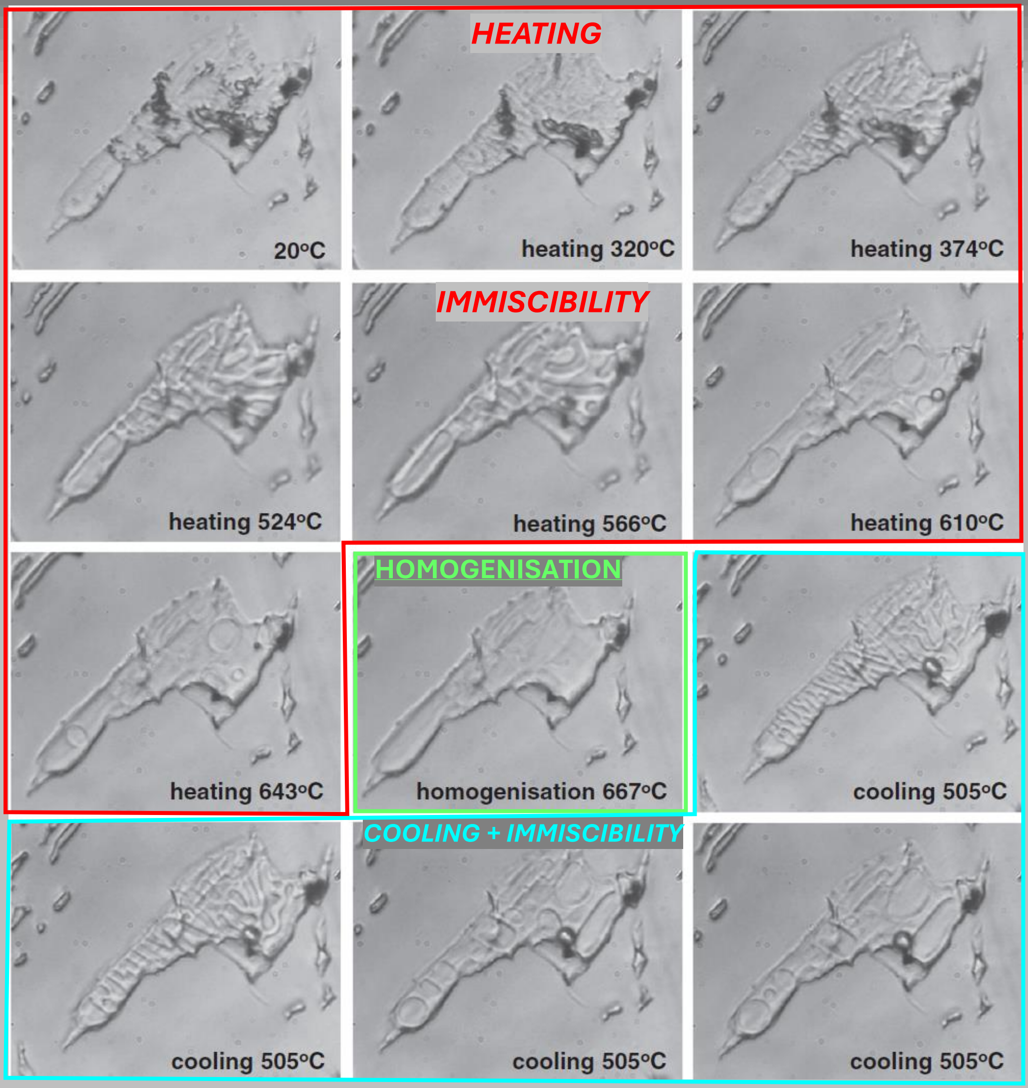
(Kamenetsky et al. 2009)

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



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

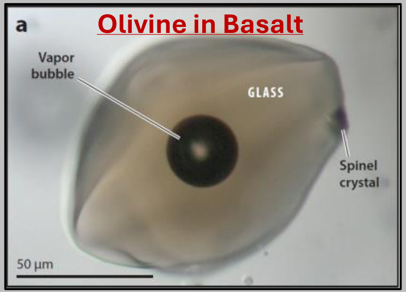
Experimental Heating/Cooling of Melt/Fluid Inclusions in Olivine



Kamenetsky et al., (2013) – Melt inclusion in olivine (Koala kimberlite, Canada)

- **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

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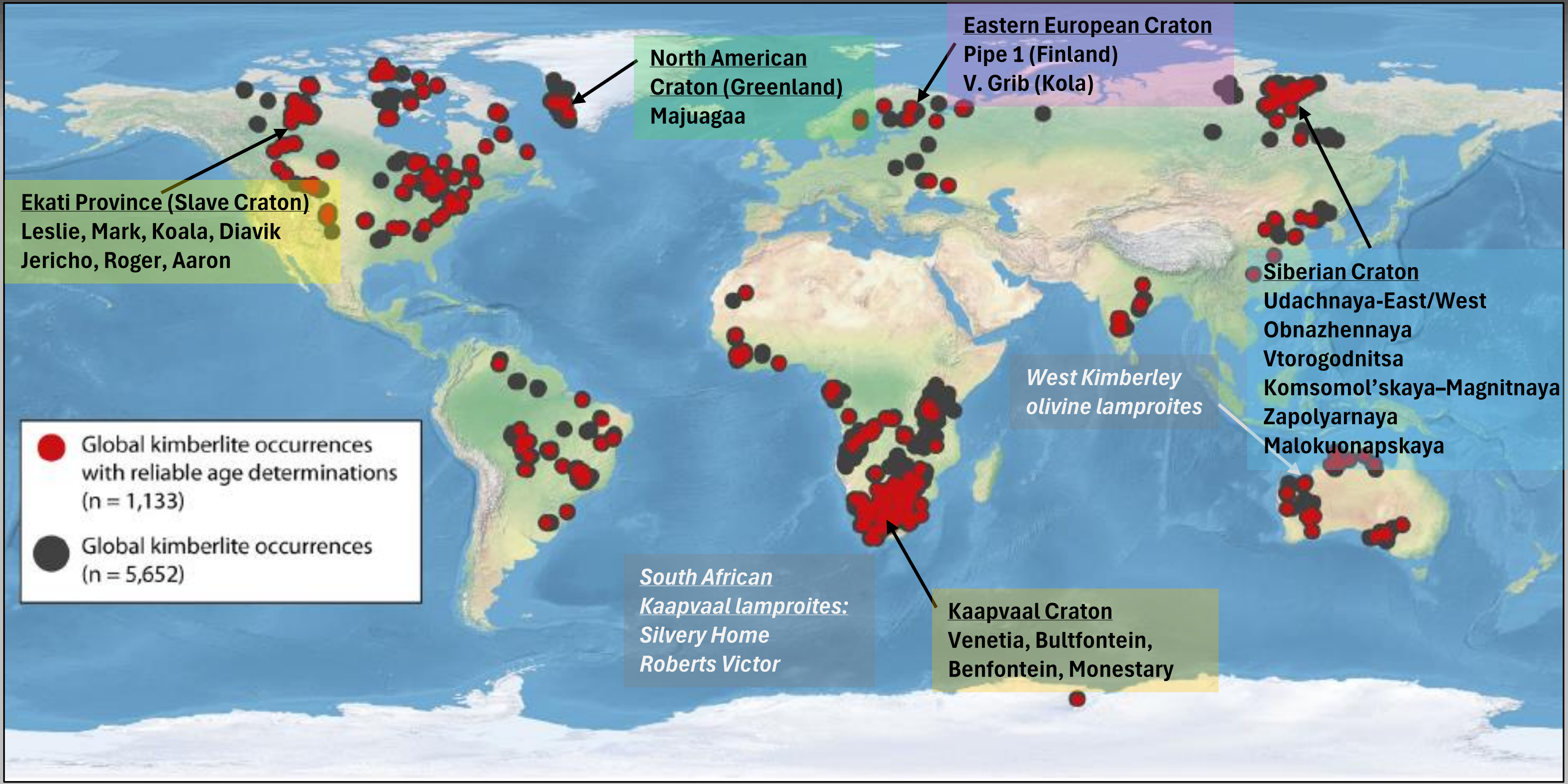
Studies of Melt/Fluid Inclusions in Olivine



Tappe et al. (2018)

- 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_2).
- No aqueous fluid or silicate glass found.
- More than >60 mineral species identified (Golovin and Kamenetsky, 2023).

Daughter Mineral Assemblages

Dominated by:

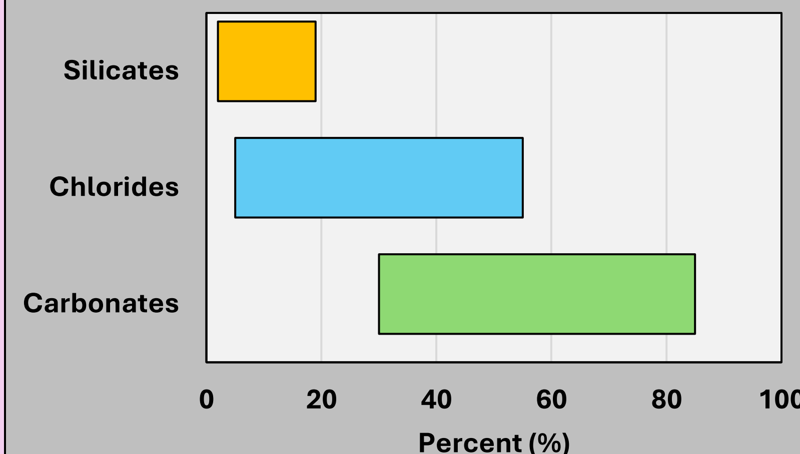
Carbonates *(alkali/alkali-earth-bearing Ca-Mg-Na-K-(Ba-Sr))*

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)*

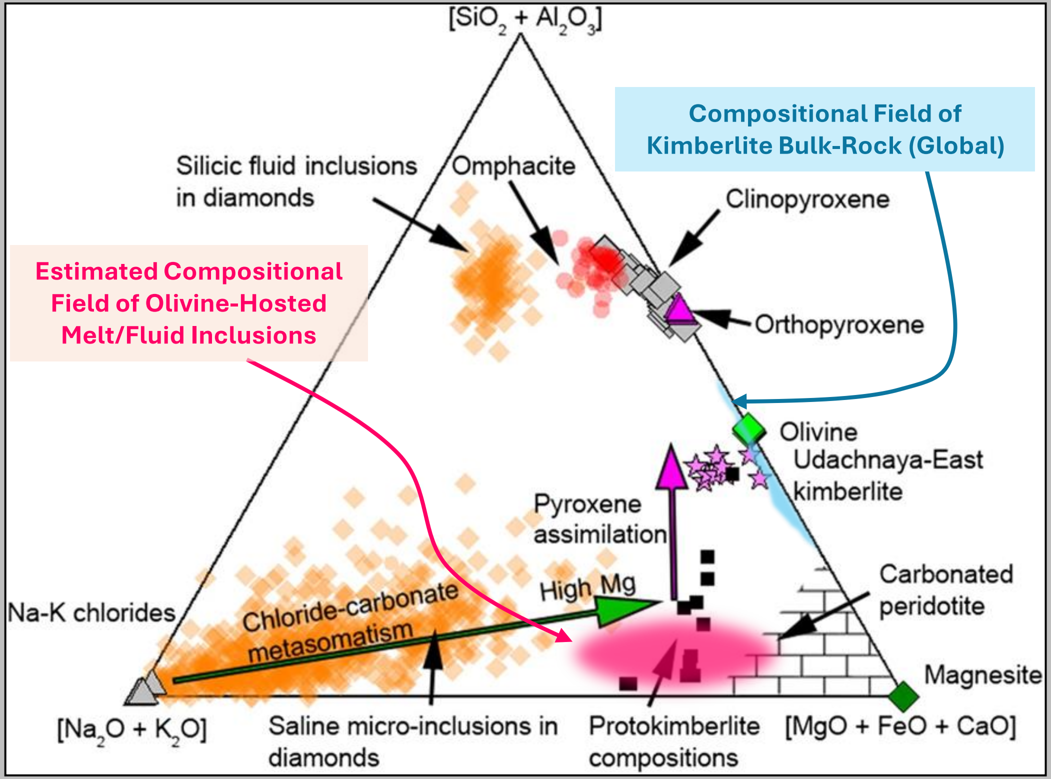


Upper and lower estimates of silicates, chlorides and carbonates in olivine-hosted melt inclusions from kimberlites
(Golovin and Kamenetsky, 2023 + references therein)

Significance of Melt/Fluid Inclusions in Olivine

- Primary + Secondary + Pseudosecondary Melt Inclusions = Same compositions
- Melt Inclusions are enriched in Na_2O, K_2O, CaO, CO_2 and Cl, contain low-to-moderate MgO and SiO_2 and depleted in H_2O.

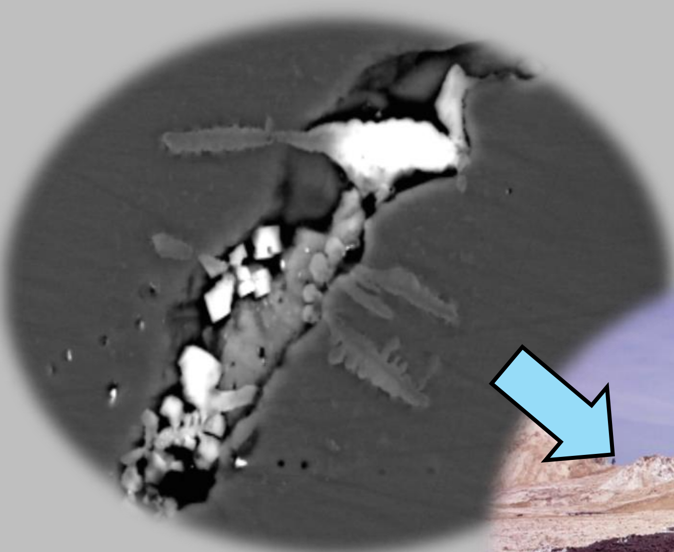
The composition of melt inclusions is in stark contrast to the kimberlite bulk-rock.



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_2O-poor** compared to kimberlite bulk-rock.



Melt Inclusions look more like carbonatites...

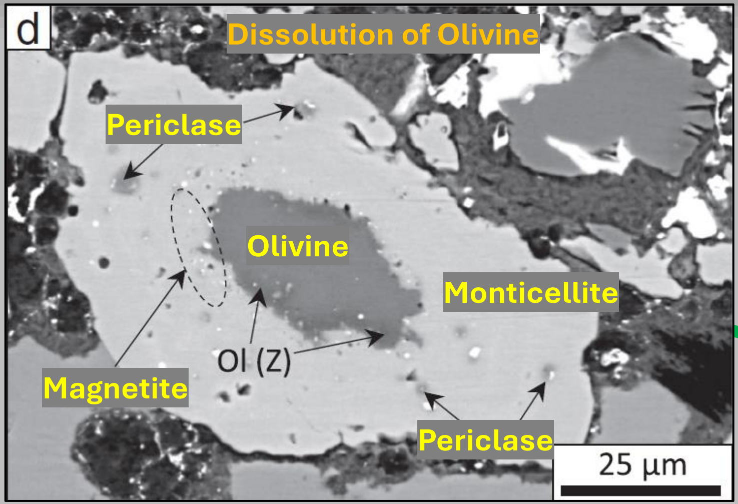
Oldoinyo-Lengai natrocarbonatite lavas (Tanzania)

Global Kimberlite Bulk Rock Averages

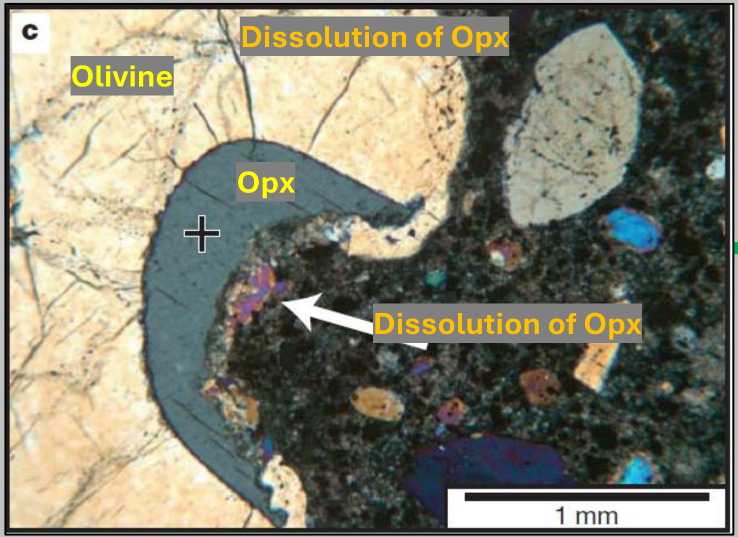
	wt.%
SiO_2	~25-35 ↓
TiO_2	~1-3
MgO	~25-35 ↓
CaO	~12-20 ↑
Al_2O_3	~1-3
FeO	~6-10
K_2O	~0.3-2 ↑
Na_2O	<0.1-0.3 ↑
P_2O_5	~0.5-2 ↑
Cl	<0.1 ↑
F	<0.1 ↑
H_2O	~5-8 ↓
CO_2	~8-13 ↑

Evolution of Kimberlite Melts

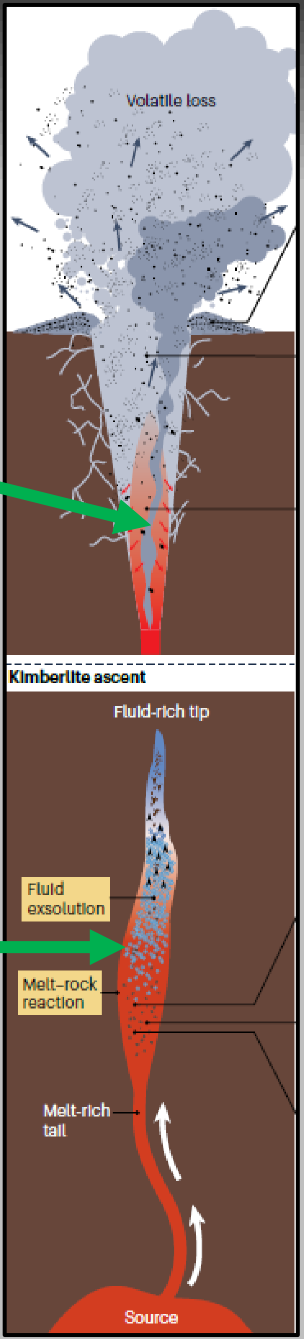
- Assimilation of mantle silicates (e.g., orthopyroxene) by carbonate-rich melt drives CO_2 exsolution and **increases the ultramafic-silicate component** of kimberlite melts.
- Decarbonation reactions as a driver of kimberlite magma ascent?
- **Carbonates + alkalis, halogens, P, S lost** during kimberlite magma ascent + emplacement due to exsolution and alteration.



Abersteiner et al. (2018c)



Modified from Russell et al. (2012)



Modified from Giuliani et al. (2023)

Thank you for your attention!

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Questions?

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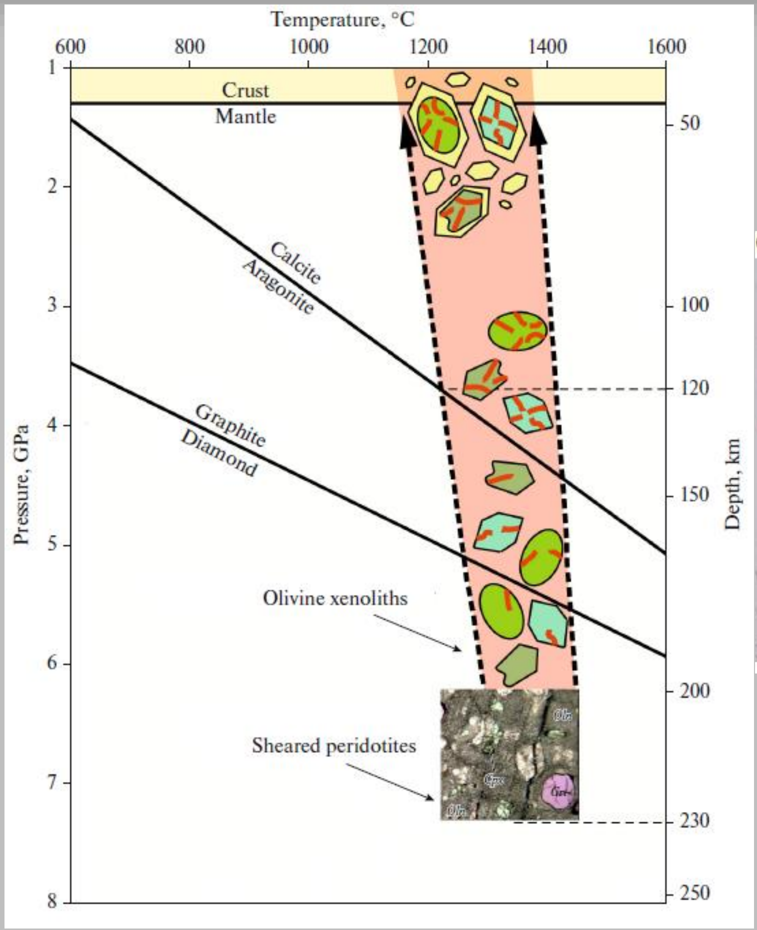
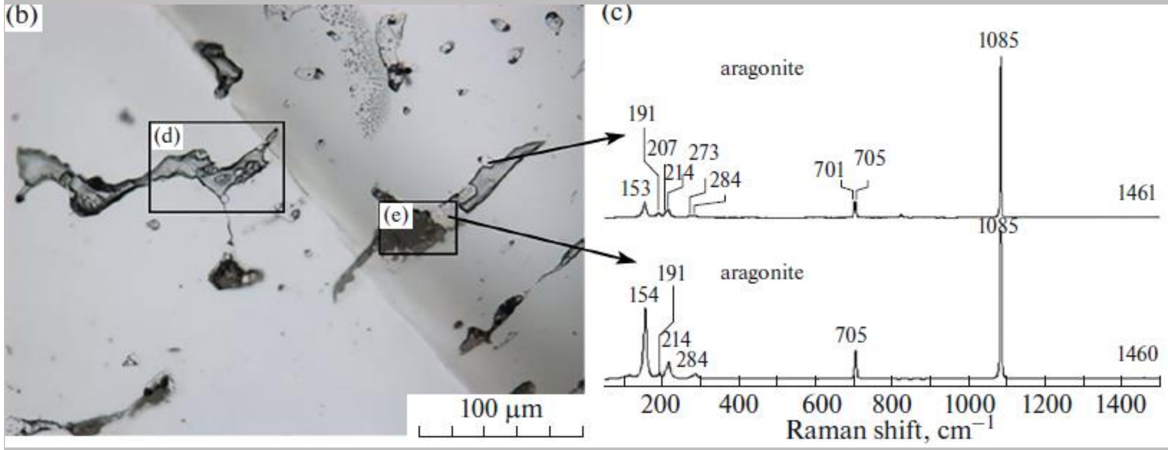
Supplementary Slides

Aragonite in MI – Evidence for Deep Entrapment?



Golovin and Kamenetsky (2023)

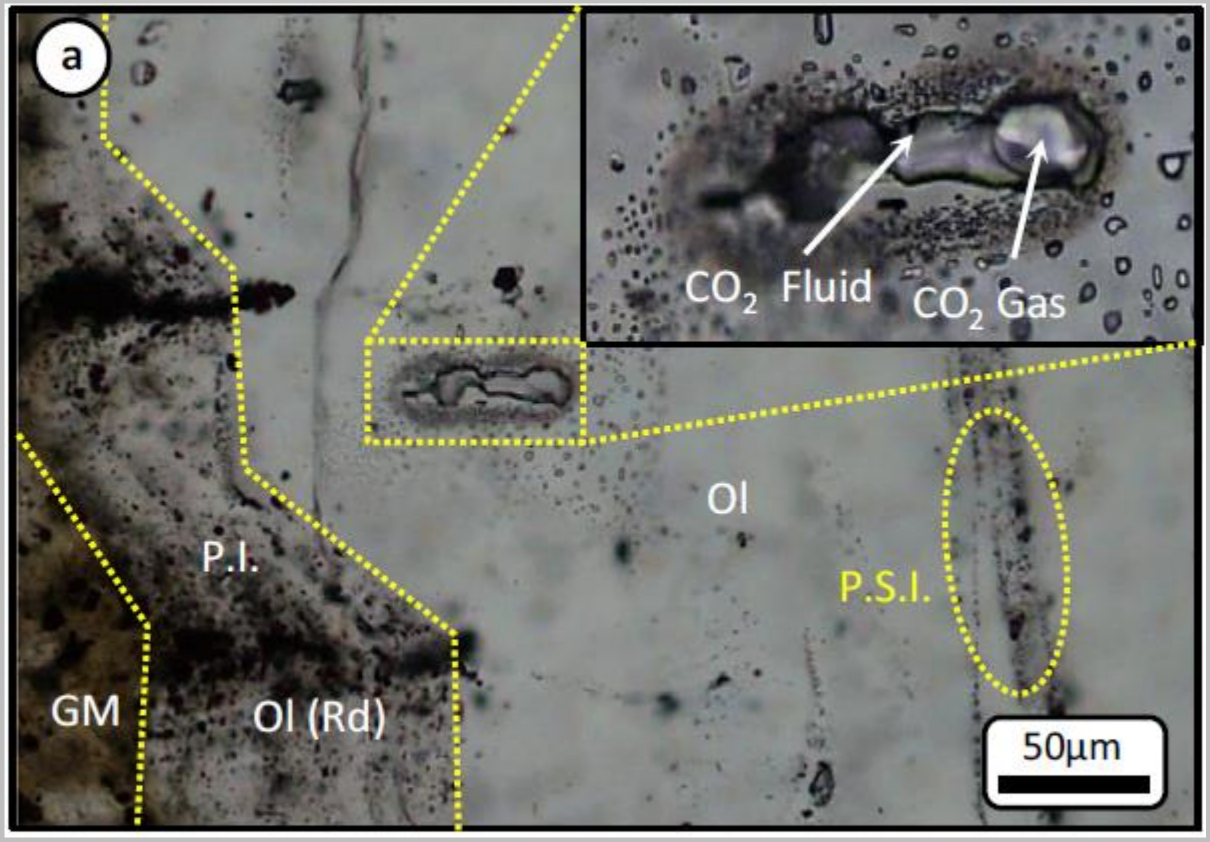


- Aragonite in olivine-hosted melt inclusions in sheared peridotites.
- Aragonite is a high-pressure polymorph of $CaCO_3$

Constraints on Deep Crustal Entrapment?

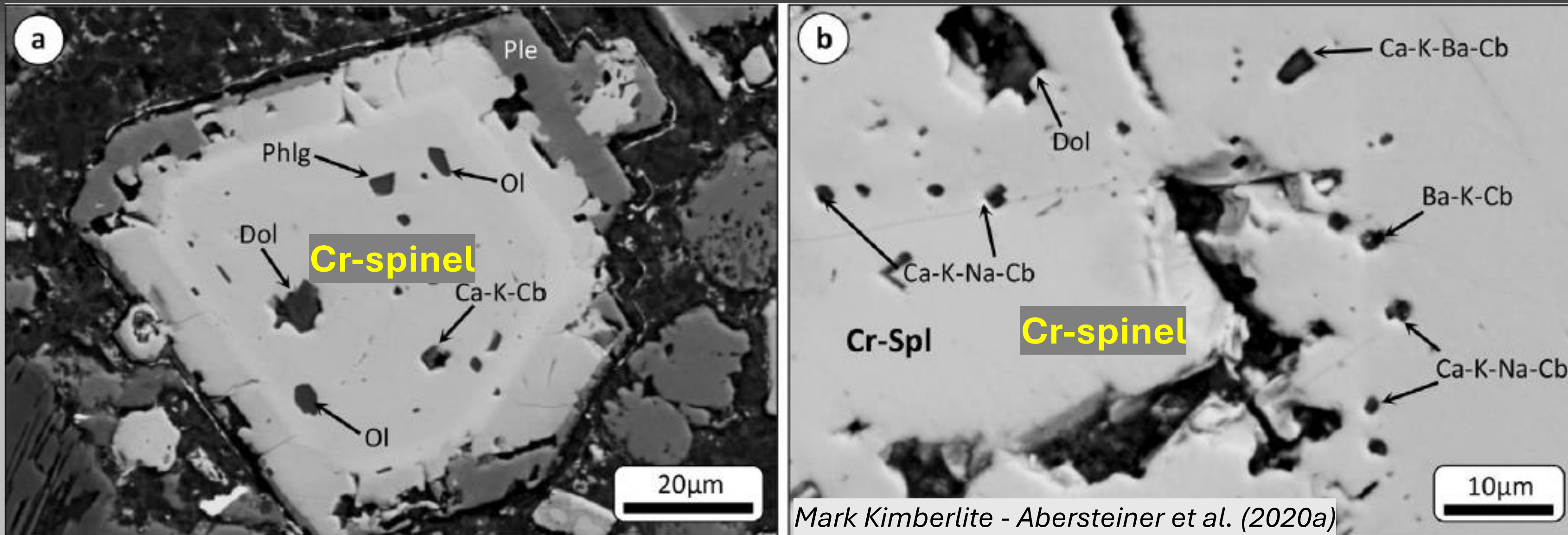
- Pseudosecondary melt/fluid inclusions containing CO_2 (Mark kimberlite, Canada).

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

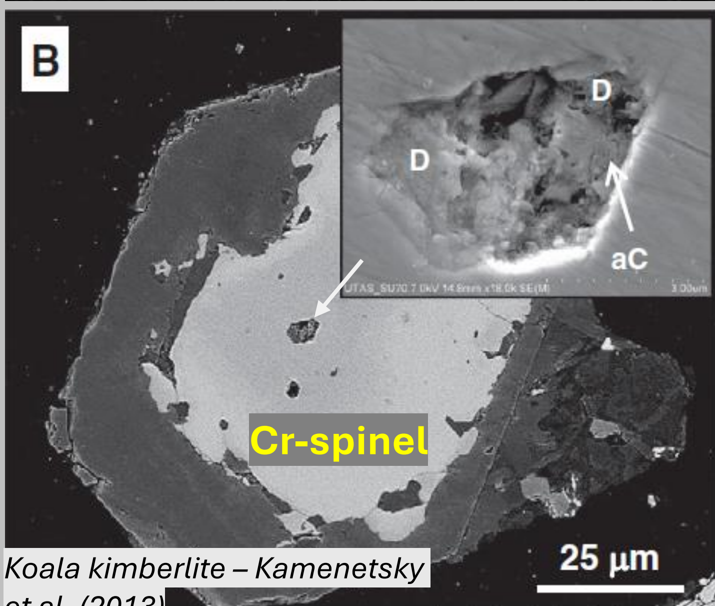


Abersteiner et al. (2020a)

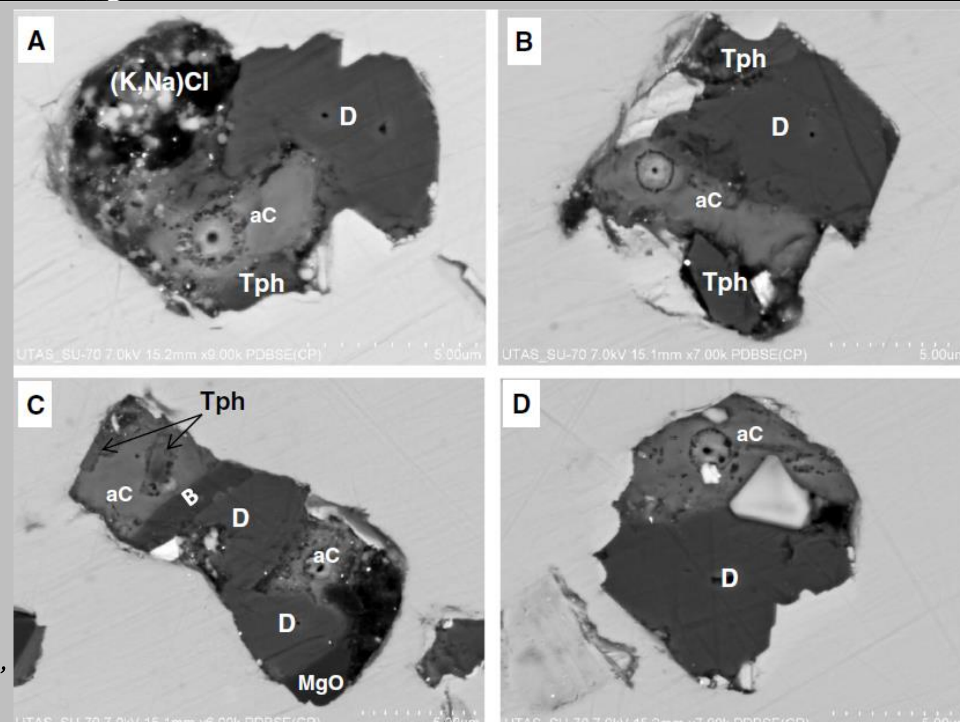
Cr-spinel hosted Melt Inclusions



Mark Kimberlite - Abersteiner et al. (2020a)



Koala kimberlite – Kamenetsky et al. (2013)



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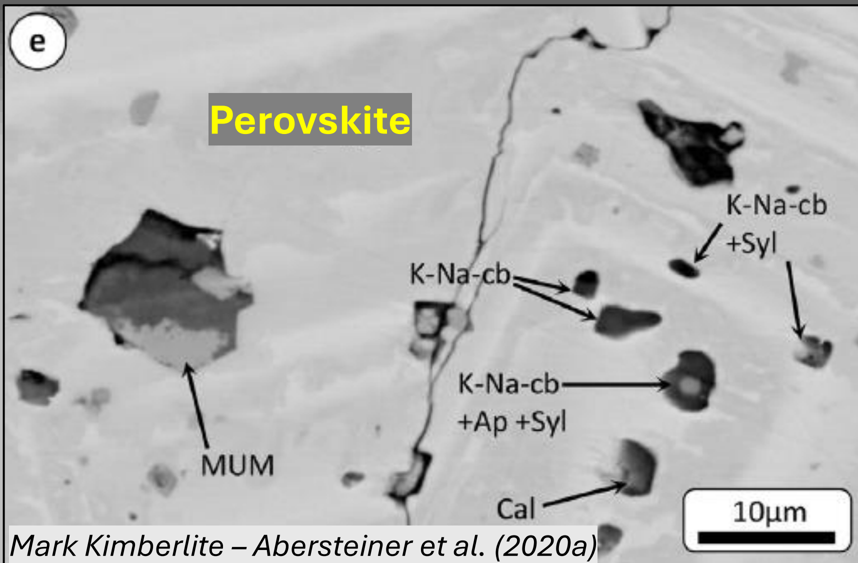
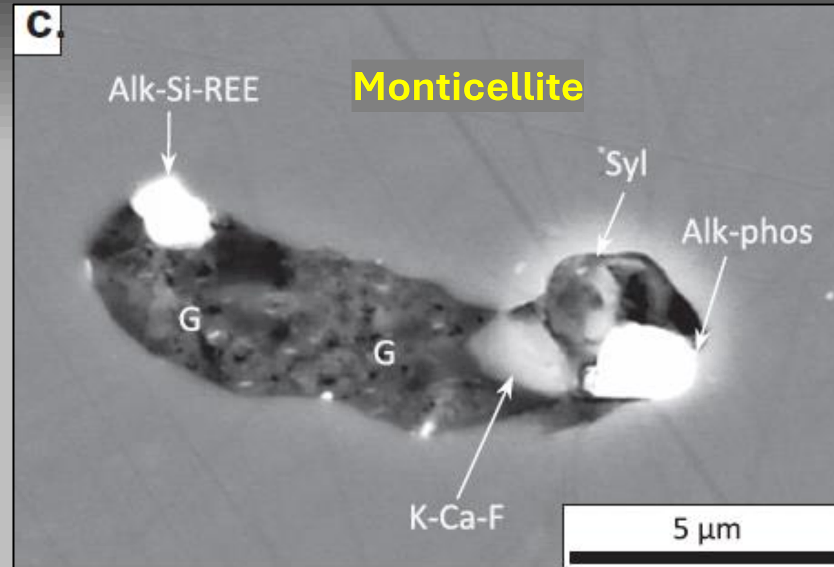
Dol/D: Dolomite, Cb: Carbonate, Ol; Olivine, Phlg: Phlogopite, Tph: Tetraferriphlogopite, aC: alkali (Na-K) carbonate, B:: Bradleyite

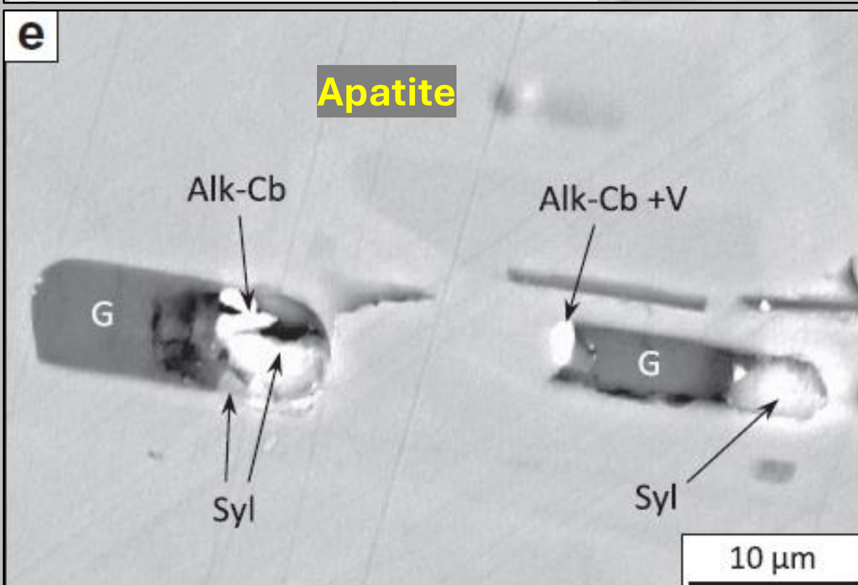
Melt Inclusions in Groundmass Minerals



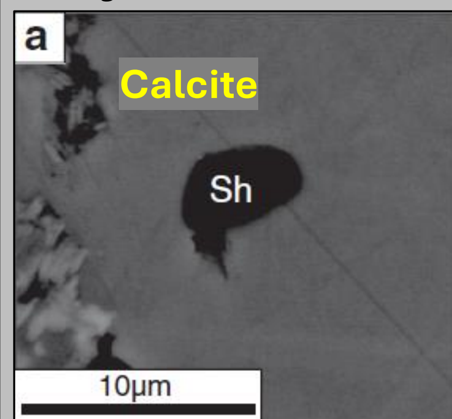
Mark Kimberlite – Abersteiner et al. (2020a)

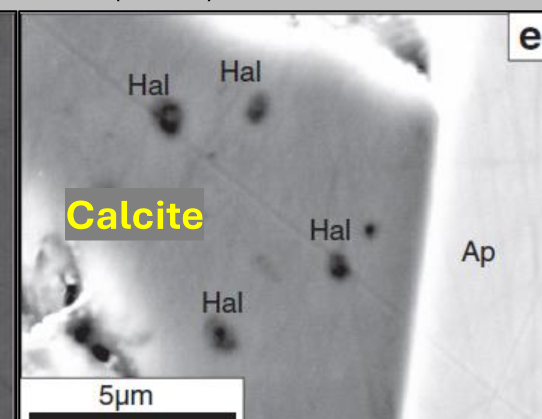


Roger Kimberlite – Abersteiner et al. (2018b)



Roger Kimberlite – Abersteiner et al. (2018b)





Venetia Kimberlite– Abersteiner et al. (2017)

MUM: Magnesio-ulvospinel-magnetite, Cb: Carbonate, Syl: Sylvite, Cal: Calcite, G: Gregoryite, Alk: Alkali, Sh: Shorite, Hal: Halite.