New models for kimberlite parental melts: composition, temperature, ascent and emplacement

Kimberlites: a major source of diamonds

- are exceptionally rare, but widespread on all major cratons;
- originate in a diamond-stability field (> 40 kbar), but do not crystallise diamonds;
- are fast ascending from mantle depths with a load of mantle and crustal xenoliths;
- are emplaced in small-volume dykes and diatremes;
- highly explosive emplacement and eruptions;
- "…is regarded by …the geological and geochemical community with an aura of glamour and mystique" (Eggler, 1989)

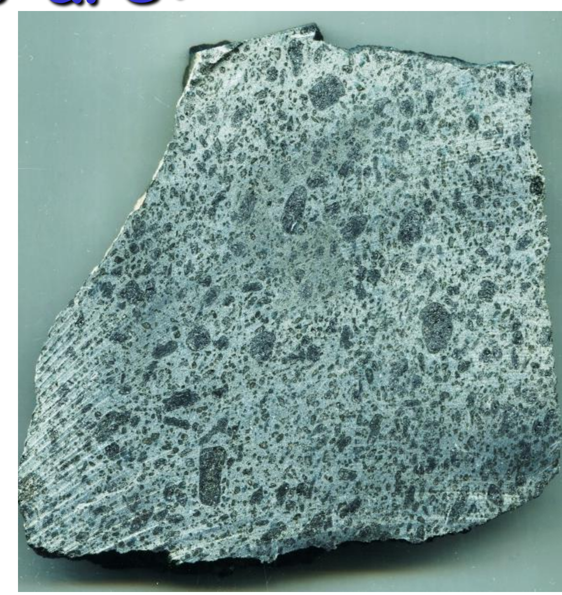
Kimberlite Parental Melt: existing dogma

Aphanitic Whole Rocks = Parental Melt

Definition: "Kimberlites are a clan of volatile-rich (dominantly CO_2) **potassic ultrabasic** rocks…." (R. H. Mitchell, 1986)

Hypabyssal group-I kimberlites are:

1. Ultramafic (MgO> 22 wt%; Mg# > 85);
2. High-Fo olivine cumulate, rare other minerals, no liquidus pyroxenes;
3. Low "basaltic" component: high $SiO_2/Al_2O_3>8$, low $Na_2O < 0.2$ wt%;
4. Strong and variable hydration >2.7 wt% H_2O (serpentine), $H_2O/CO_2 >1$;
5. Exceptional enrichment in incompatible trace elements and depletion in HREE



Unnamed kimberlite from Antarctica

Problem: "…the kimberlitic rock is both a **contaminated and altered** sample of its parent melt" (J. D. Pasteris, 1984)

What is wrong with an ultrabasic melt…?

Phenocrysts assemblage: olivine phenocrysts only, "melt"-olivine disequilibrium, no other common phenocrysts (pyroxenes & plagioclase;

Composition: mismatch between low-Al, low-Na kimberlite and other silicate magmas;

Composition: mismatch high Mg# (high-F) and trace/volatile elements enrichment (low-F);

Temperature: mismatch between calculated temperatures calculated (>1350°C) and "recorded" temperatures (<800°C);

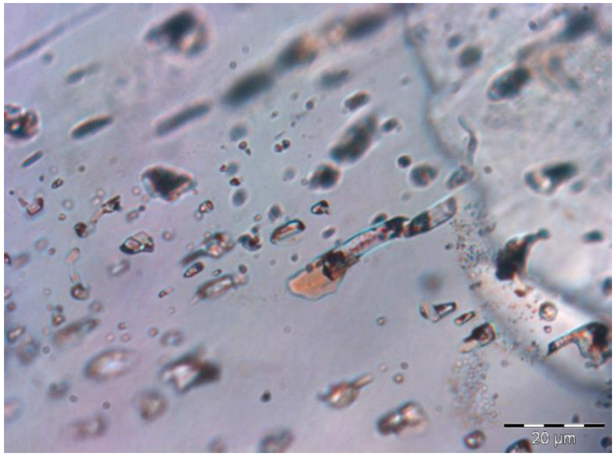
Rheology: mismatch between inferred mush of ultramafic melt + abundant solids (crystals/xenoliths) and low viscosity – low density - high buoyancy;

Unique explosivity style: what explodes in the ultramafic magma?

Our approach to kimberlite parental melt

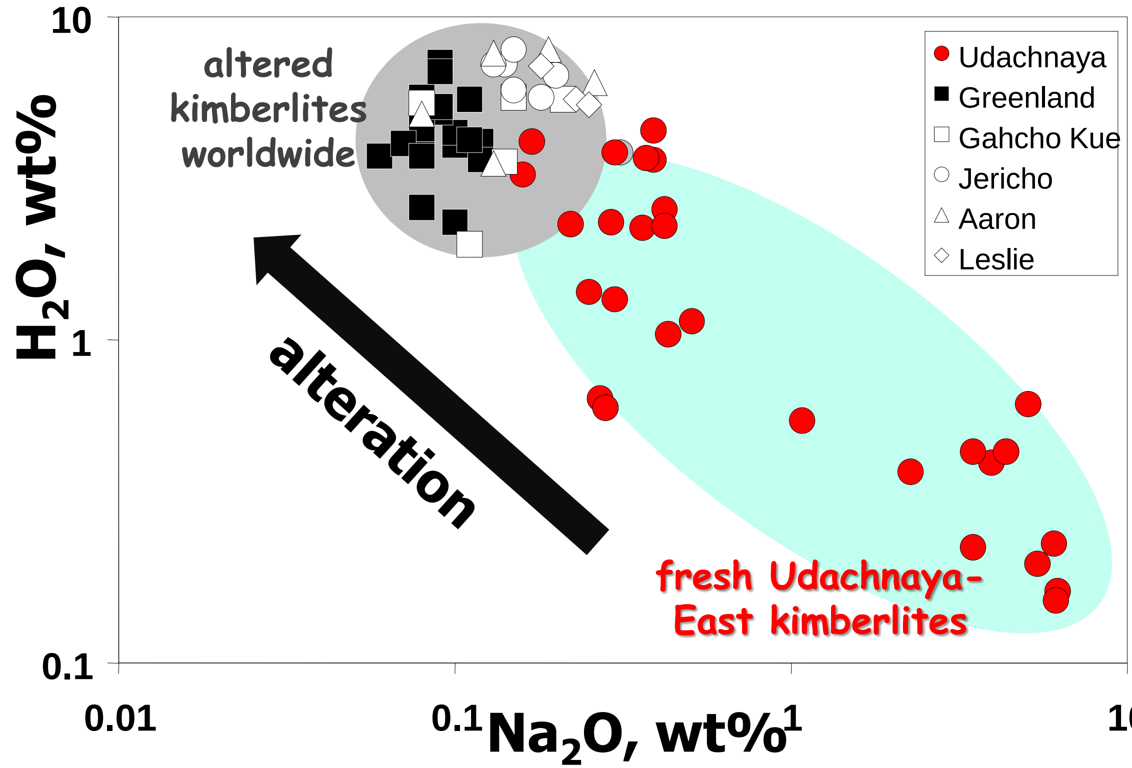
- Study of least altered kimberlite samples;
- Study of groundmass assemblage;
- Study of olivine phenocrysts;
- Study of melt inclusions in olivine, Cr-spinel, perovskite, apatite, monticellite, phlogopite etc

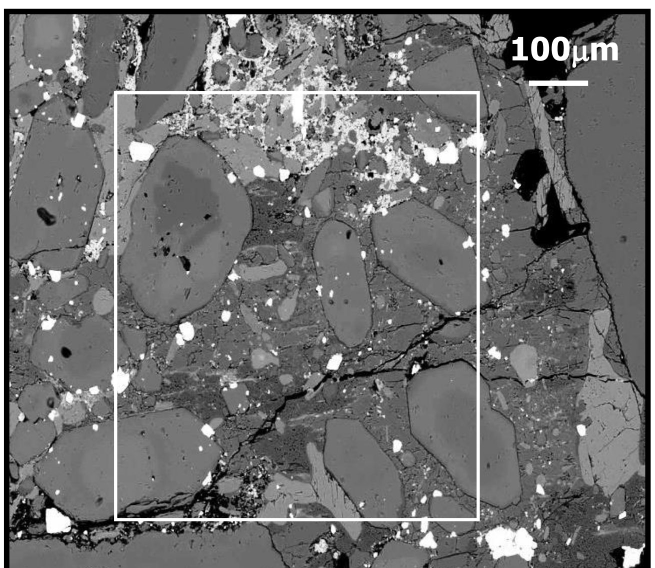
Prerequisite: kimberlites from Udachnaya-East (Siberia), EKATI cluster, Gahcho Kué, Diavik, Jericho (Canada), Majuagaa (W. Greenland), Wesselton, Bultfontein, Venetia (S. Africa), pipe #1 (Finland) and Antarctica.

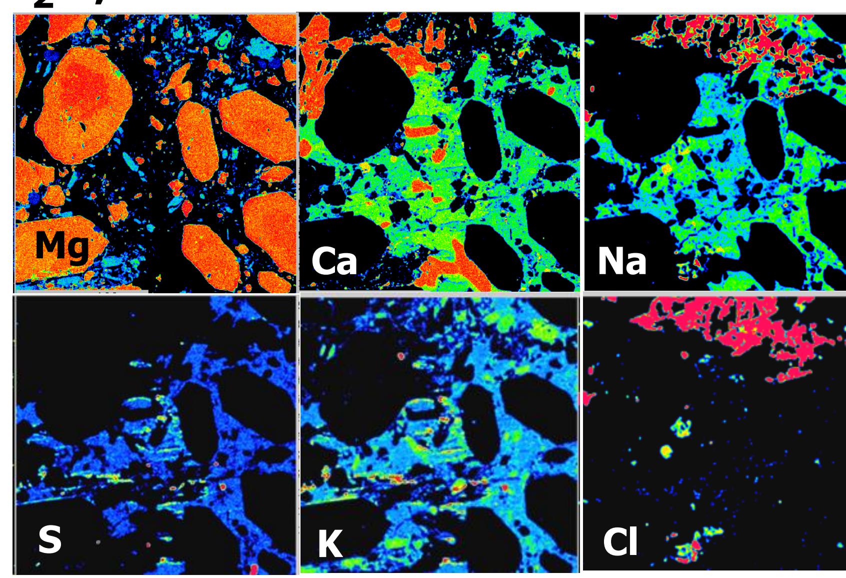


Udachnaya-East : an unaltered “flagship” in kimberlite family

	wt%
SiO_2	26.71
TiO_2	1.25
Al_2O_3	1.75
FeO	8.09
MnO	0.14
MgO	31.33
CaO	12.19
Na_2O	3.23 *<0.4*
K_2O	1.33
P_2O_5	0.49
SO_3	0.48
CO_2	9.42
H_2O	0.38 *>2.7*
Cl	2.38
Total	99.17
H_2O-leach	9.24

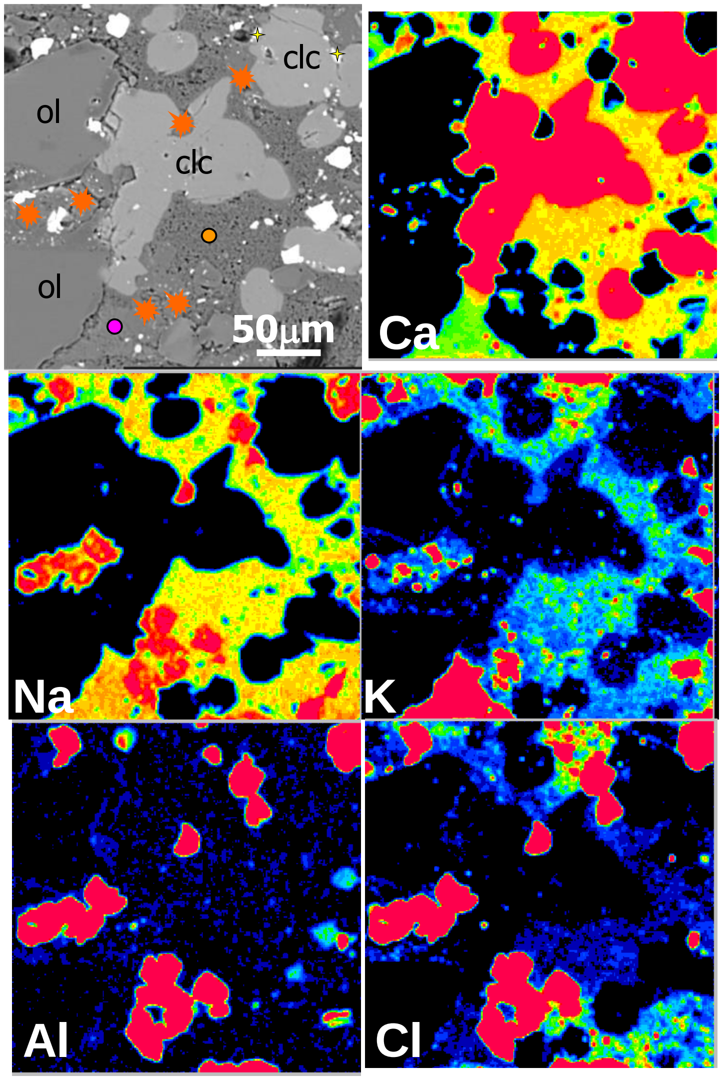




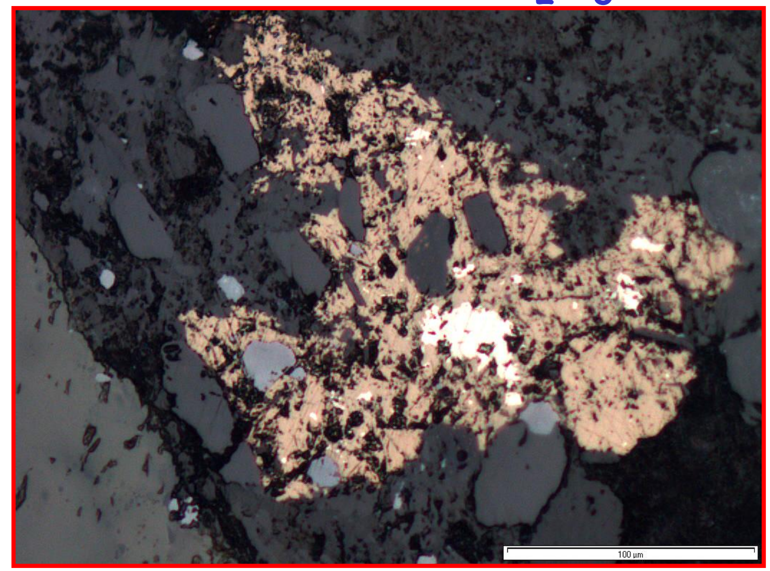


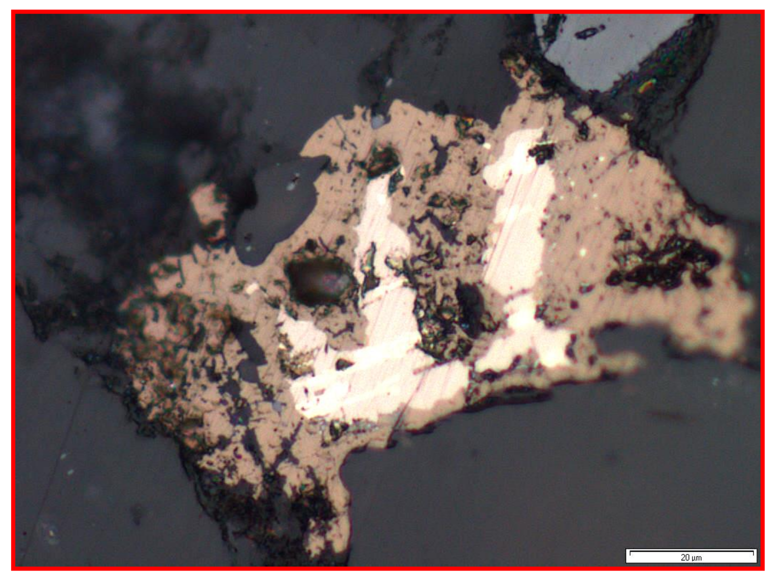
Udachnaya-East : an unaltered "flagship" in kimberlite family

Sodalite $Na_8Al_6Si_6O_{24}Cl$

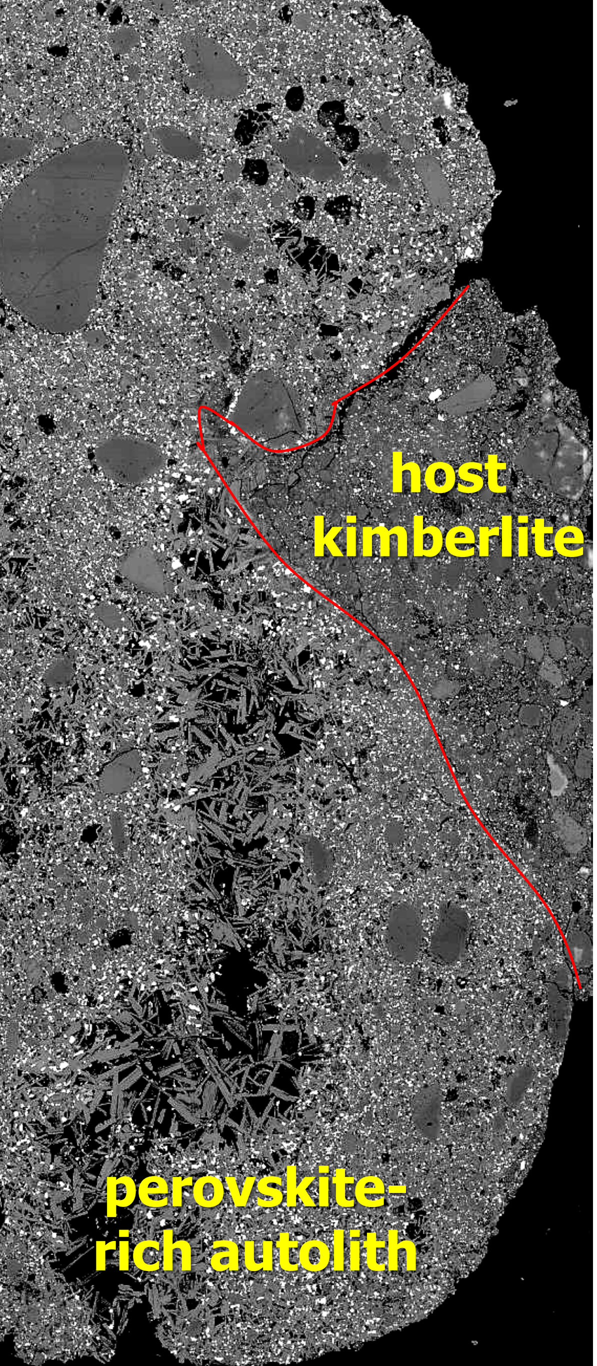


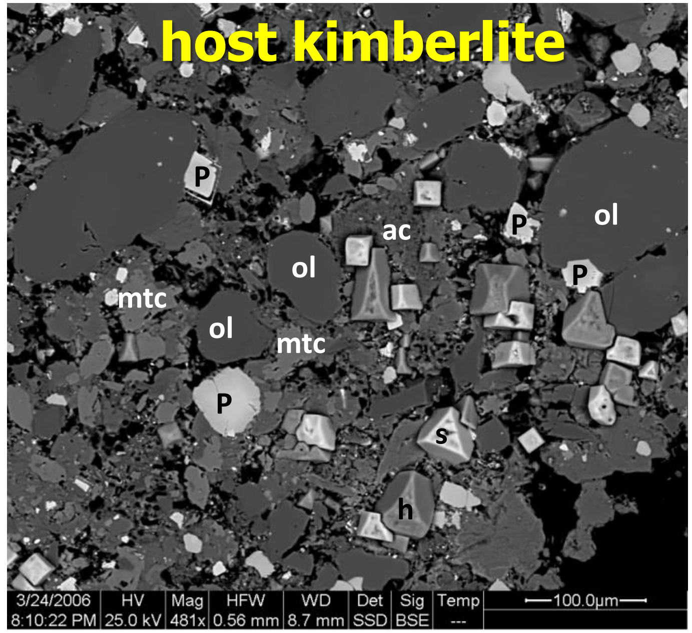
Djerfisherite $K_6(Cu,Fe,Ni)_{25}S_{26}Cl$
Rasvumite KFe_2S_3





Udachnaya-East : an unaltered "flagship" in kimberlite family



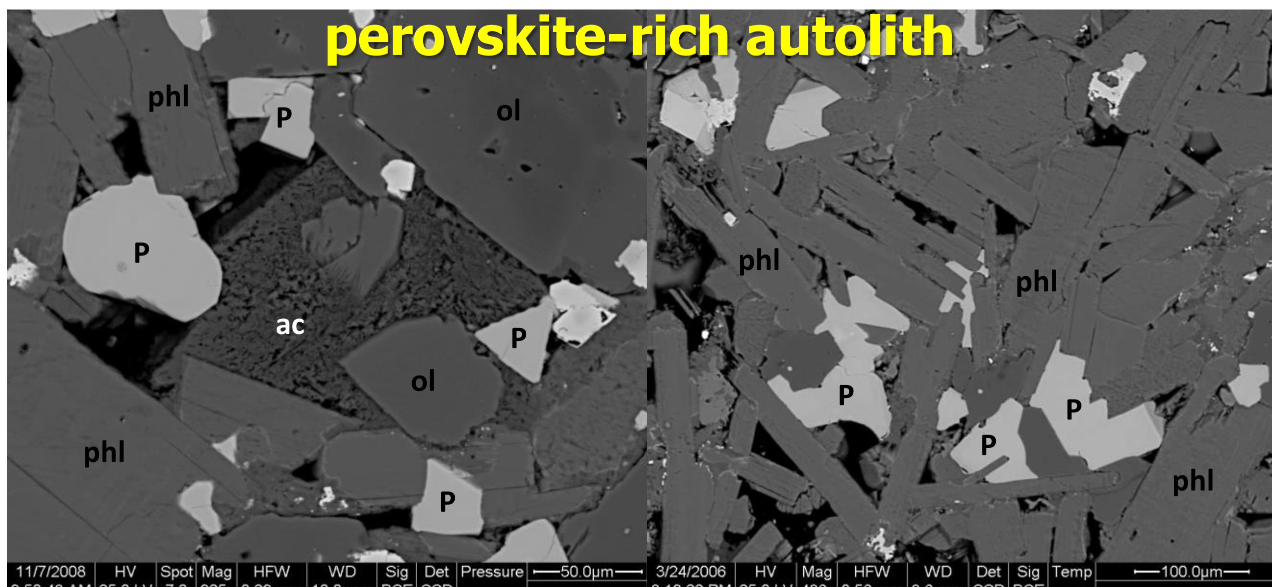


Mantle origin:
isotope compositions
(perovskite)

$^{87}Sr/^{86}Sr = 0.7031$

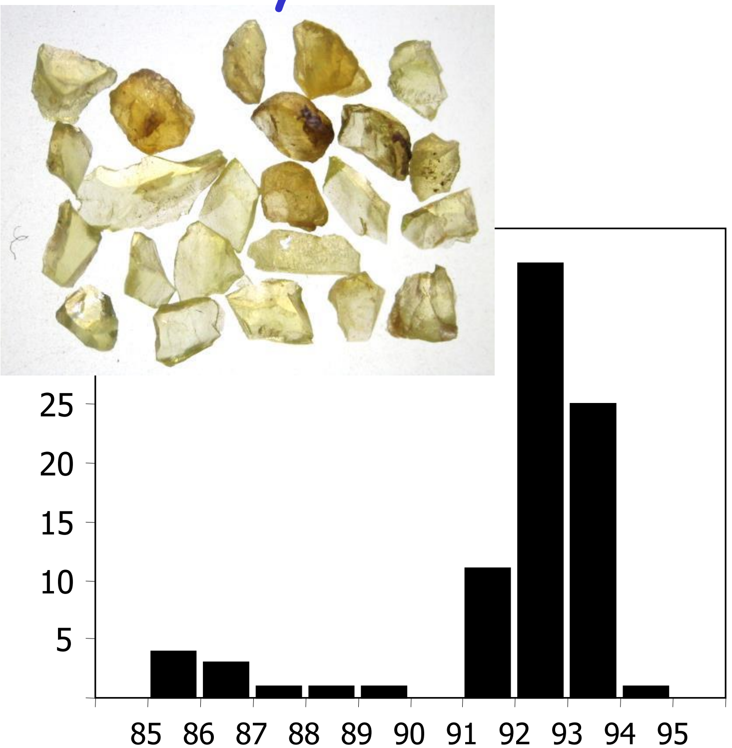
εNd = +5.0

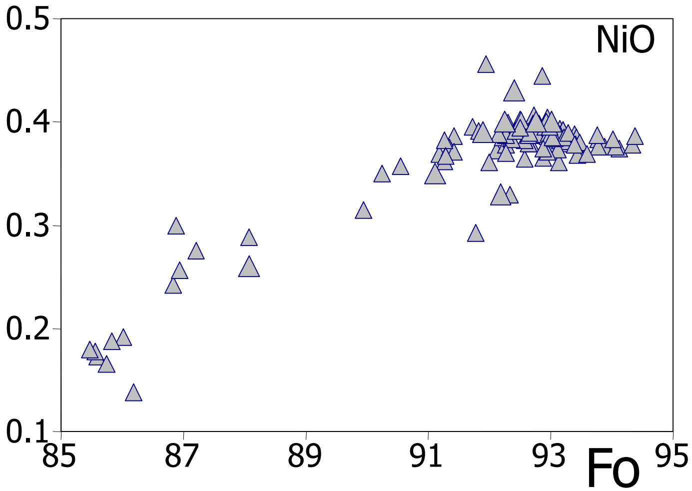
εHf = +5.3



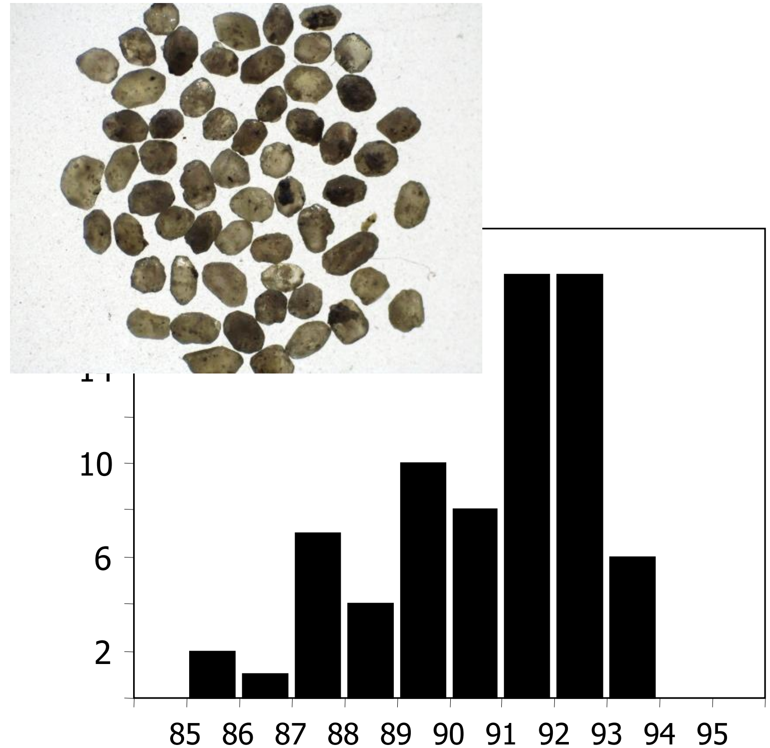
Udachnaya-East : an unaltered “flagship” in kimberlite family

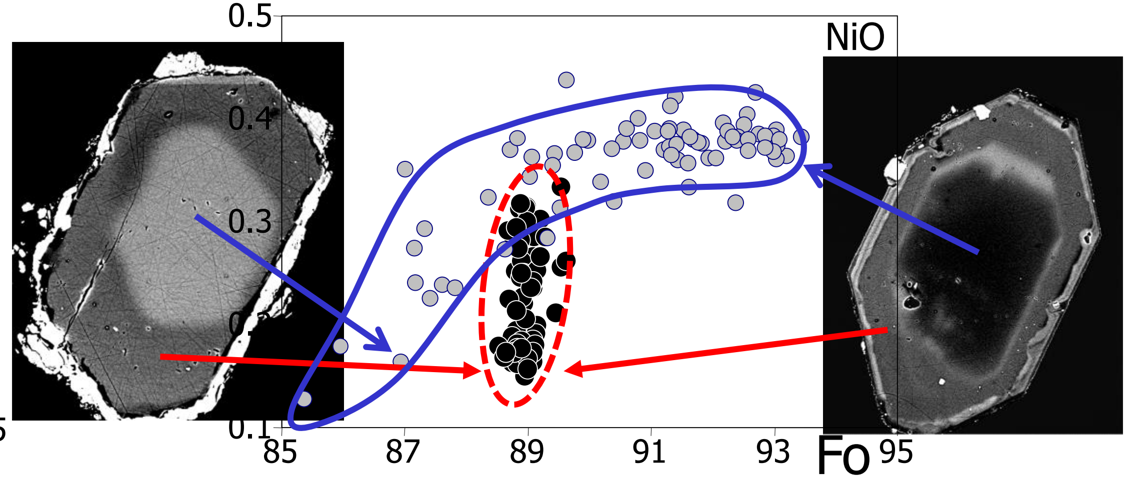
Macrocrysts



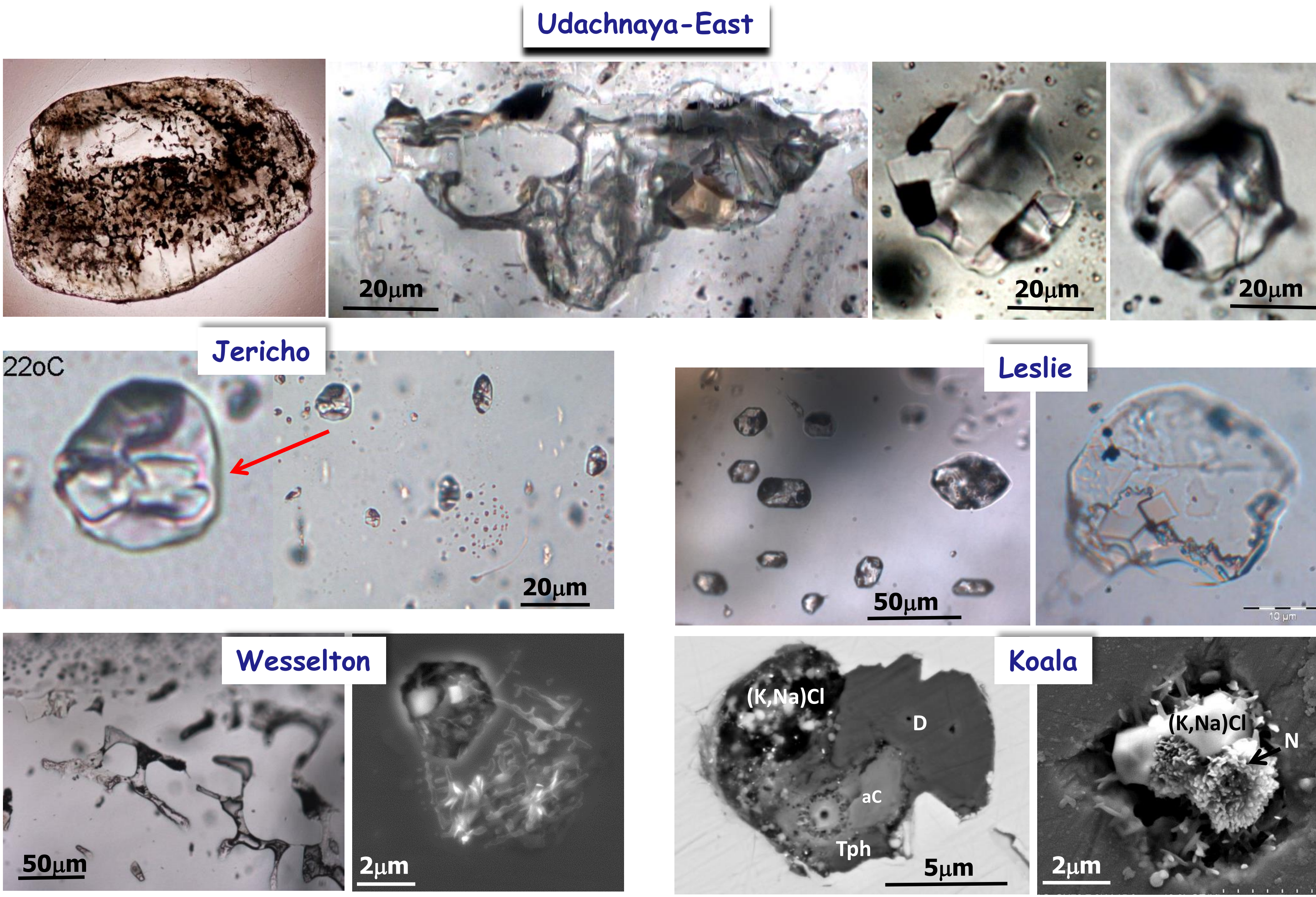


Phenocrysts



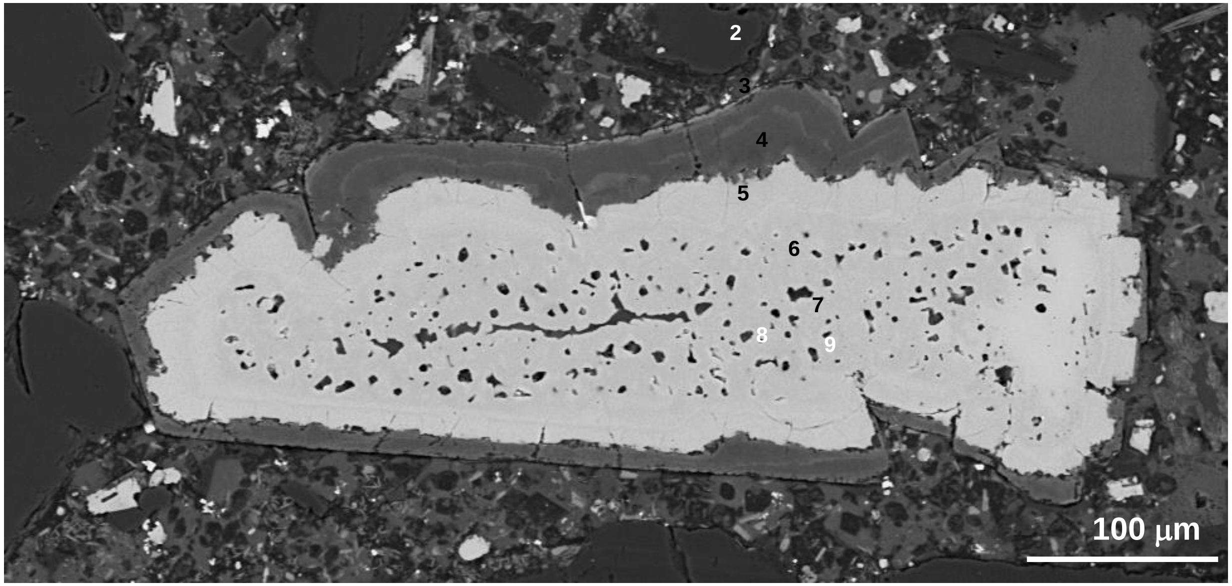


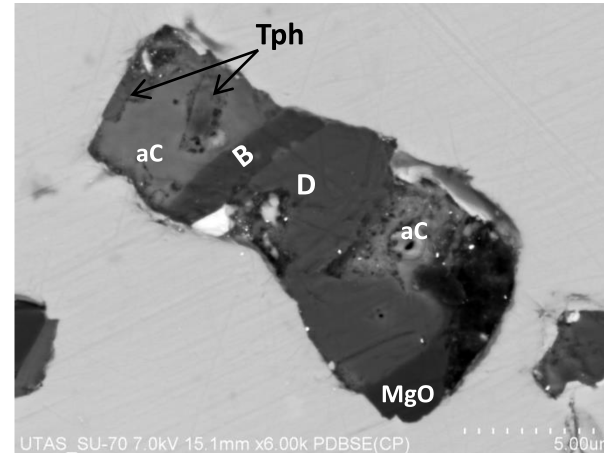
Alkali carbonate-chloride melt inclusions: common in ALL kimberlites

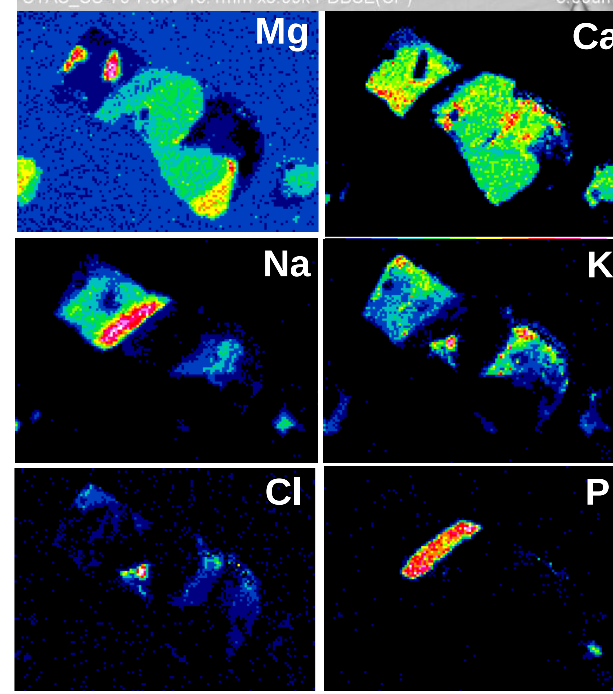


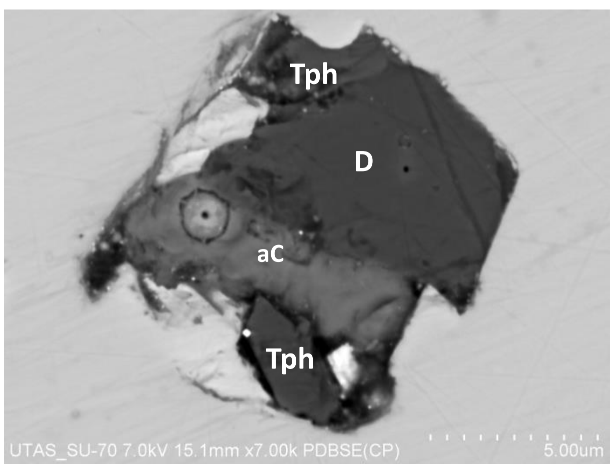
Alkali carbonate-chloride melt inclusions: common in ALL kimberlites

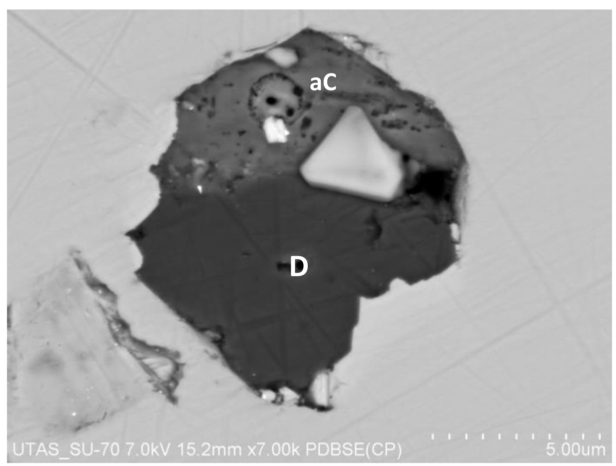
Cr-spinel, Koala pipe, EKATI cluster, Canada









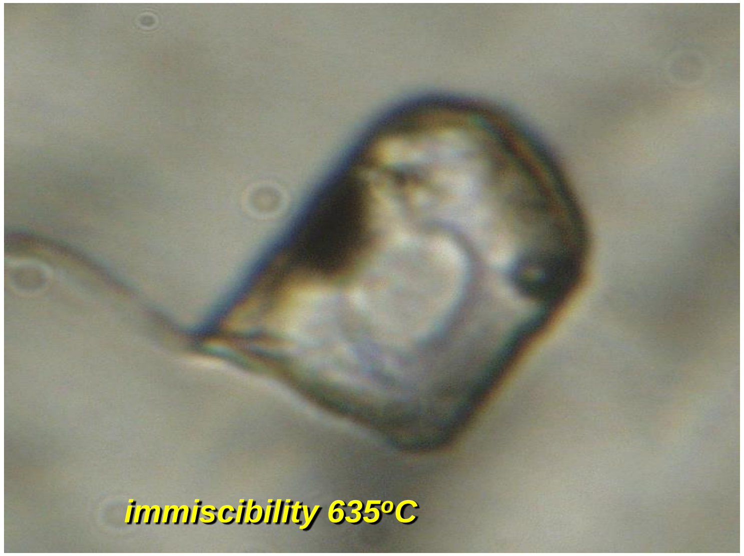


Melt homogenisation temperature ~ 670^{o}C;

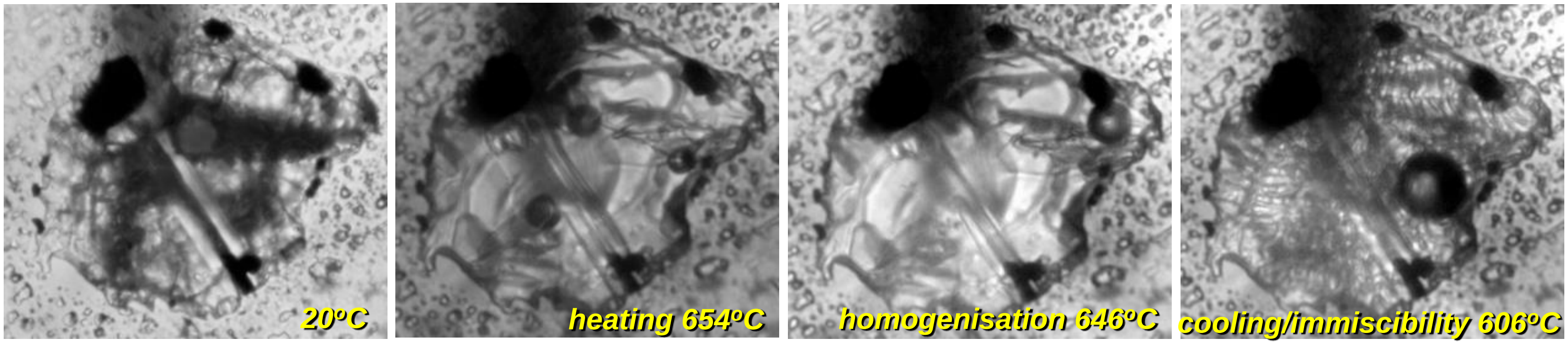
Carbonate-chloride melt immiscibility < 670^{o}C:

common in ALL kimberlites

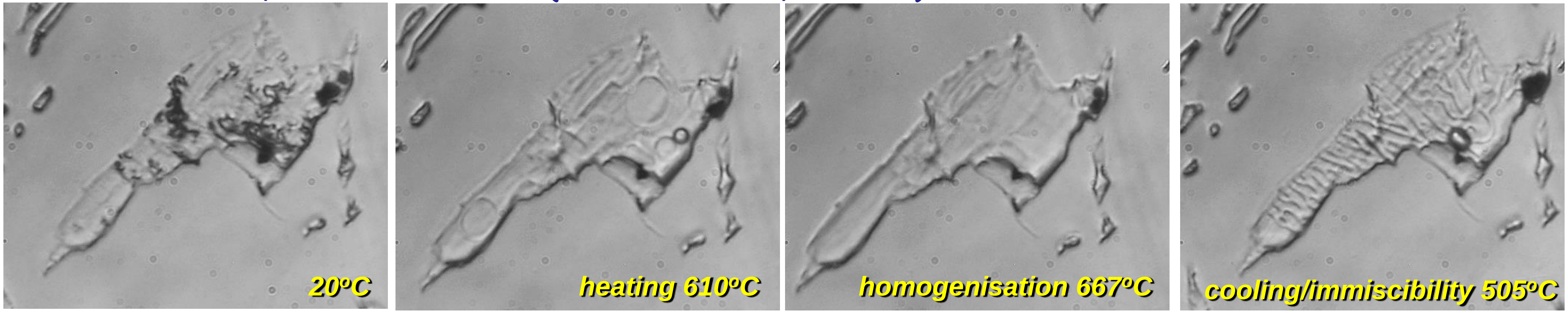
Olivine, Leslie kimberlite
(EKATI cluster, Canada)



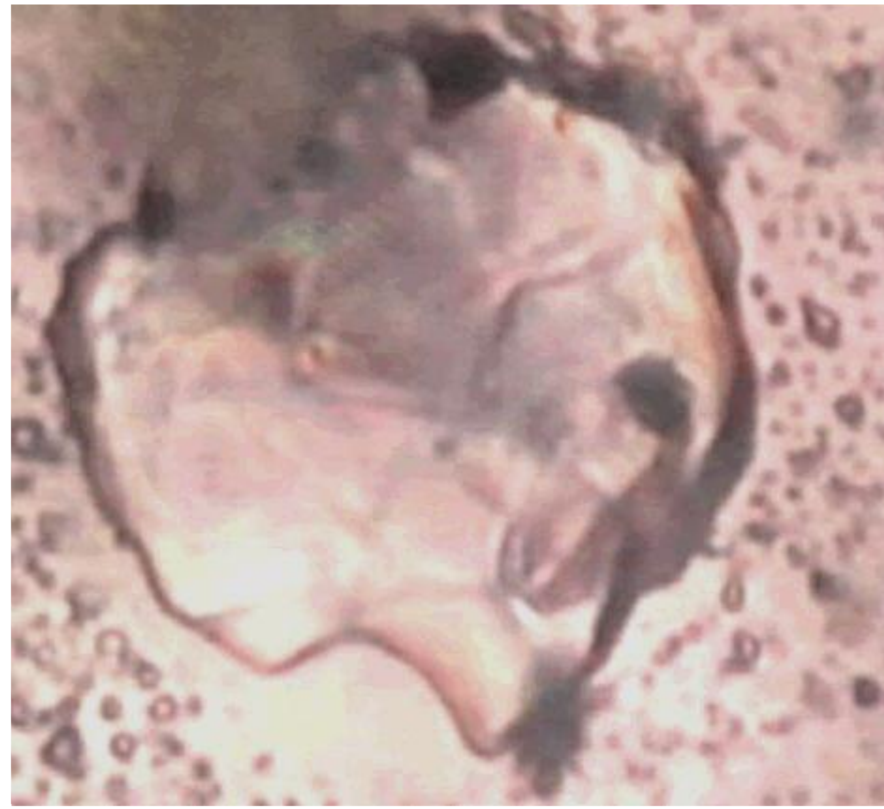
Olivine, Udachnaya-East kimberlite (Siberia, Russia)



Olivine, Koala kimberlite (EKATI cluster, Canada)



Melt homogenisation temperature ~ 670^oC: common in ALL kimberlites

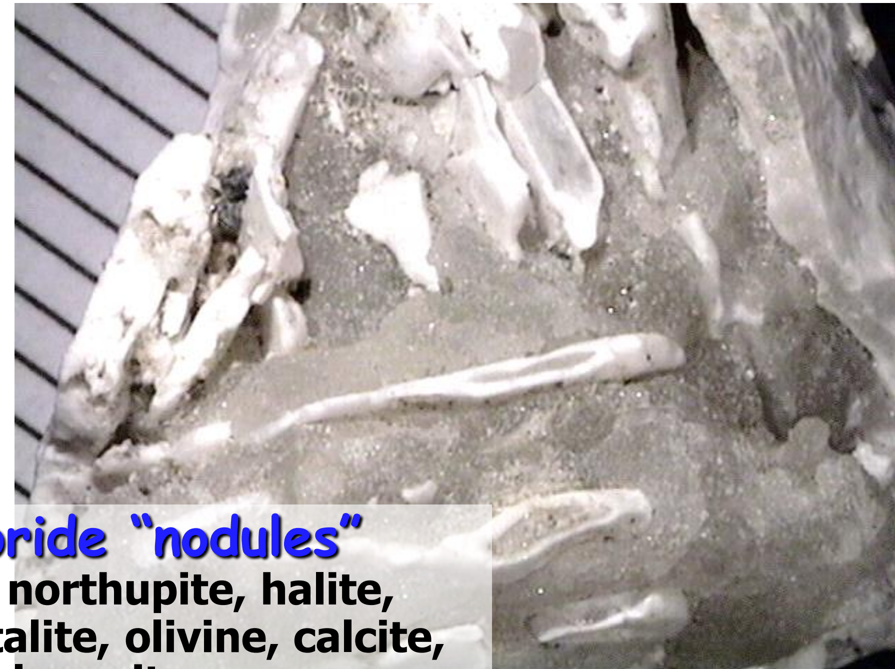


Carbonate-chloride melt immiscibility < 670^oC: common in ALL kimberlites

Udachnaya-East kimberlite: carbonate-chloride “pools” of residual melt

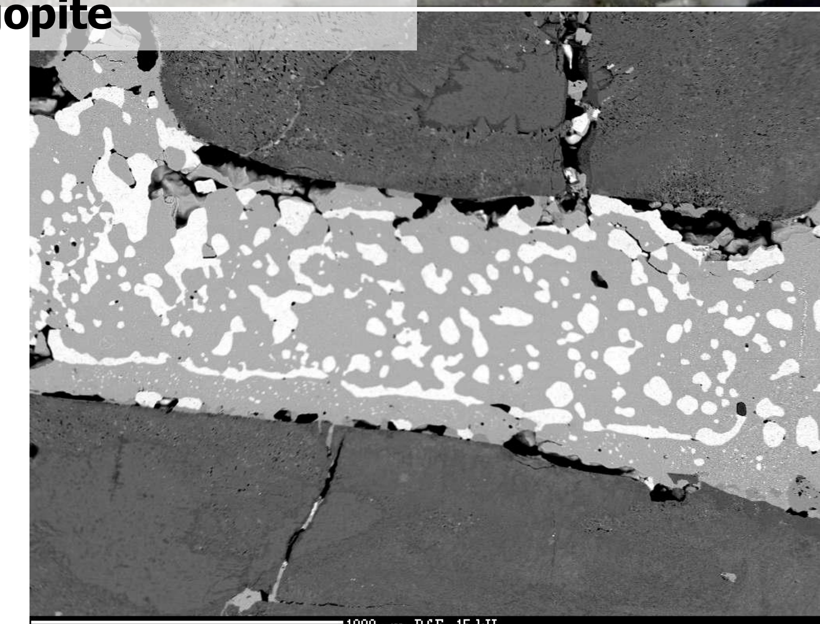
Chloride “nodules”

Udachnaya-East kimberlite: carbonate-chloride “pools” of residual melt



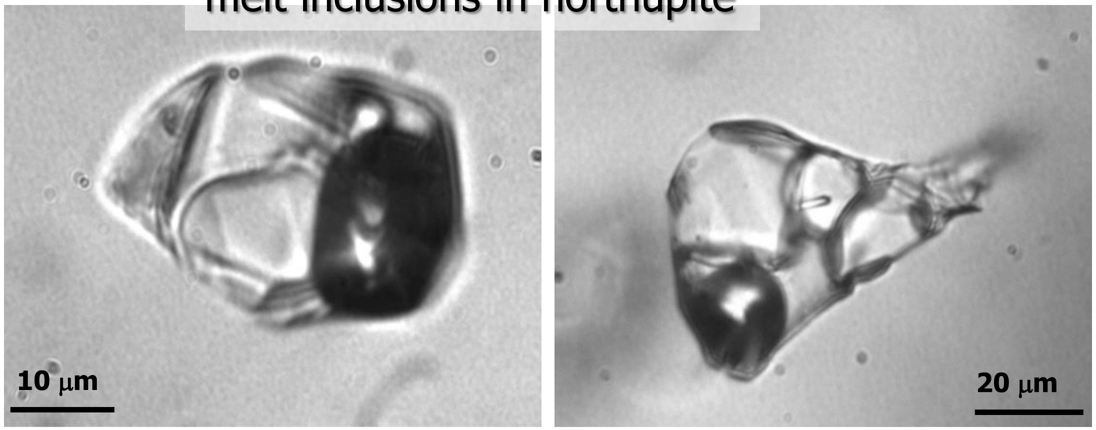
Carbonate- chloride “nodules”

nyerereite; shortite; northupite, halite, sylvite, apatite, aphthitalite, olivine, calcite, tetraferriphlogopite

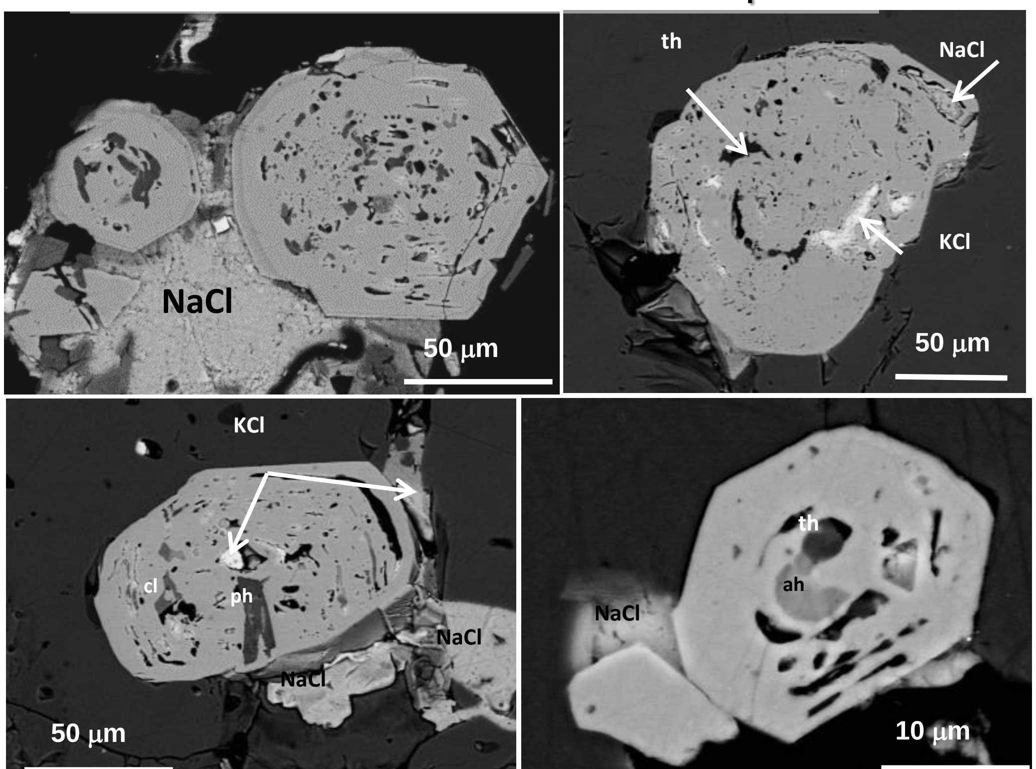


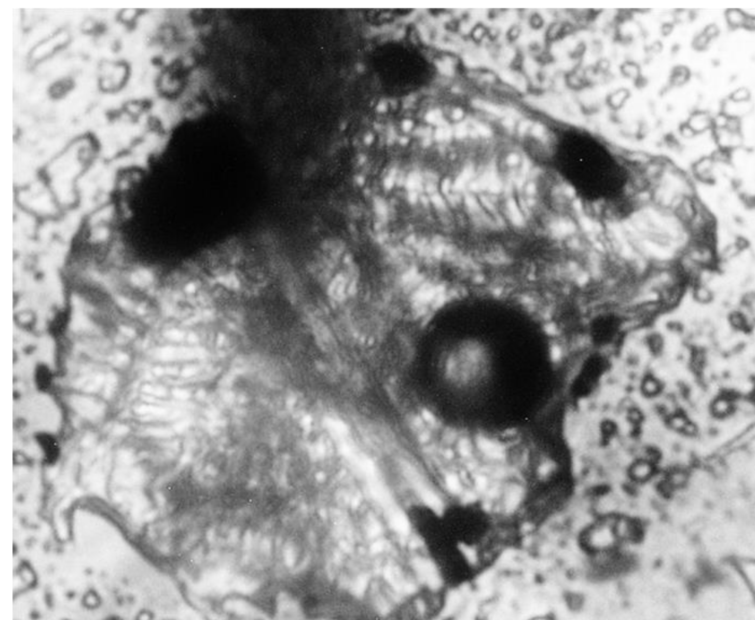
Udachnaya-East kimberlite: carbonate-chloride "pools" of residual melt

melt inclusions in northupite



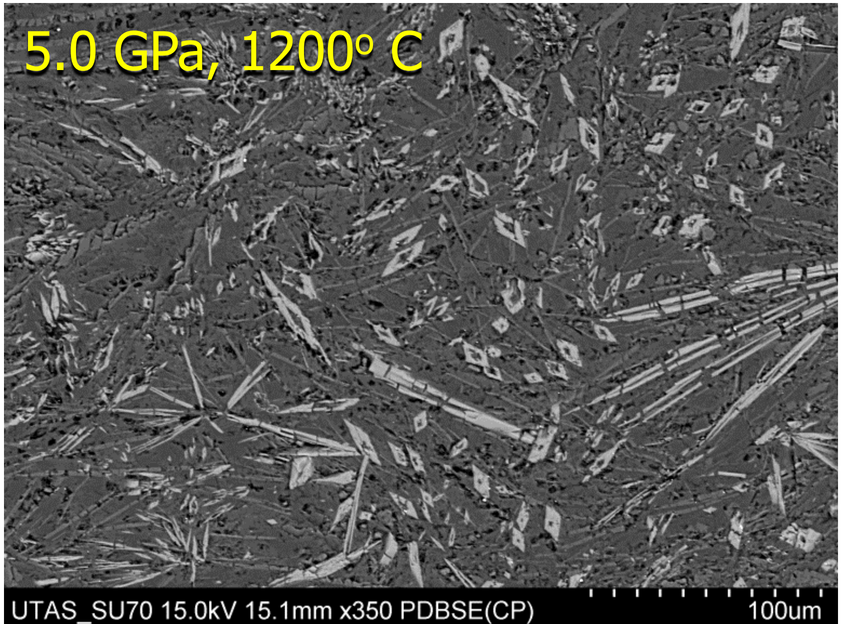
melt inclusions in shortite-hosted apatite

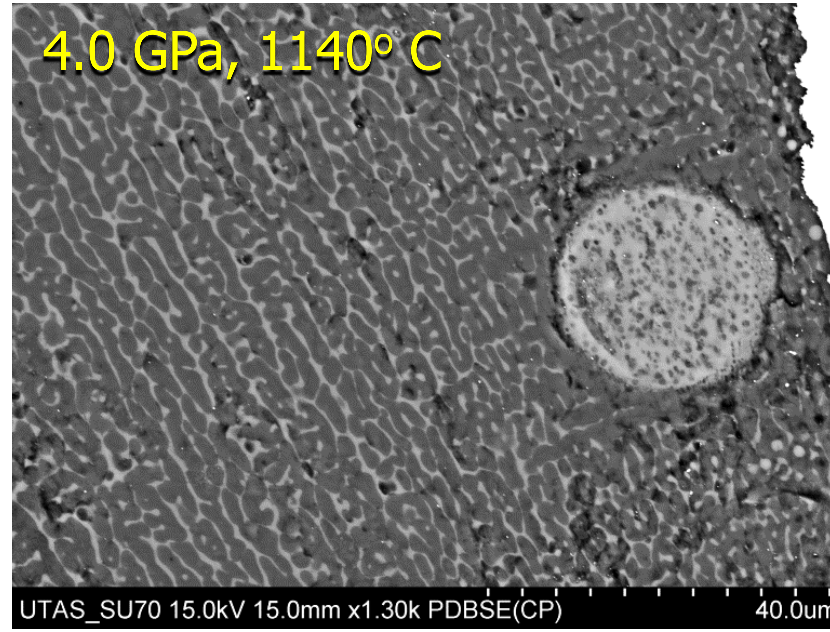


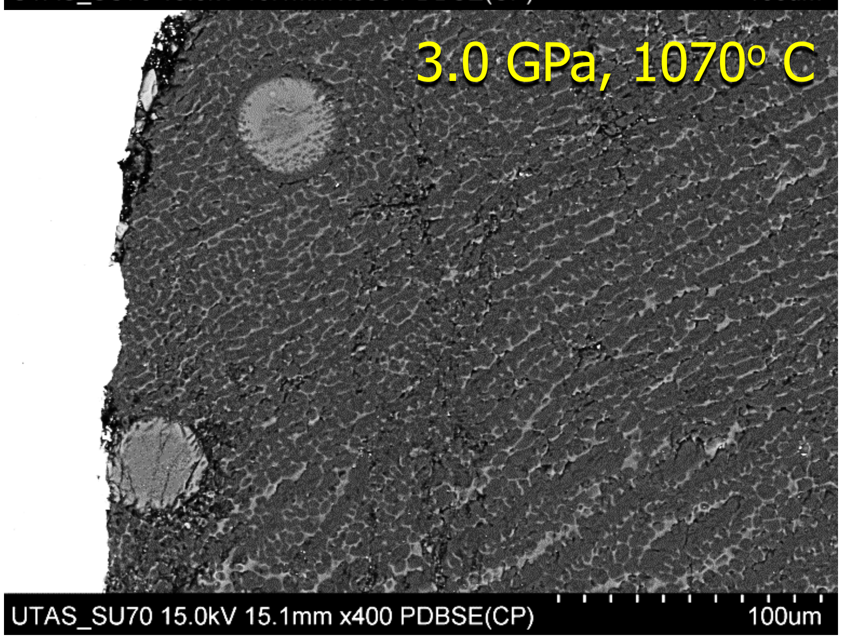


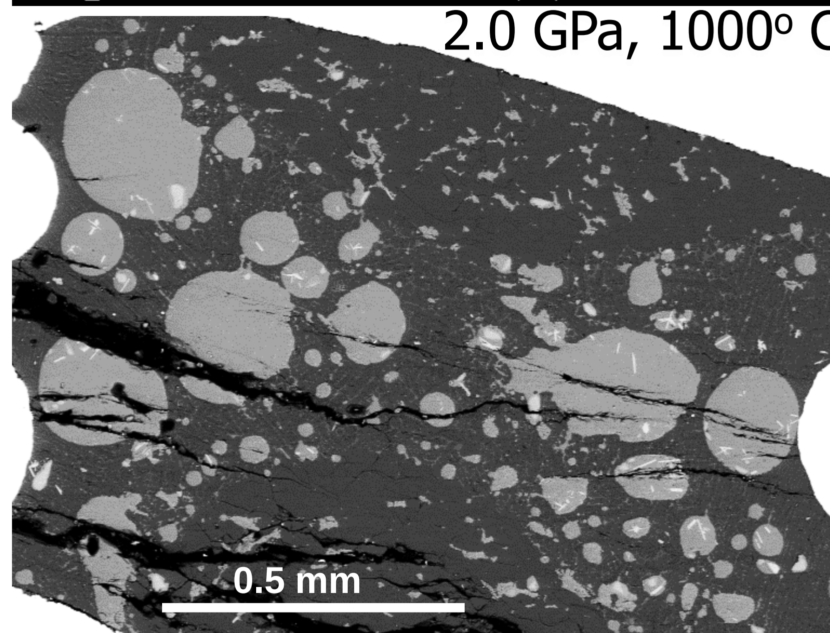
melt inclusion in olivine at ~590^{o}C

Carbonate-silicate melt immiscibility in the system 80%Na_2CO_3 – 20%Opx at mantle conditions: experimental approach









New “kimberlite ascent” model: a storyline

What drives explosive emplacement of kimberlites?

1. Alkali carbonate - chloride primary melt composition can be responsible for inferred rheological properties (low density and viscosity and related high buoyancy) and fast ascent to the surface and preservation of diamonds;

2. Kimberlite primary melt entraps mantle and crustal rocks, dissolves mantle silicate minerals (essentially orthopyroxene), becomes S-saturated, experiences carbonate-silicate liquid unmixing and becomes loaded and saturated in **olivine**;

3. Neither primary nor secondary water is present, as manifested by rock composition, fresh olivine and absence of serpentine;

4. No decarbonation is caused by sub-surface crystallisation of olivine (< 10-20%) and melt decompression, so CO_2 is not released as a gaseous phase.

If H_2O and CO_2 gases are not involved
what causes explosive eruption?

Kimberlite Magma emplacement: new facts

Kimberlite explosions are unexpectedly powerful for such small volumes

"The initial breakthrough of the magma at the surface is likely to have been violent and highly explosive…with excavation of the pipe from the top down, as the fragmentation surface in the magma column drops quickly upon vent opening" (**Porritt & Cas, 2009**)

"At Lac de Gras...excavated steep-sided pipes were empty to ~400-500 m depth before eventually being infilled by kimberlite" (**Kopylova & Hayman, 2008**)

"The sustained eruption proceeds to "drill" down into the country rock, efficiently excavating down to >750 m below surface" (**Moss et al., 2009**)

"…the (Venetia) K2 eruption was a protracted explosive event …presence of layered breccias and pyroclastic rocks to a considerable depth (>900 m) requires that the pipe was deeply excavated prior to filling" (**Brown et al., 2009**)

Explosions occur when kimberlite is cold and solid

Uncharred wood in Diavik kimberlite (photo Greg Yaxley)

"From a few of the diamond pipes rare leaves, turtle bones and fish parts have been recovered….Abundant wood specimens ….are in various states of carbonization. Some specimens have not been exposed to any burning and look like normal cedar logs"
www.napegg.nt.ca/newsletters/oct99

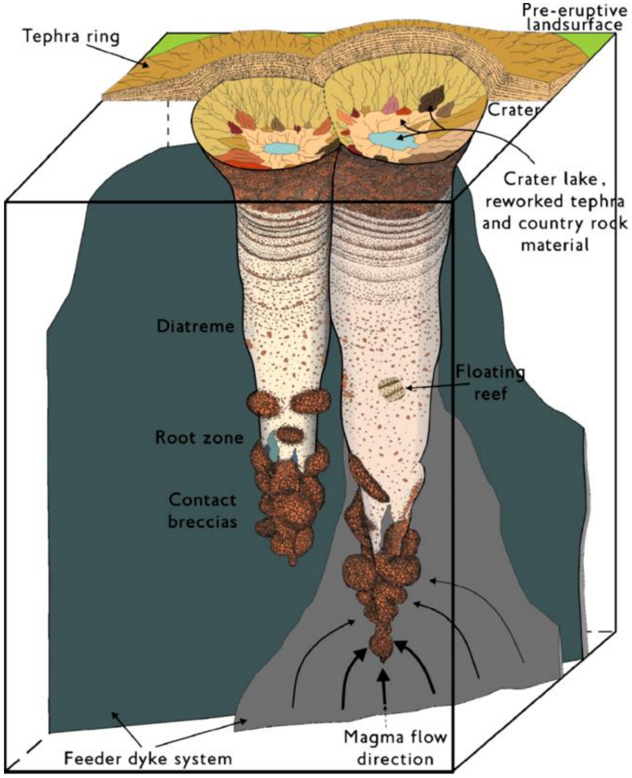
"…Relatively fresh, often charred – but not petrified – wood found only in China today, has been encountered in drill core at depths up to 400 metres. …coniferous trees were uprooted and incorporated into the pipes"
http://www.diavik.ca/Geo.htm

"Most clasts…show no evidence of being thermally metamorphosed. The presence of bituminous shale and carbonized wood indicate that high temperatures did not occur during diatreme emplacement " (**Mitchell, 1986**)

Kimberlite emplacement: prevailing models

1. Fluidisation: rapid degassing and expansion of magmatic volatiles (CO_2 and H_2O) in an open system that creates "…a bed of particles, which develops fluid-like properties as a consequence of the flow of interstitial gas" (Sparks et al., 2006).

2. Hydrovolcanism/phreato-magmatism: interaction of magma or magmatic heat with an external source of water… "diatremes form on dykes in hard rocks ..wherever there is a local potential for thermohydraulic explosive interaction of the rising magma with groundwater contained in fractures and faults" (Lorenz & Kurszlaukis, 2007) .



V. Lorenz & S. Kurszlaukis, 2007

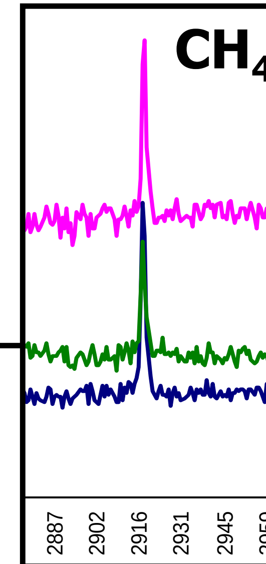
"Emplacement of the (Yubileinaya) pipe occurred over an **extended time span** with intermittent phases of volcanic quiescence and consolidation…. There is neither textural evidence that **violent degassing of a juvenile gas phase** has caused pipe excavation, nor that **external water** was present during the main phase of volcanic eruptions" (Kurszlaukis et al., 2009, Lithos)

Kimberlite emplacement: new model

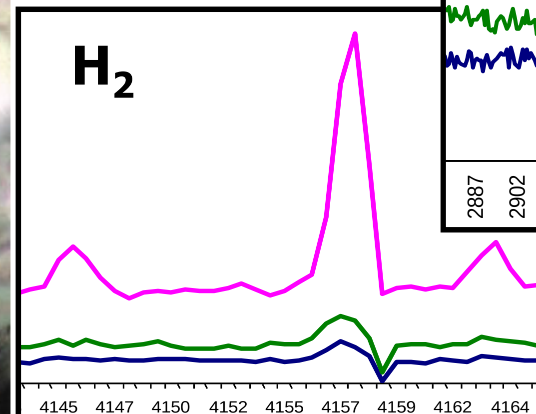
Magma-derived and serpentisation-derived **CH_4** and **H_2 blended with air** result in combustion and powerful explosion

New kimberlite emplacement model: Rationale

1. Spontaneous outgassing: ~10^5 m^3/day of gases N_2, **CH_4** and **H_2** at 50-70 atm from deep boreholes drilled through the unaltered block of the Udachnaya-East kimberlite (Marshintsev, 1986; Drozdov et al., 1989)



2. CH_4 and **H_2** in olivine-hosted fluid inclusions in the Gahcho Kué kimberlite (Slave craton, Canada): Raman spectroscopy

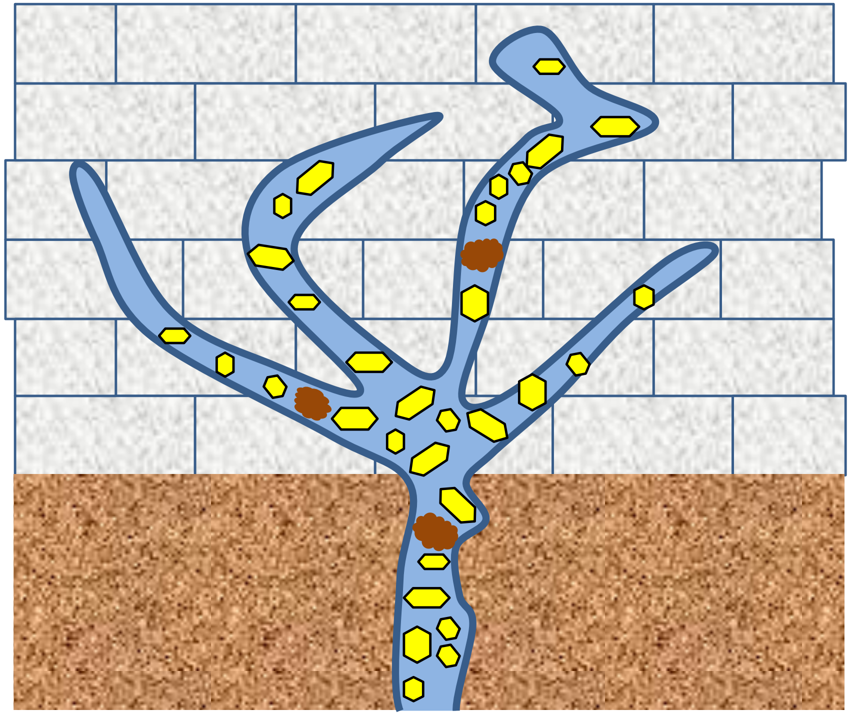


3. CH_4 and **H_2** are produced during serpentinisation of olivine: examples from present-day CH_4 and H_2 production in various continental (Abrajano et al., 1988; Neal and Stanger, 1983; Coveney et al., 1987; Charlou et al., 1998) and oceanic areas (Haggerty, 1991; Kelley, 1996) where mafic-ultramafic rocks are present.

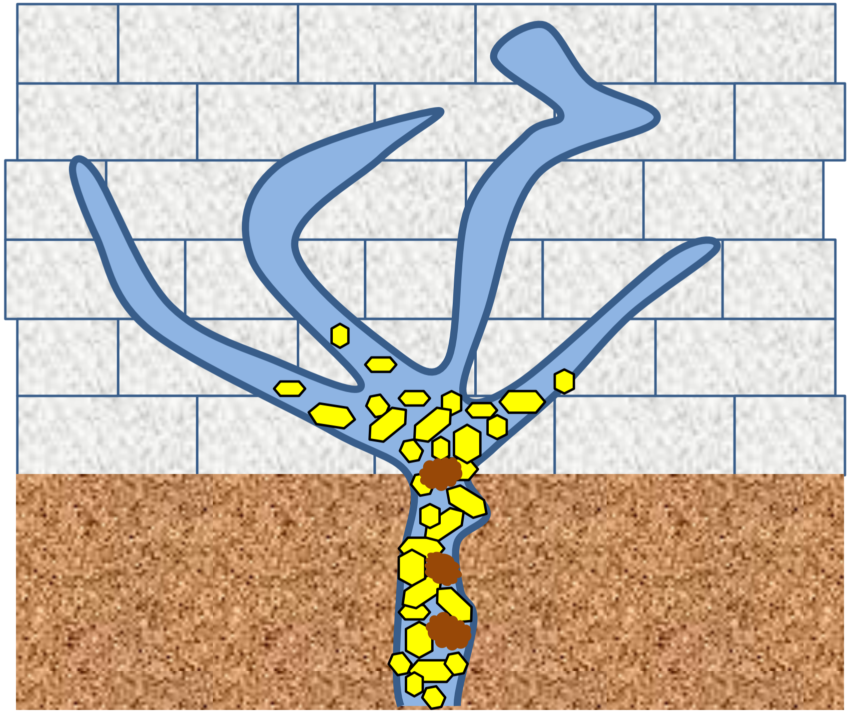
$$15\ \mathrm{Ol}\ (Fo_{90}) + 20.5\ H_2O \rightarrow \mathrm{Mt} + 7.5\ \mathrm{Serp} + 4.5\ \mathrm{brucite} + H_2$$

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

New kimberlite emplacement model: a storyline

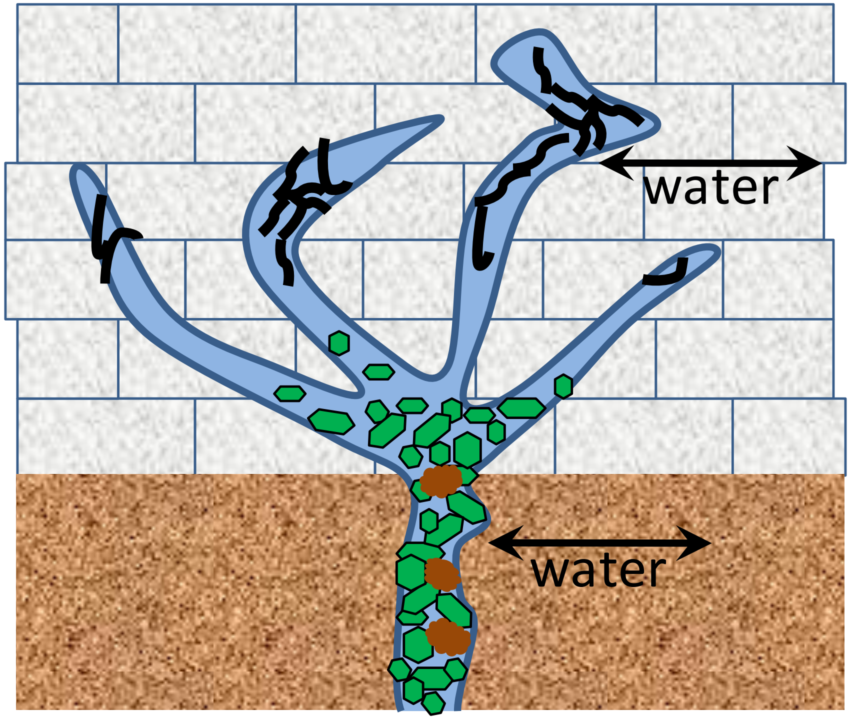


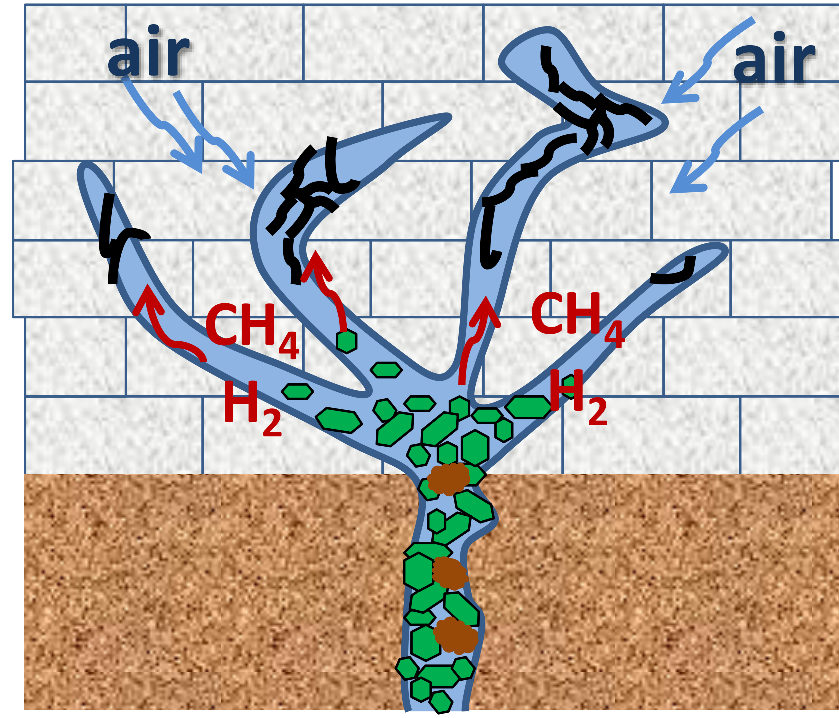
1. Emplacement of the kimberlite magma (~65% carbonate-chloride-silicate liquid + ~35% solids – olivine, mantle & crustal xenoliths and xenocrysts) as subsurface dykes



2. Gravitational separation of solids from the residual carbonate-chloride liquid in dykes. Olivine-rich cumulates with interstitial melt (“root zones” of hypabyssal kimberlites). Solidifying melt-rich zones with scattered solids in the upper parts of dykes.

New kimberlite emplacement model: a storyline

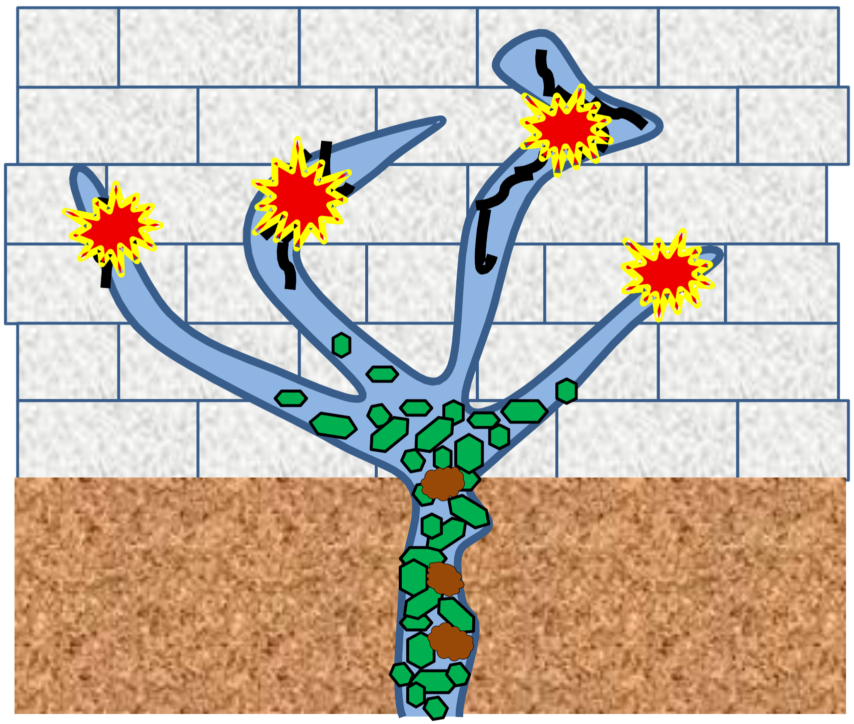




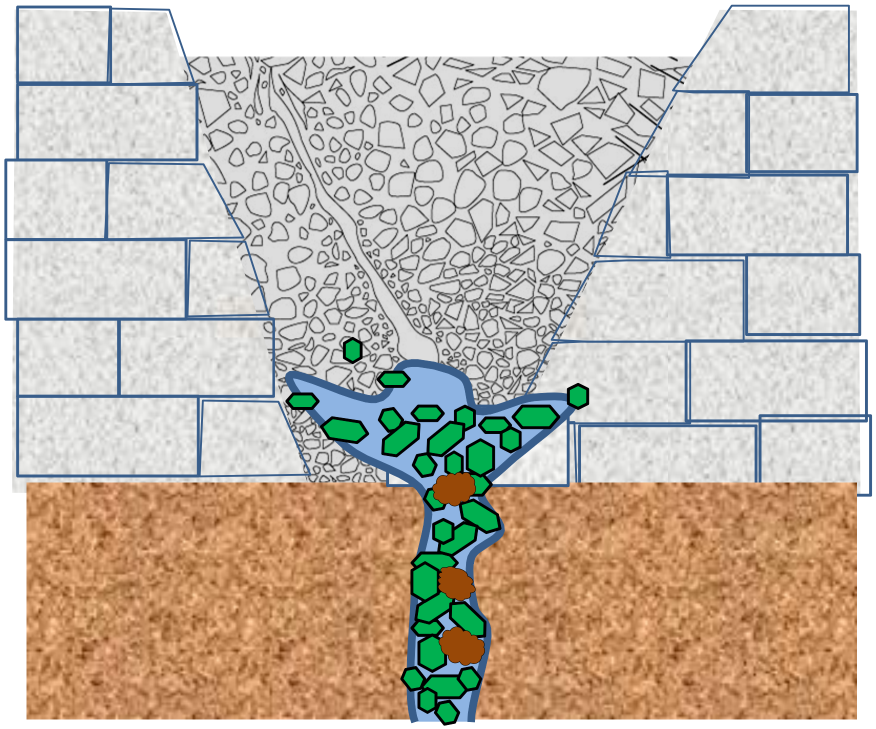
3. Water-soluble alkali carbonates and chlorides are leached out. Interconnected caverns are created throughout upper parts of dykes; whereas water causes serpentinisation of olivine in the "root zones"

4. Cavernous system act as a "vacuum pump" for free gases in this environment: magmatic, postmagmatic and ambient gases (mixture of air, water vapour and magma-derived volatiles).

New kimberlite emplacement model: a storyline

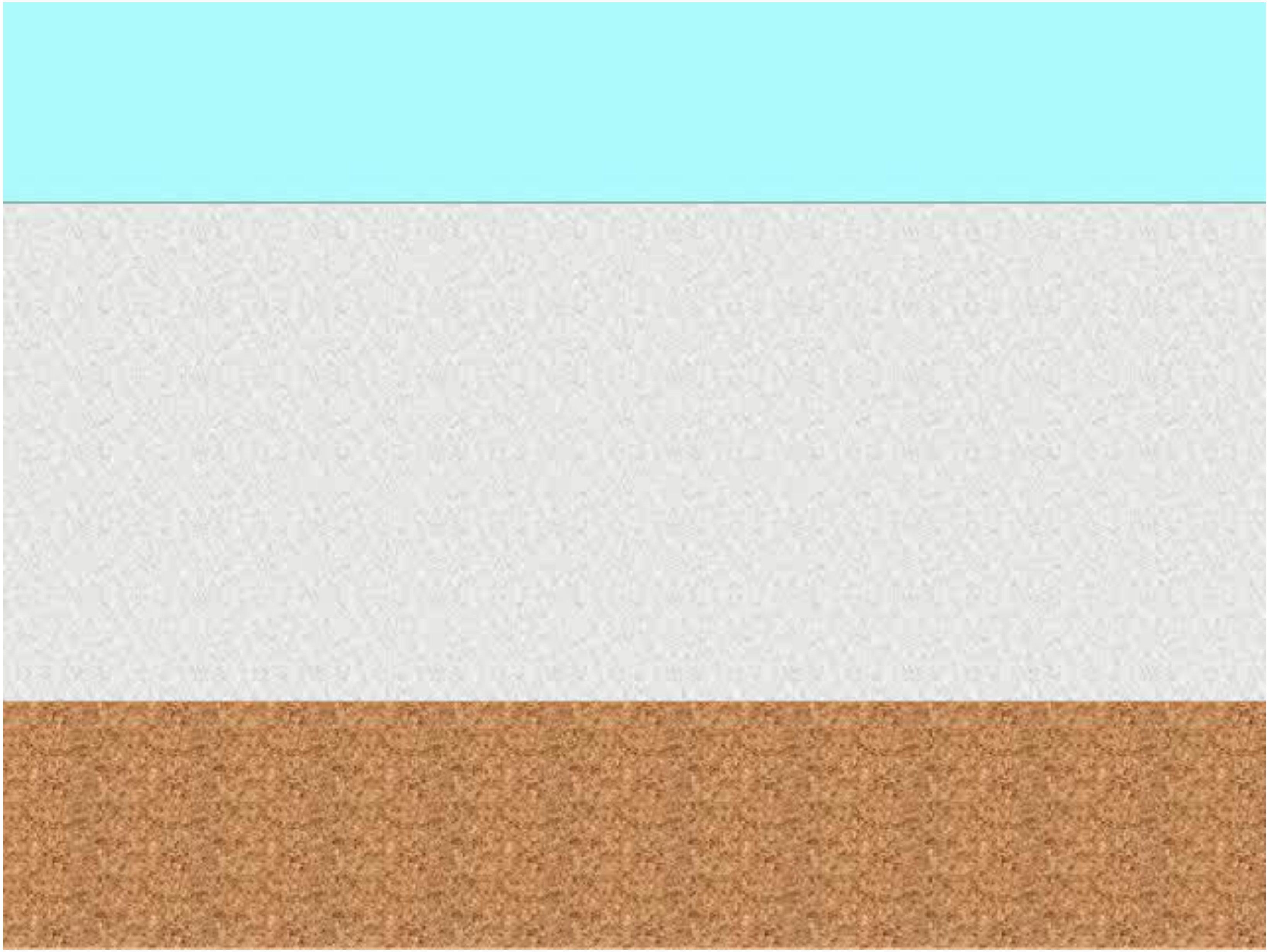


5. Gas-mixing and pressurisation (by expanding serpentine) in caverns cause detonation. One explosion may cause chain reaction by sending shock waves.



6. Vertical and lateral explosive boring. Fragmentation inside the dyke system and country rocks . Collapse of rocks from the top and walls ➡ Growth of carrot- shaped "diatremes" by excavation from top down. Natural autoclave for microdiamonds.

New “kimberlite emplacement” model: a storyline



Udachnaya (*fortuitous*)
Удачная model of kimberlite

1. new approach to kimberlite melt composition and temperature
2. new estimates of rheological properties of kimberlite magmas
3. new mechanism of the kimberlite magma ascent
4. new ideas on the source of explosive energy/forces