U-Th-K rich domains inside the Earth

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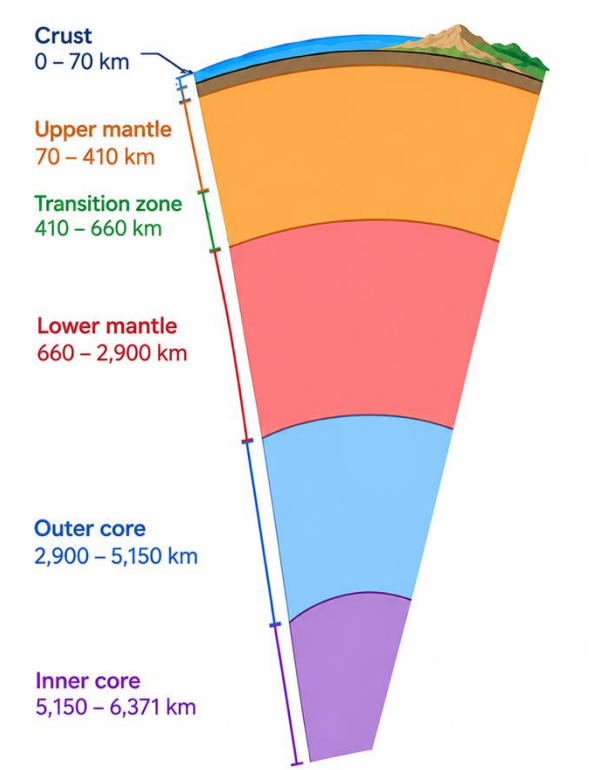
Composition of BSE: Implication to mantle structure

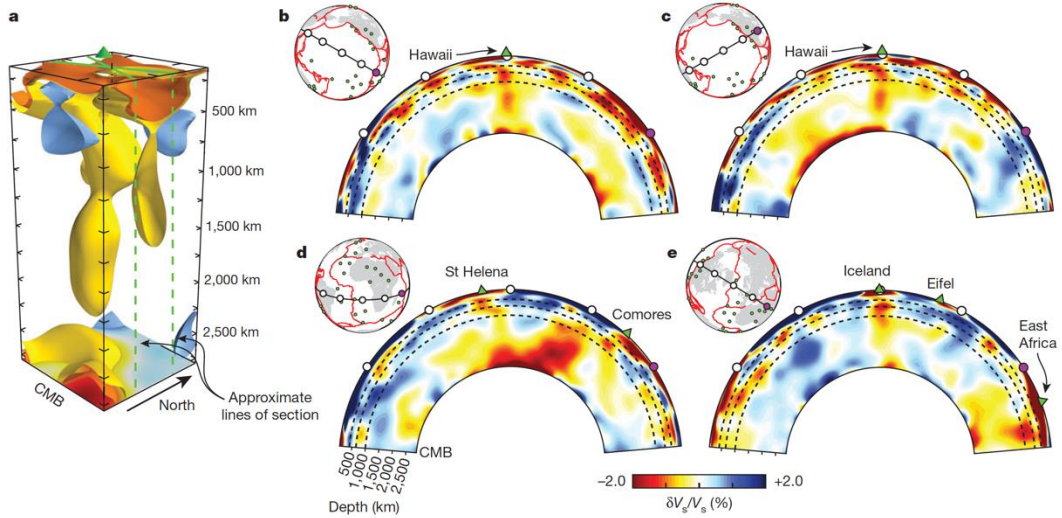


	Bulk Silicate Earth				
		Superchondritic			
	Chondritic (MS)	0.2 ε higher (JJ)	0.07 ε higher, adjusted	0.07 ε higher, erosion, (F22J22)	EC model (per Bill)
U, ppb	20	14	17	10 to 14	23
Th, ppb	80	55	67	40 to 56	90
K, ppm	240	166	201	120-169	1872
	Upper mantle				
U, ppb	12	12	12		12
Th, ppb	46	46	46		46
K, ppm	139	139	139		139
	Lower mantle				
U, ppb	20	12	16		24
Th, ppb	80	46	62		93
K, ppm	240	139	187		2476

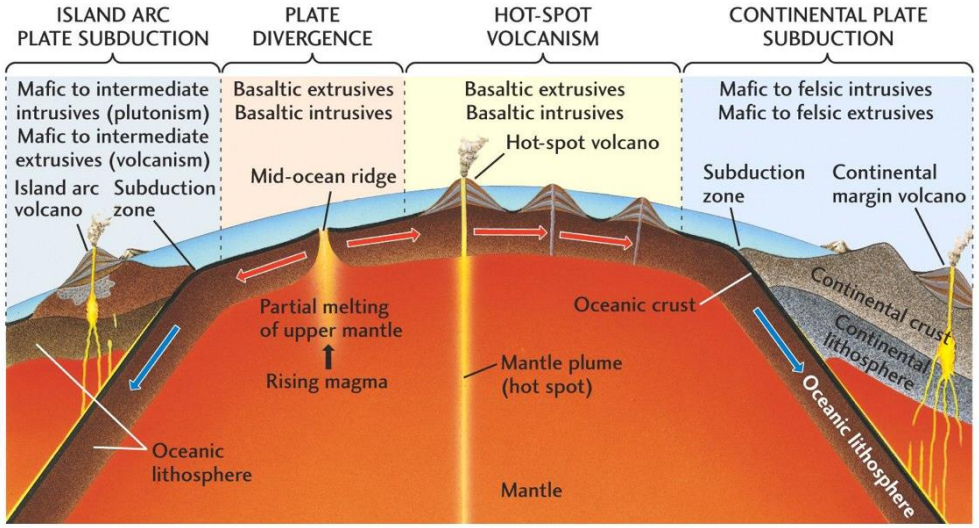
- Chondritic Earth model, the whole lower mantle is primitive (or unprocessed)
  - Lower mantle and upper mantle are chemically different
- Superchondritic (0.2 ε ^{142}Nd higher) Earth model, the whole mantle has been processed
  - Lower mantle and upper mantle have the same chemical composition
- Superchondritic (0.07 ε ^{142}Nd higher) Earth model
  - Lower mantle and upper mantle are chemically different
  - Lower mantle has less HPEs than chondritic Earth composition
- Enstatite Chondrite Earth model
  - U-Th similar to chondritic Earth model
  - Very K-rich lower mantle

What would be the implications of the chemical differences between the upper and lower mantles for the style and dynamics of mantle convection?

Mantle Heterogeneity

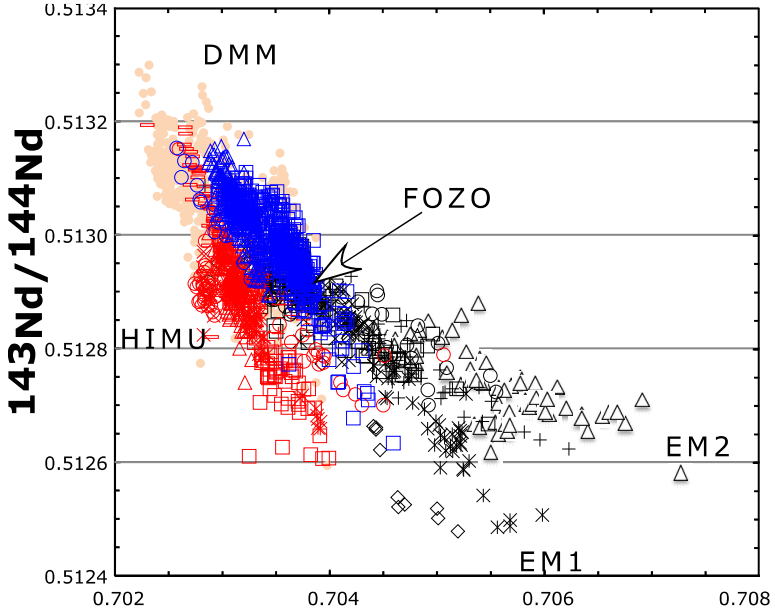


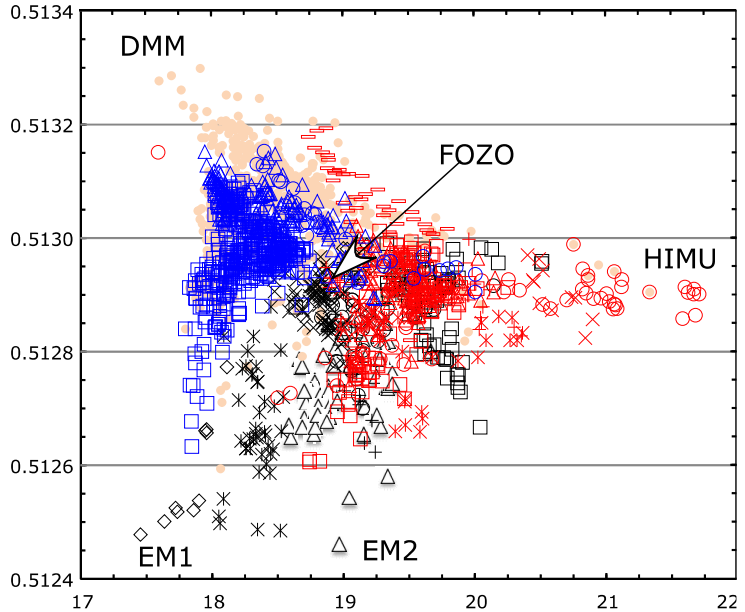
French and Romanowicz (2015)



http://www.soest.hawaii.edu/oceanography/courses_html/OCN201/laboratory/Lab_Readings/VolcanoReading

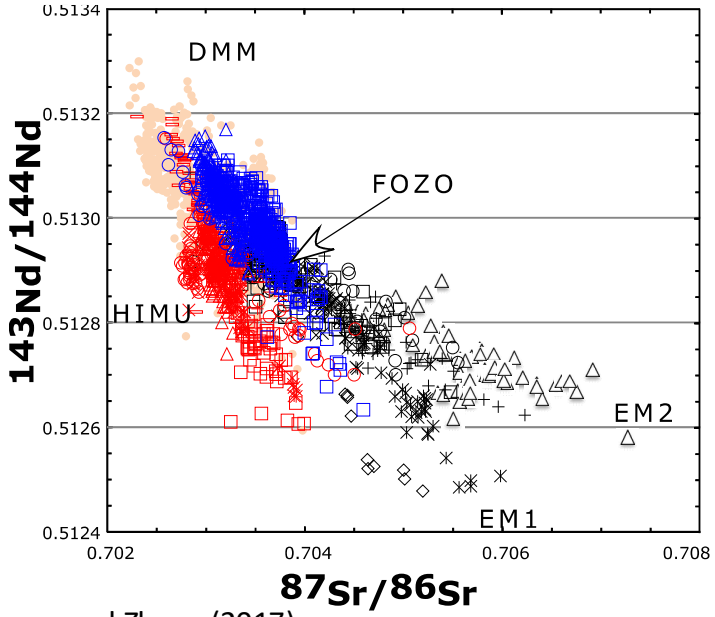
- Element and isotopic compositions are used as "fingerprints"
- Elements are fractionated in different ways by different geological processes
- Radiogenic isotope compositions reflect time-integrated element patterns
- Large isotopic variations in oceanic basalts require several mantle endmembers
- **What are the relationships between mantle endmembers and geophysical reservoirs?**

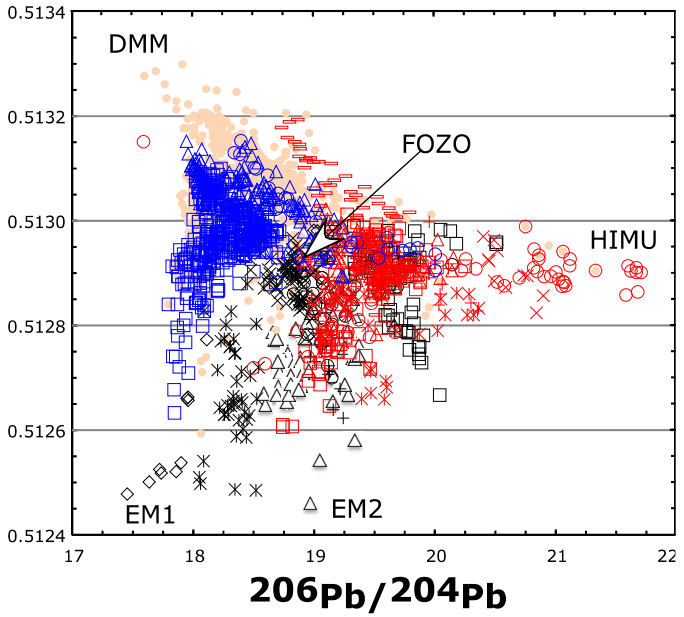




Huang and Zheng (2017)

Mantle Heterogeneity





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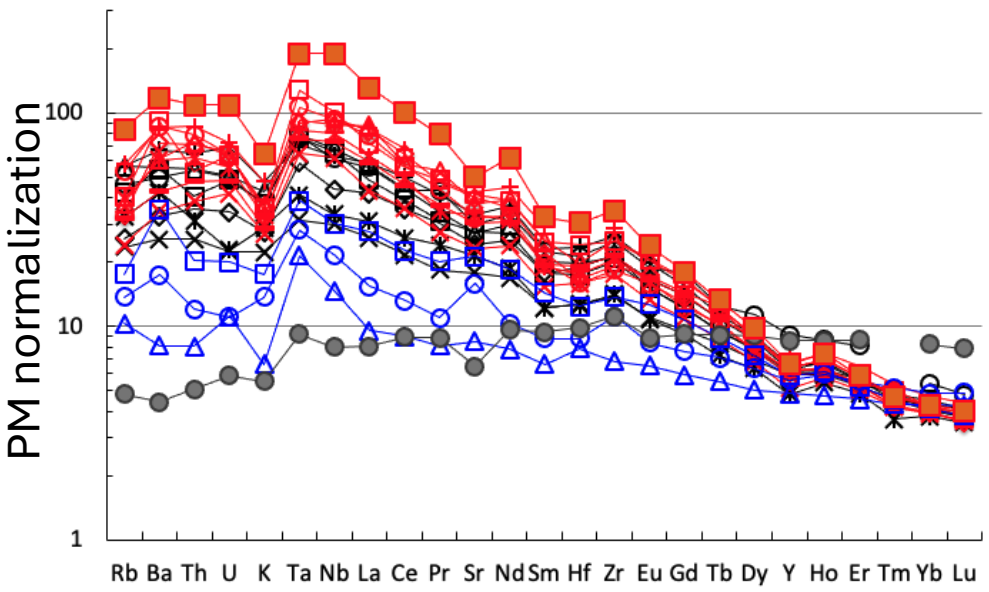

Huang et al. (2020)

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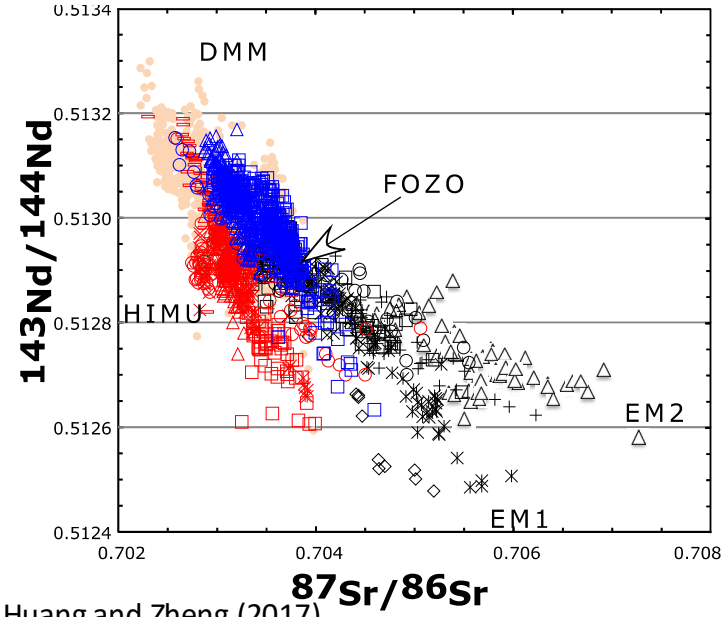
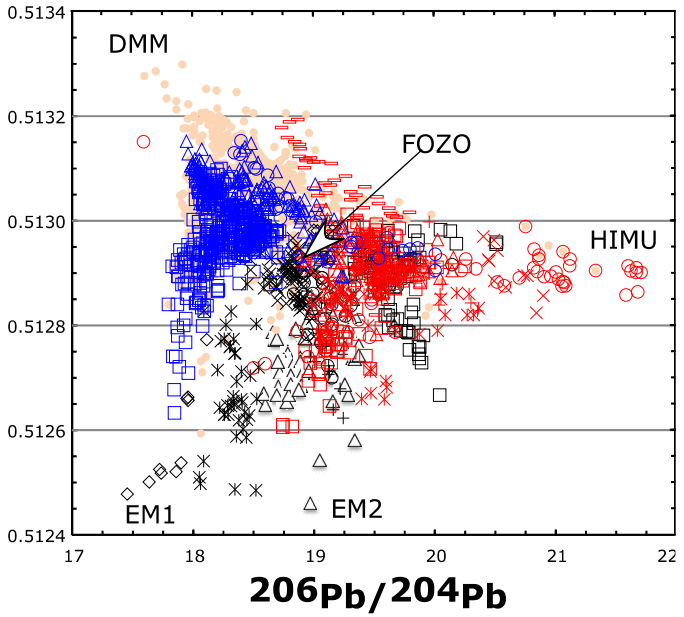
- EM I, EM II (enriched mantle)
  - recycled oceanic crust + sediment
- DMM (depleted MORB mantle)
  - upper mantle
- FOZO (FOcus ZOne)
  - high $^{3}He/^{4}He$, probably from the lower mantle
- HIMU (high U/Pb)
  - recycled altered MORB, probably with carbonates
  - carbonatite-metasomatized subcontinental lithospheric mantle

Mantle Heterogeneity





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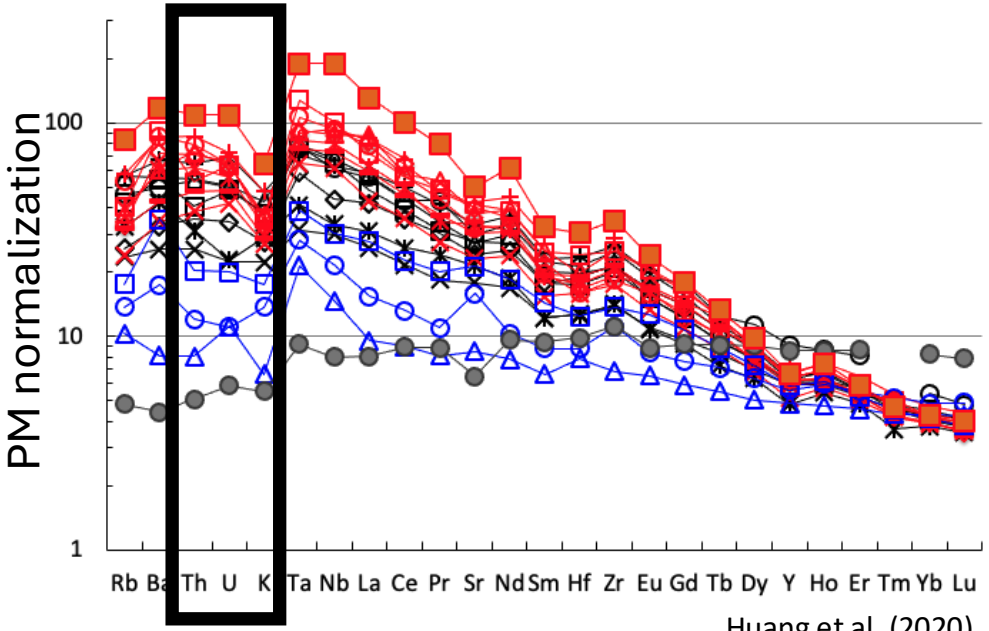

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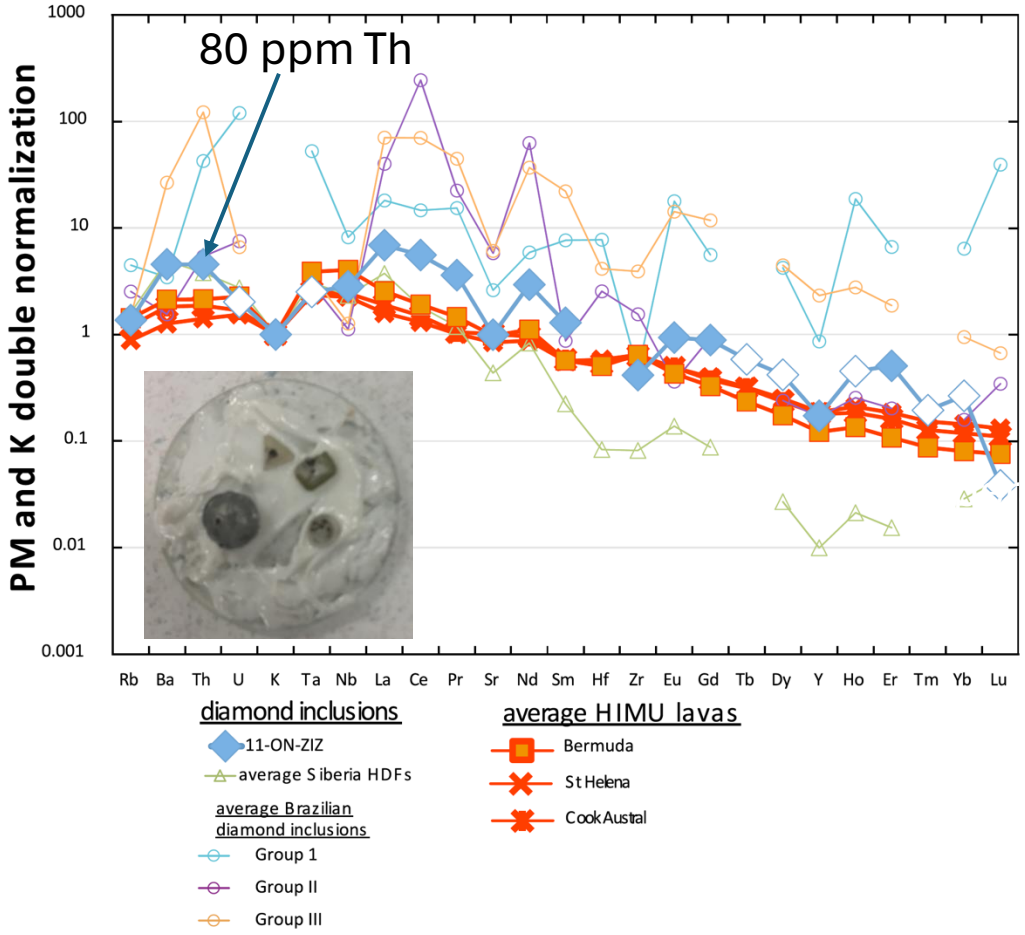
- HIMU (high U/Pb) – **also rich in U-Th-K, comparable to continental crust**
  - recycled altered MORB, probably with carbonates
  - carbonatite-metasomatized subcontinental lithospheric mantle

HIMU geochemical signature from the transition zone: Evidence from diamond inclusion



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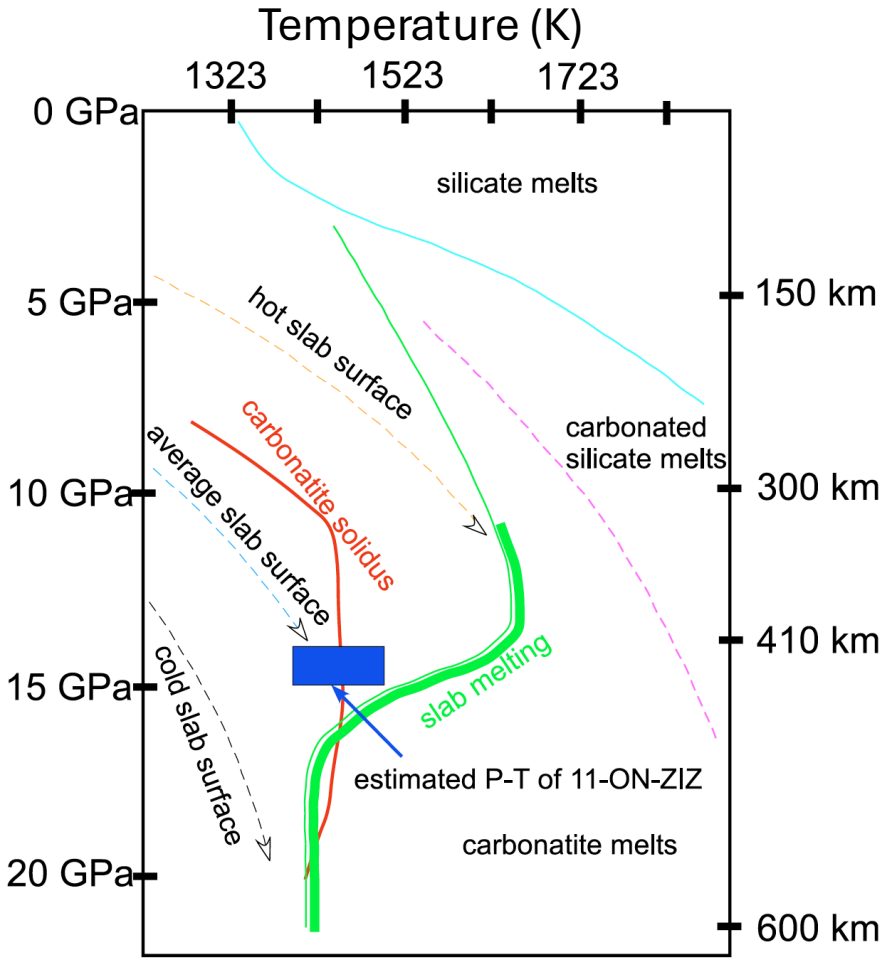

modified from Thomson et al. (2016)

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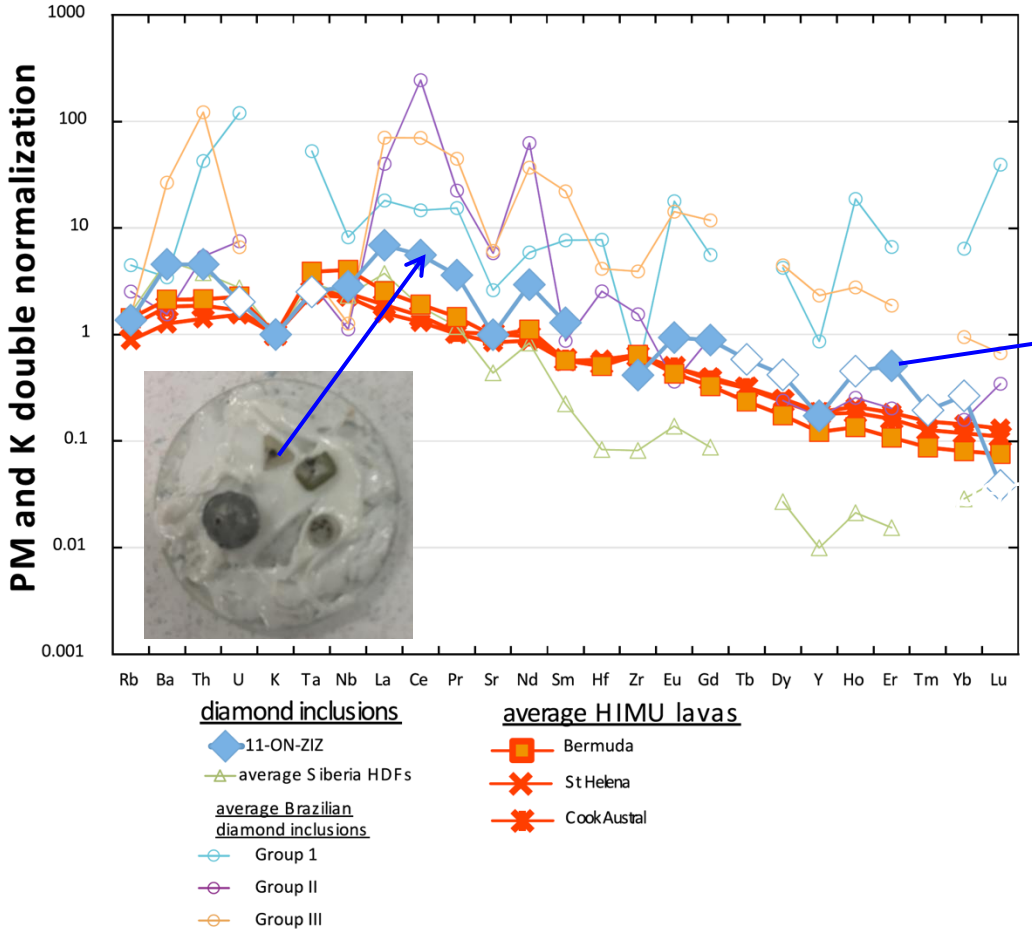

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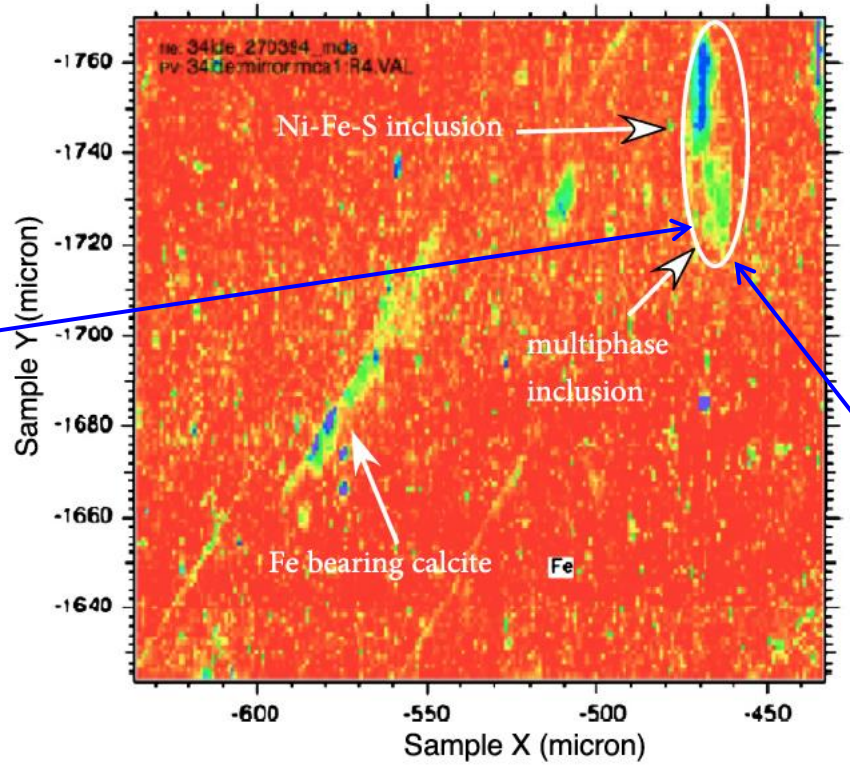
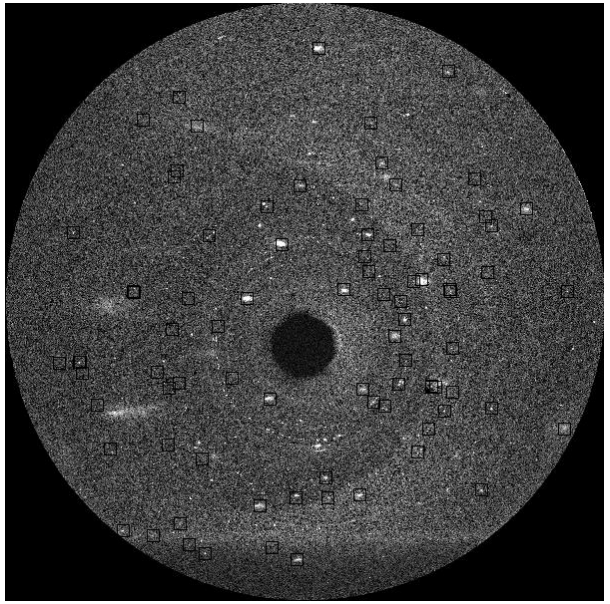


garnet-TAP (10Å phase)-liebermannite-ilmenite

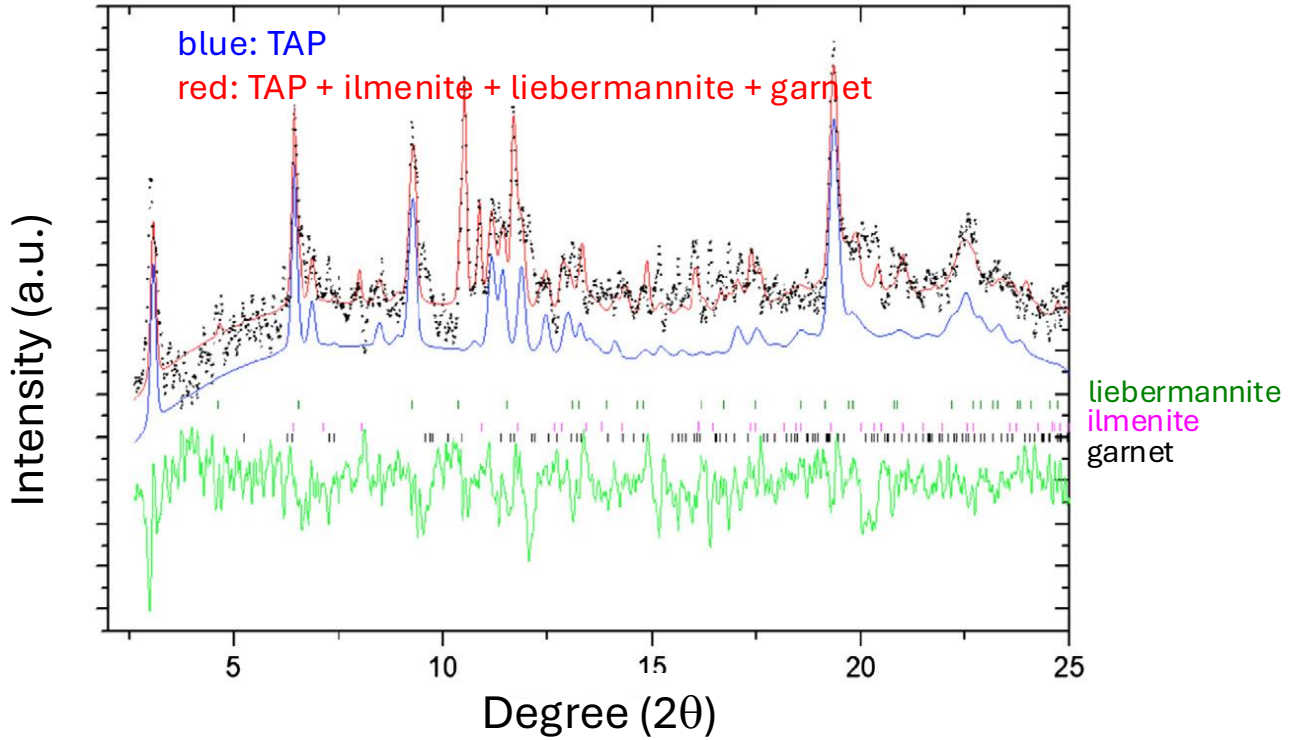
~5 x 50 microns

- Triangle-shaped diamond : 11-ON-ZiZ
  - from CalTech mineral collection
  - unknown provenance
- Thickness: 1.0 mm
- Double polished with top and bottom faces normal to [111]
- Synchrotron XRD, XRF, IR
- LA-ICP-MS

Mineralogy of HIMU diamond inclusion



garnet generates
single crystal diffraction

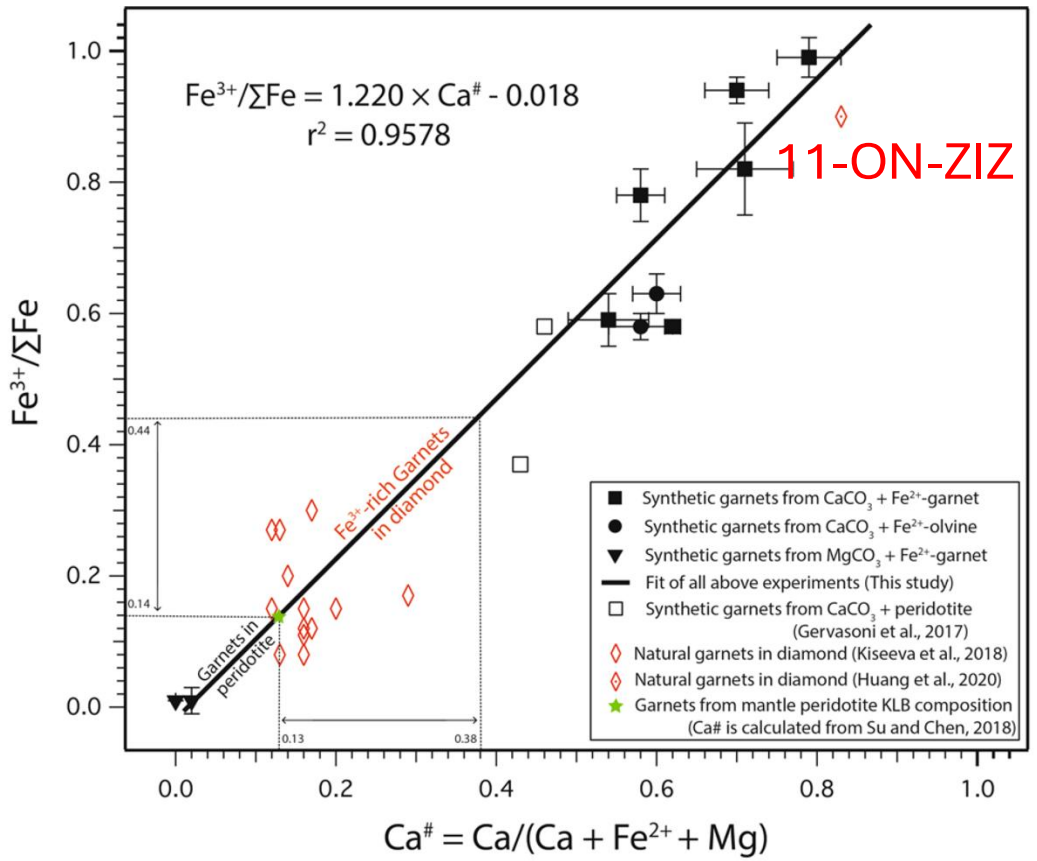


integrated diffraction pattern of fine-grained fraction from left panel

- Diffraction frame taken from the center of the inclusion
- Garnet single crystal peaks are labeled with black boxes (left)
- TAP (10Å phase), minor ilmenite, and possibly liebermannite generate the faint Debye fringes superimposed on the garnet single crystal pattern (right)

HIMU diamond inclusion is highly oxidized

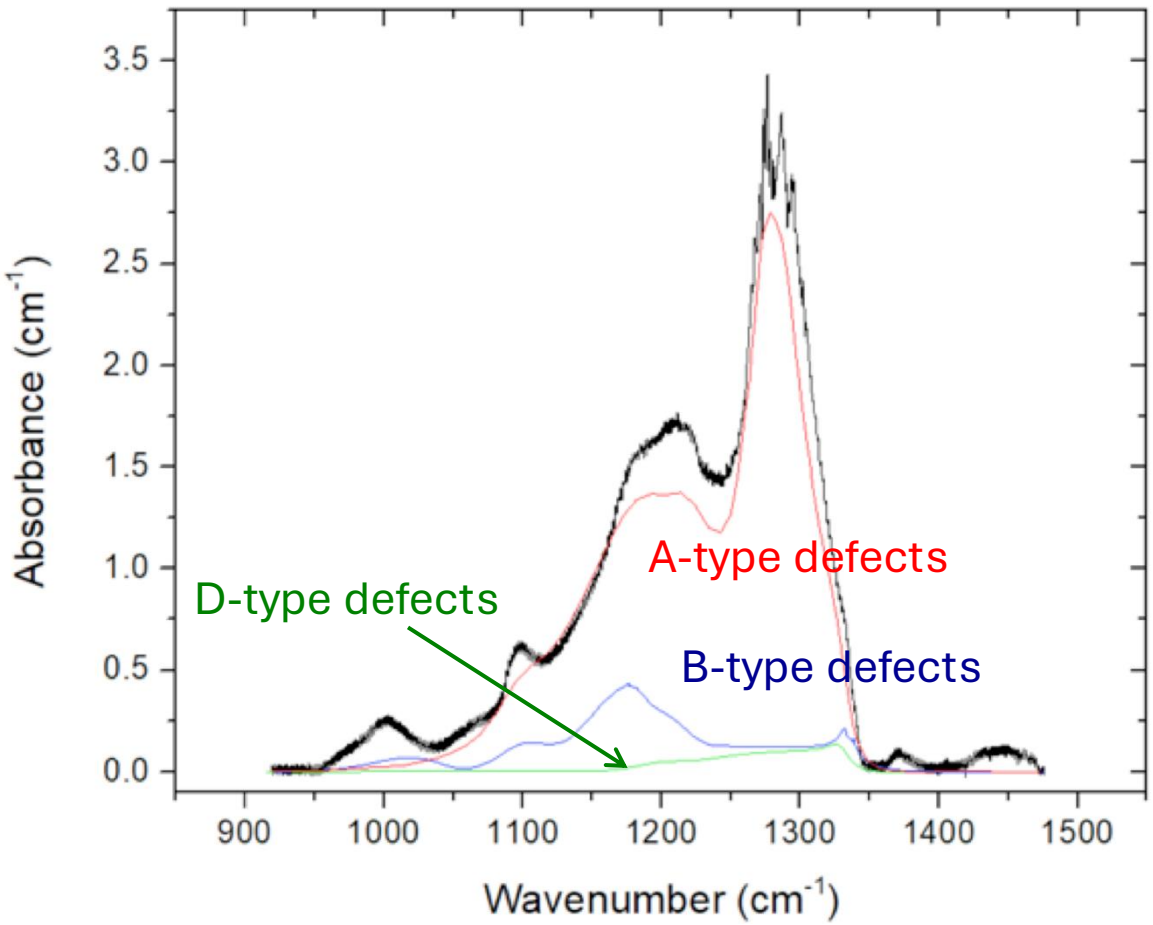
	Garnet	TAP	Liebermannite	Ilmenite	Eskolaite
Na_2O	0.24(2)	0.14(1)	0.06(6)	0	0
MgO	0.35(1)	2.63(1)	0	0.08(5)	0
Al_2O_3	0.53(2)	0.21(1)	1	0	0
SiO_2	3.33(1)	3.79(1)	3	0	0
K_2O	0.4(4)	0.06(3)	0.95(5)	0	0
CaO	2.35(0)	0	0	0	0
Sc	0	0	0	0	0
TiO_2	0.13(6)	0	0	1	0.01(1)
V	0	0	0	0	0
Cr	0.06(6)	0	0	0	1.1(1.0)
MnO	0.01	0	0	0	0
FeOT	1.0(0)	0.19(2)	0	0.92(5)	0.10(7)
mol%	77.8(2.0)	10.8(1.2)	6.5(2)	2.9(9)	1(1)



Tao and Fei, 2021

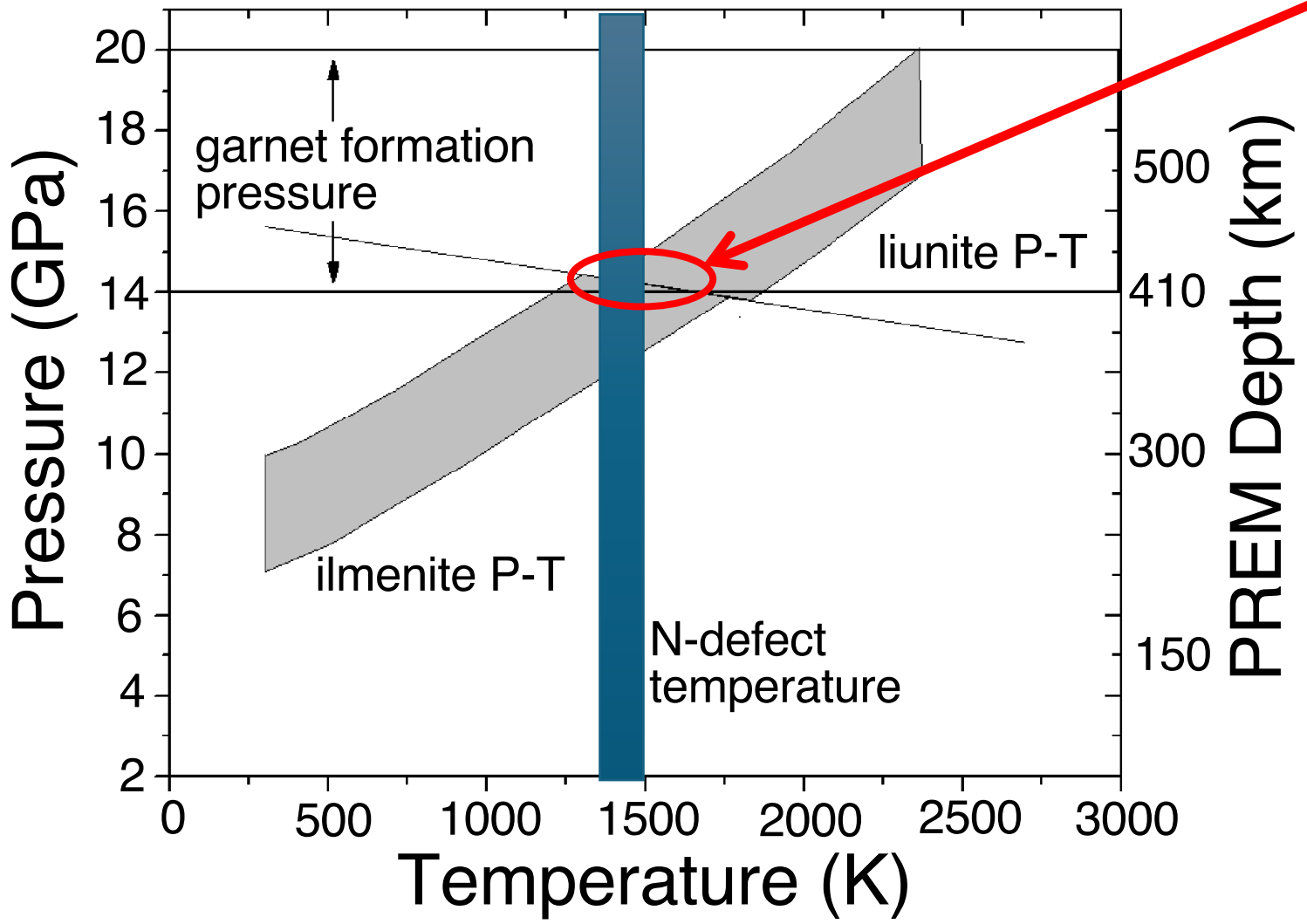
- ❑ Bulk chemical composition of the multiple-phase inclusion by LA-ICP-MS
- ❑ Relative proportions of each mineral phases by XRD
- ❑ Distribute atoms among different minerals
- ❑ $Fe^{3+}/\Sigma Fe$ of garnet is estimated using charge balance
  - ➢ consistent with experimental results

IR spectra: diamond formation temperature



- N abundance: 60-75 ppm
- A-type defects: 78-84%
- Diamond formation and residence temperatures: 1400 – 1500 K

Diamond inclusion entrapment P-T: 14-15 GPa, 1400-1500K



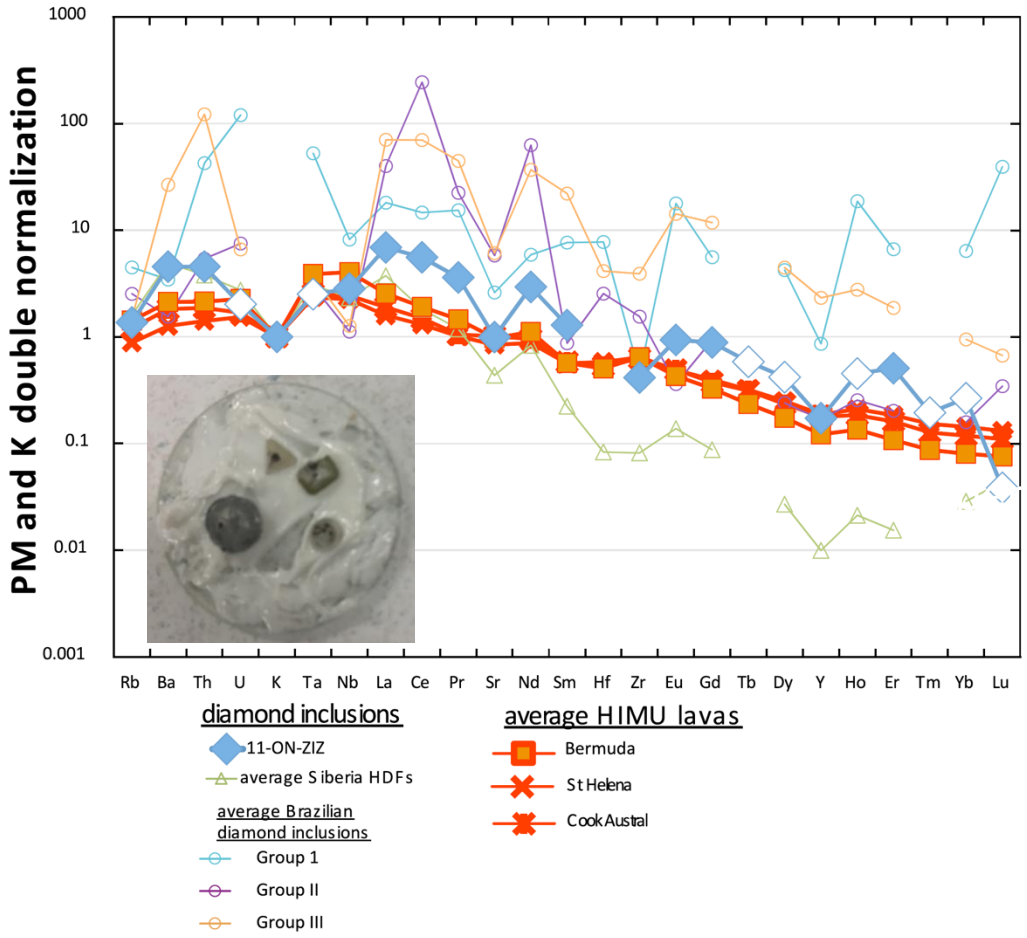
- Garnet formation pressure: majorite-rich garnet
- Ilmenite isomeke P-T: isostrain
- N defect temperature

HIMU geochemical signature from the transition zone

partial melts — reacts with Fe^{2+} silicates

carbonated MORB → carbonatite melt → diamond + Fe^{3+}-rich silicates

Rohrbach and Schmidt (2011)



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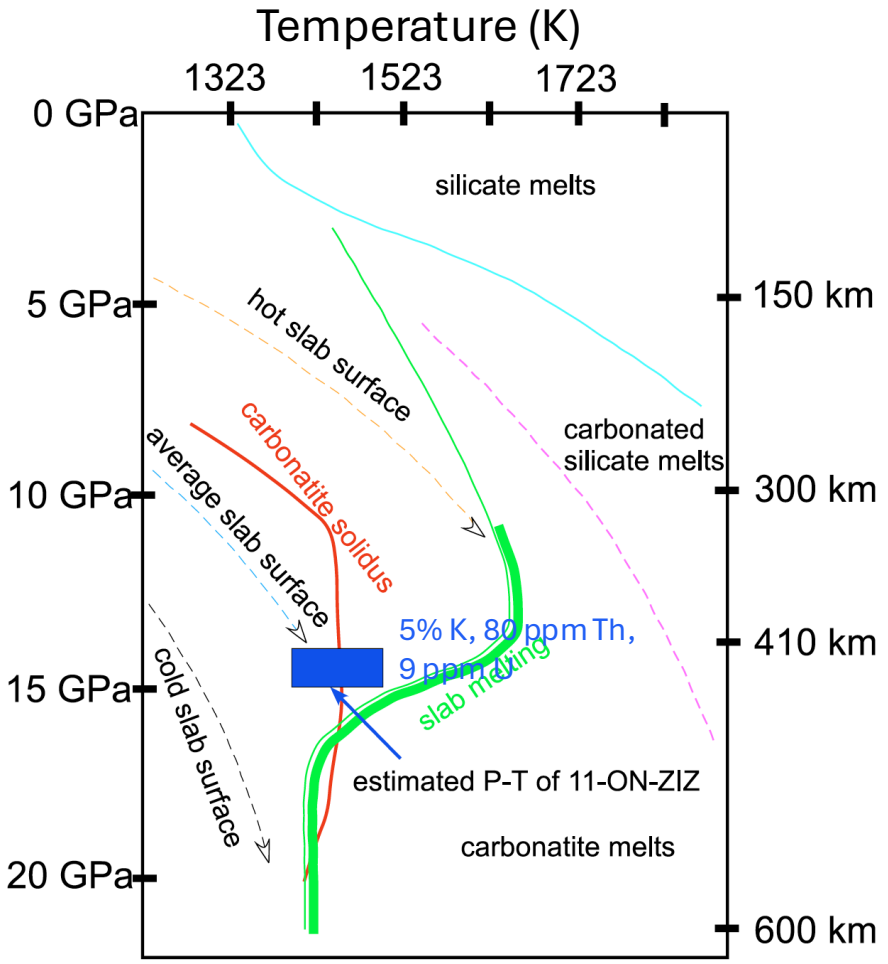
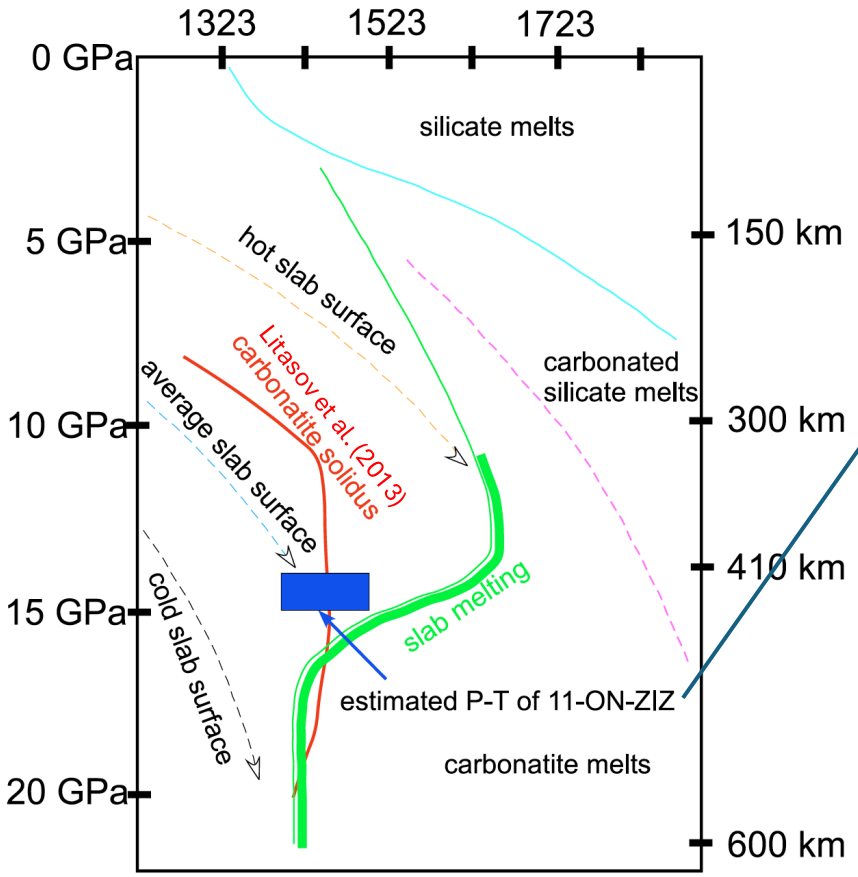
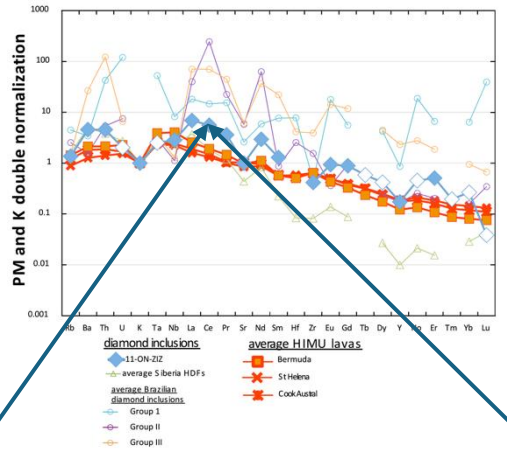


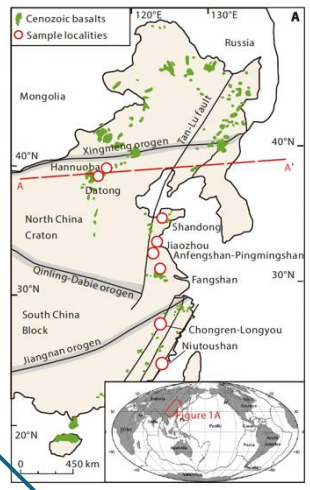
modified from Thomson et al. (2016)

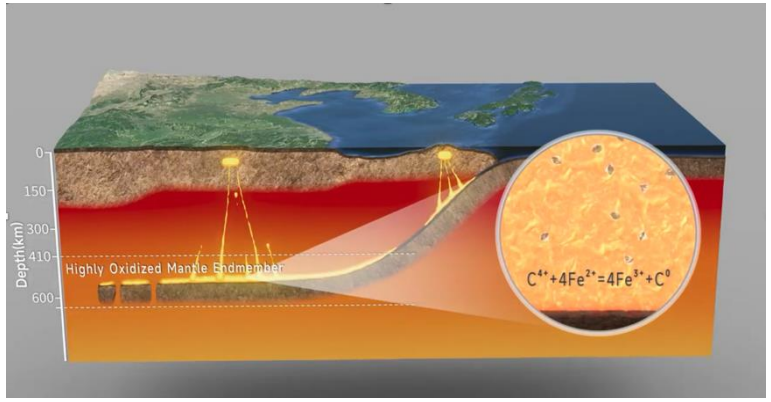
- Diamond inclusion entrapment P-T at the solidus of carbonated MORB
- HIMU source: recycled ancient MORB + carbonate at the mantle transition zone
- U-Th-K rich mantle domains at shallow transition zone

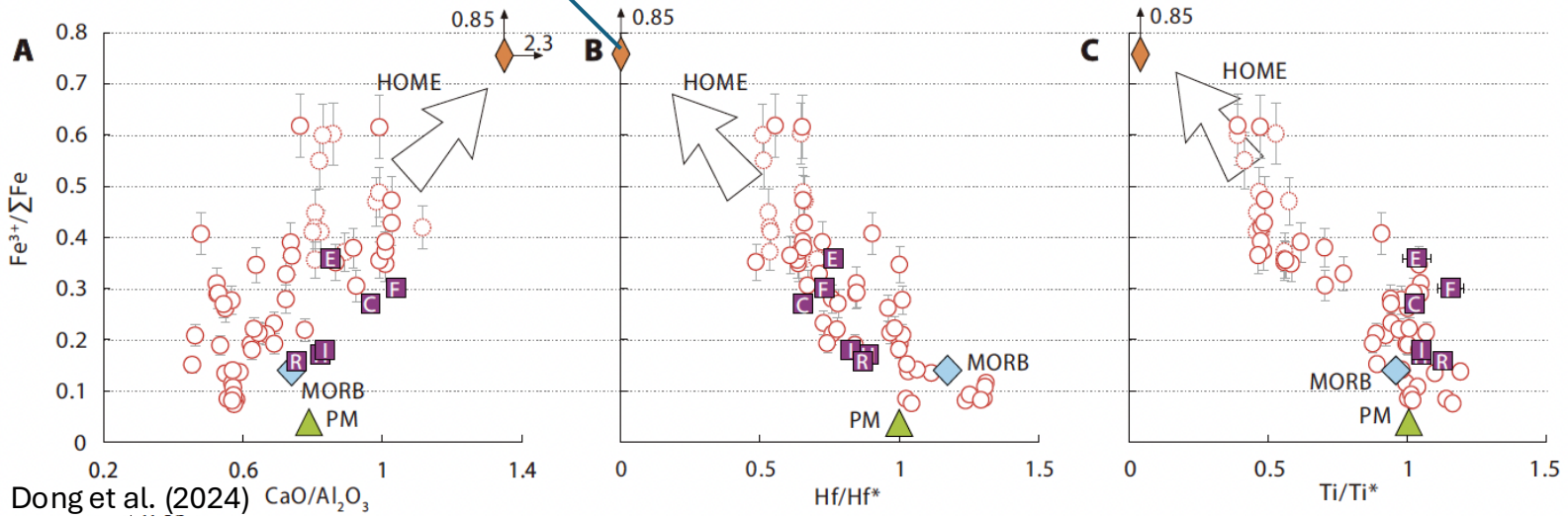
HIMU geochemical signature from the transition zone







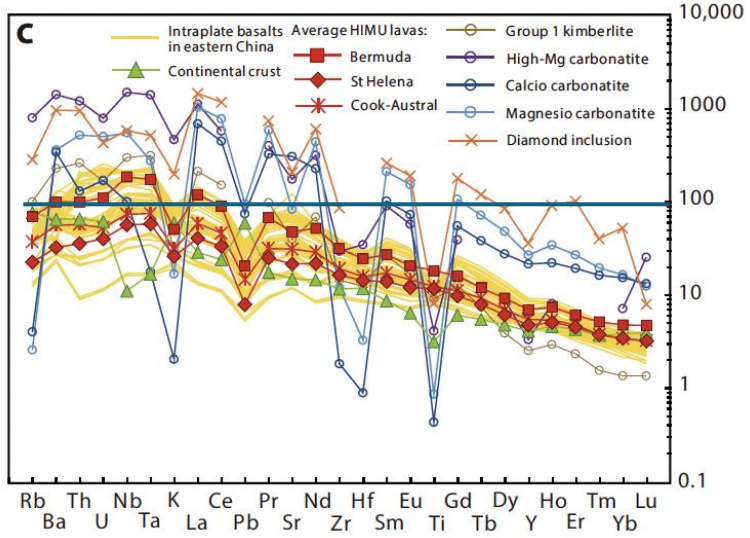




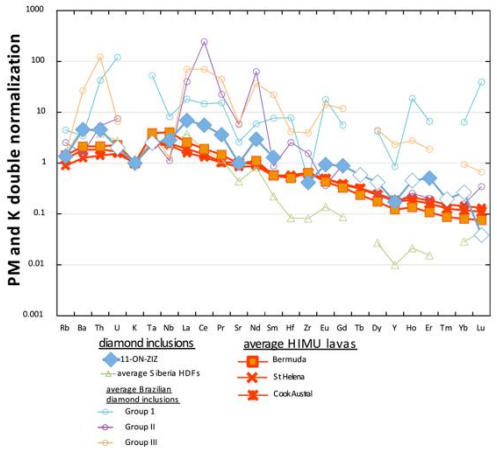
Dong et al. (2024)

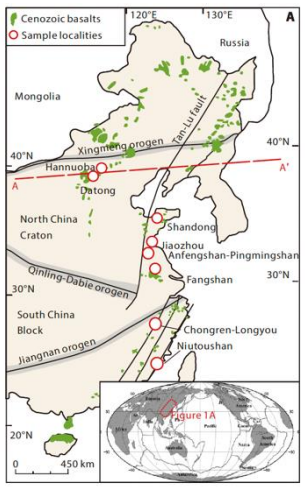
- ❑ Highly oxidized mantle endmember (11-ON-ZIZ) sampled by eastern China basalts and global OIBs
- ❑ U-Th-K-rich domains in the transition zone

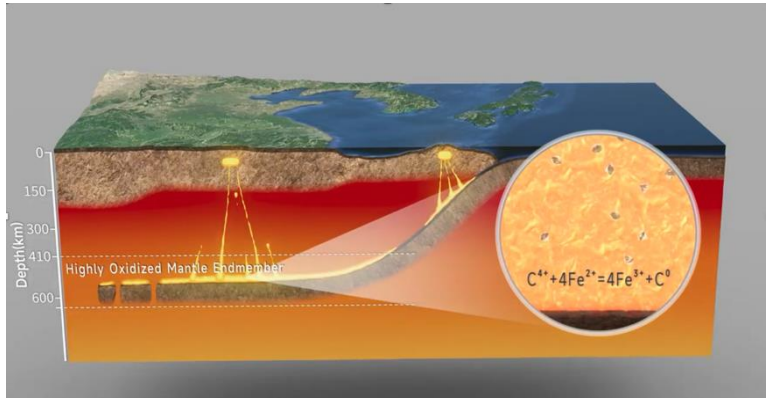
HIMU geochemical signature: High U-Th-K

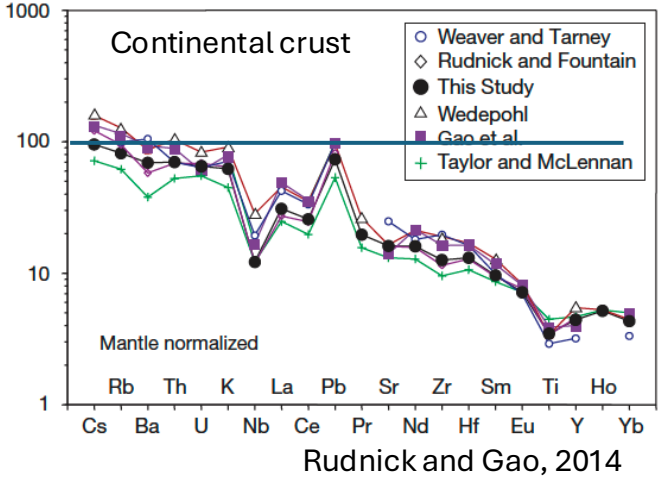


PM normalization

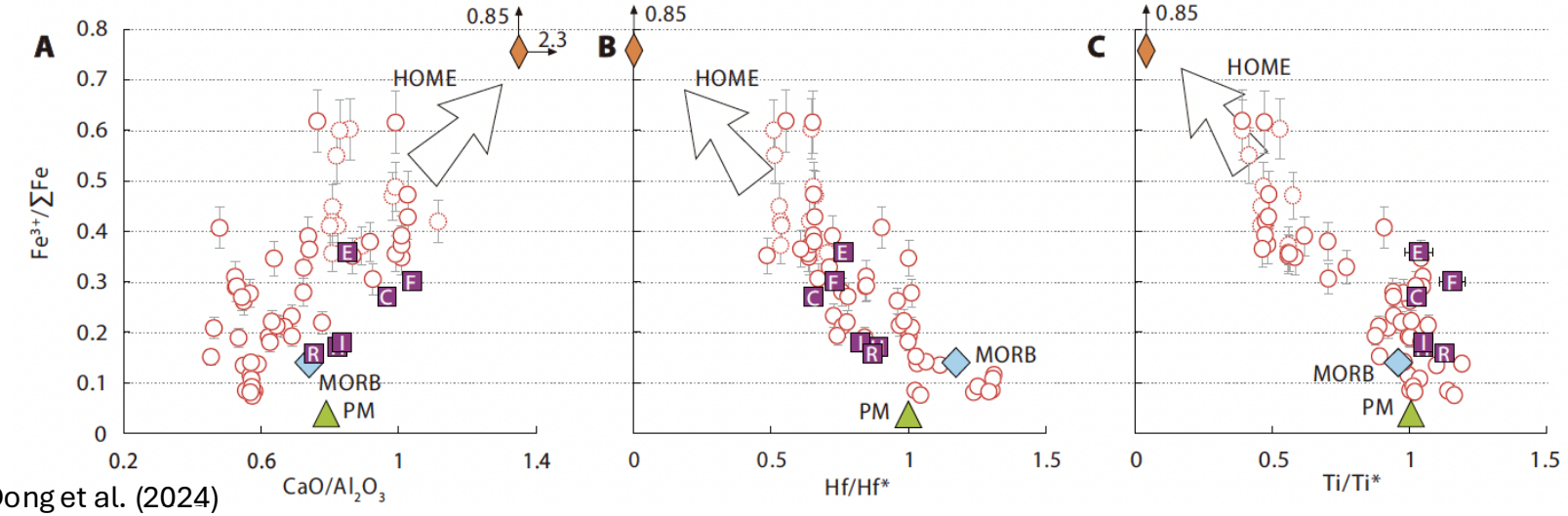








Rudnick and Gao, 2014



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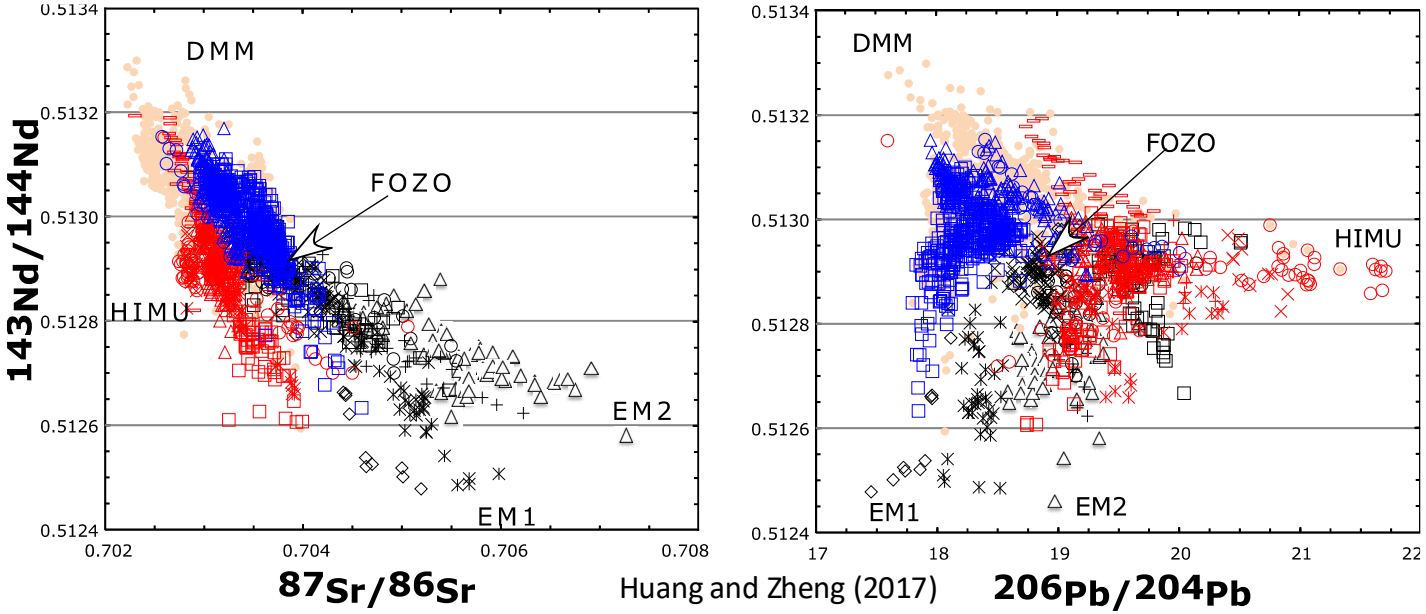
HIMU geochemical signature variably distributed in OIBs



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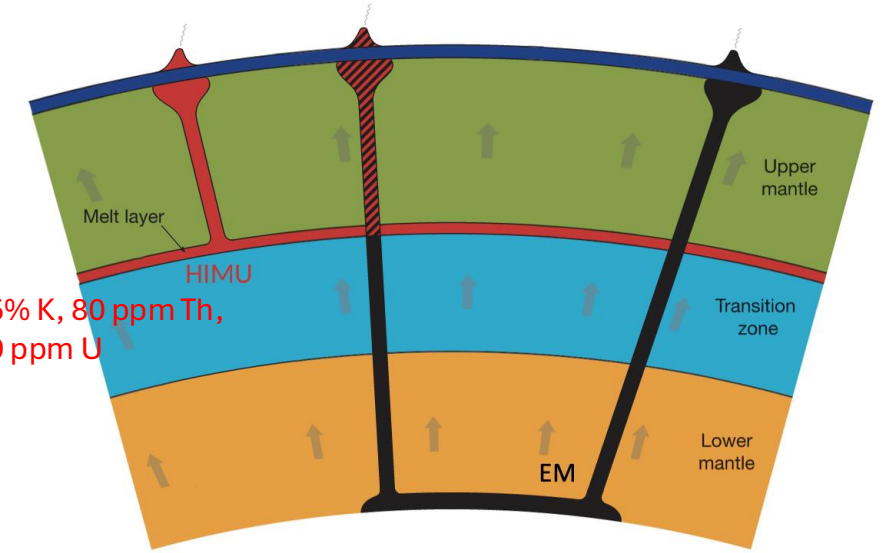
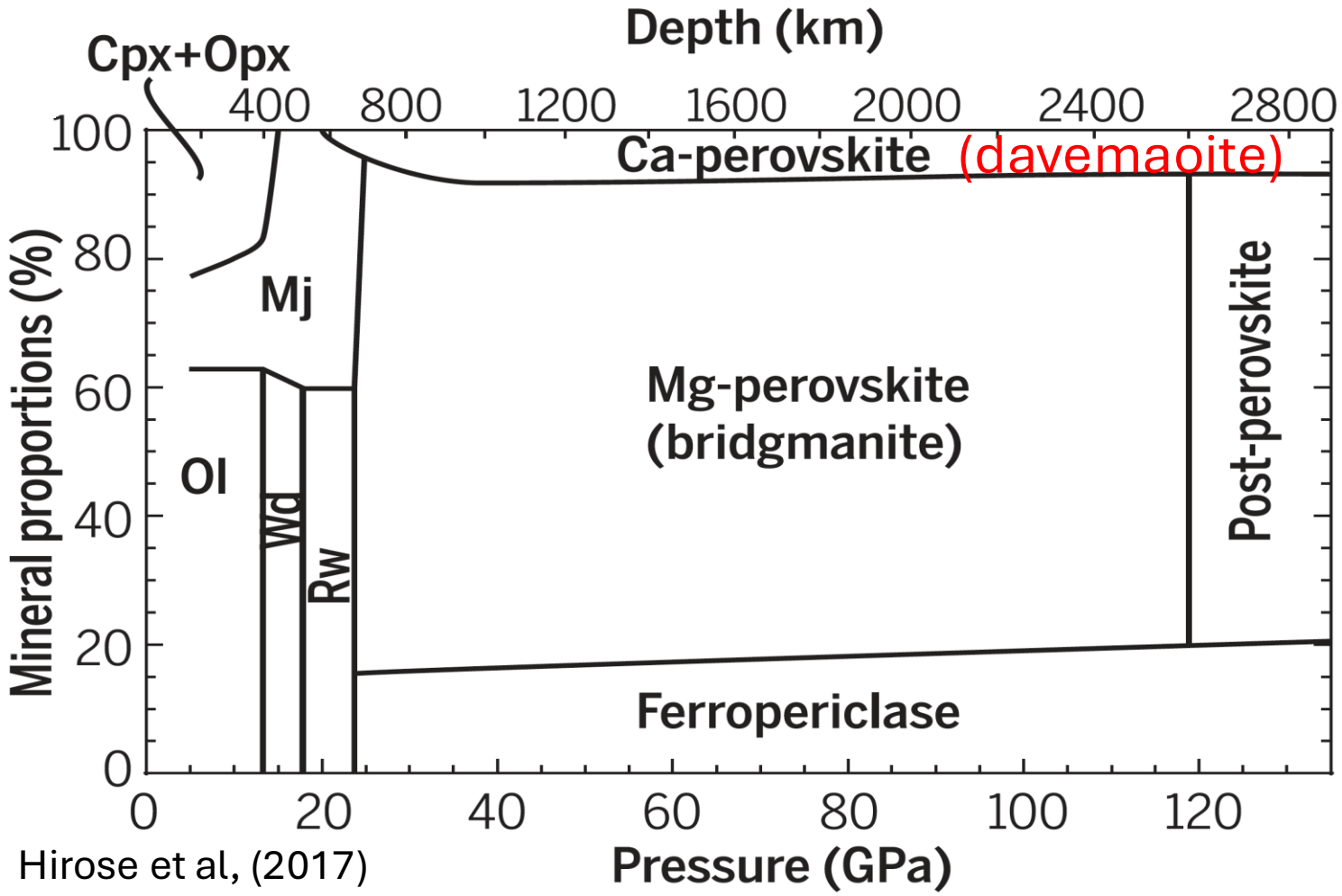


Modified from Bercovici and Karato (2003)

- Oceanic basalts form a continuous isotopic and compositional spectrum
- EM-dominated mantle plumes may originate from deep lower mantle
  - e.g., Samoa
- HIMU-dominated mantle plumes may originate from the transition zone
  - e.g., Bermuda, St Helena, Cook-Austral
- HIMU endmember contributes variably to global OIBs
  - HIMU source may be a global layer within the shallow transition zone
  - entrainment of transition zone material by mantle plumes of deeper origin

davemaoite: lower mantle host for K-Th-U



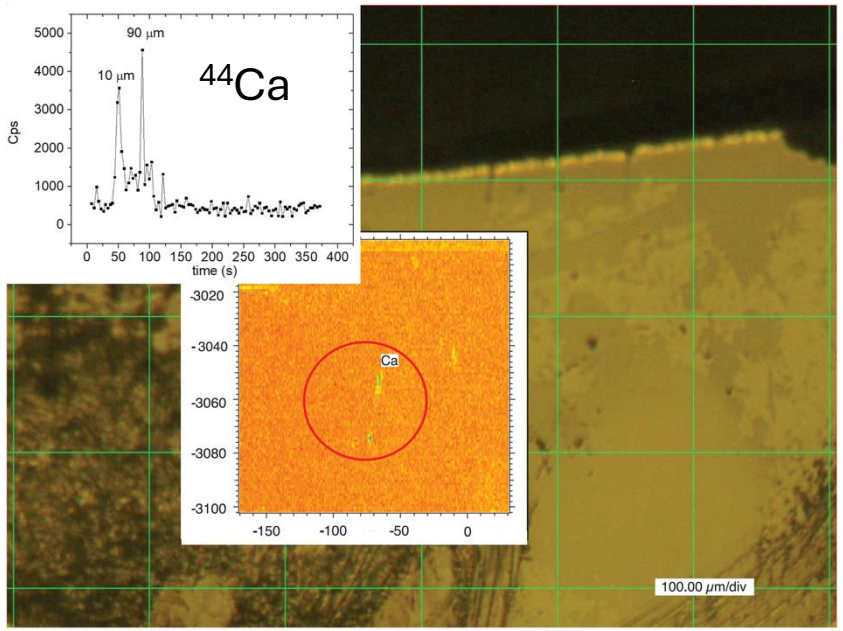
$CaSiO_3$

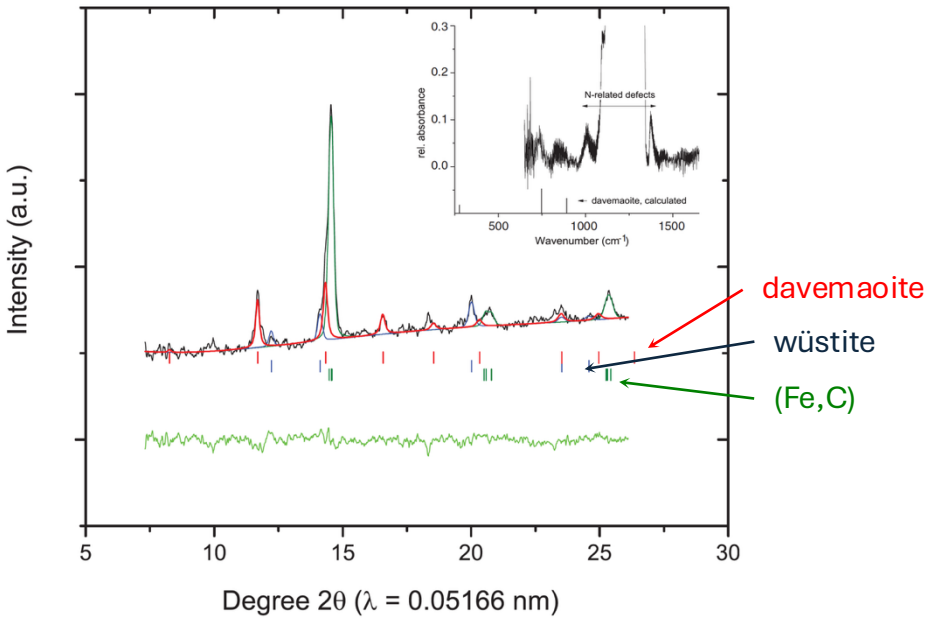
$(Mg,Fe)SiO_3$

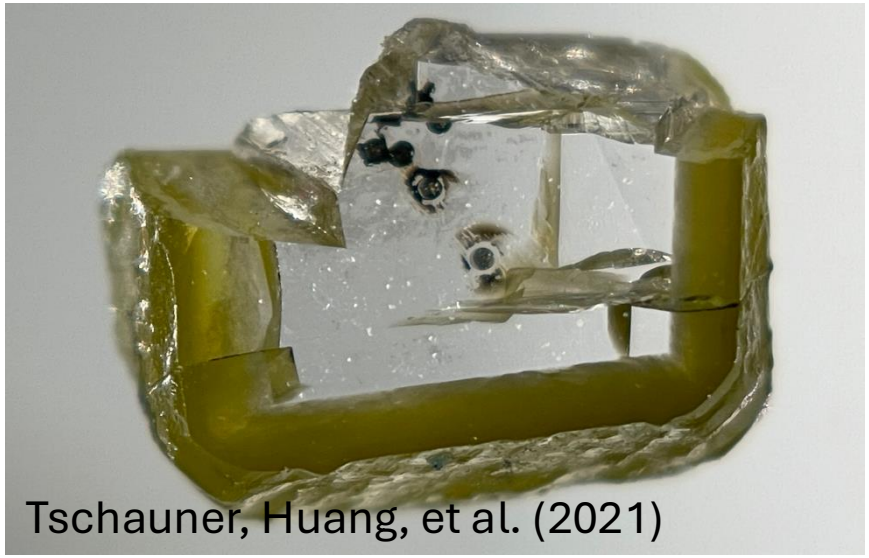
$(Mg,Fe)O$

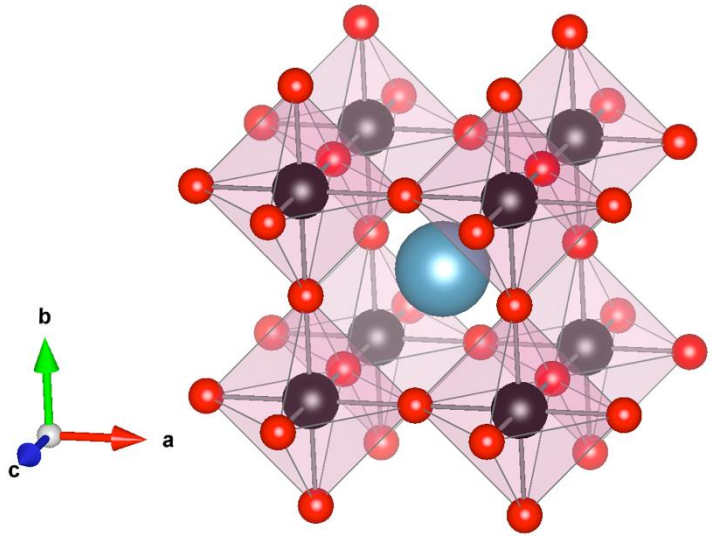
Hirose et al, (2017)

davemaoite: lower mantle host for K-Th-U







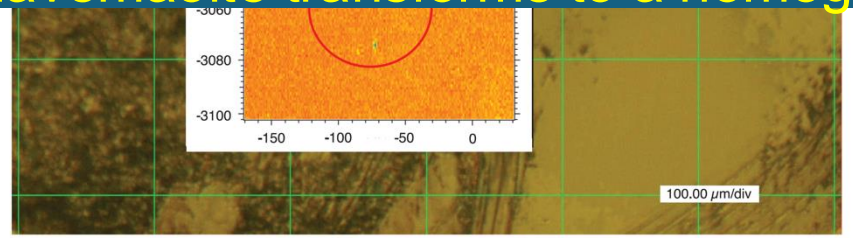


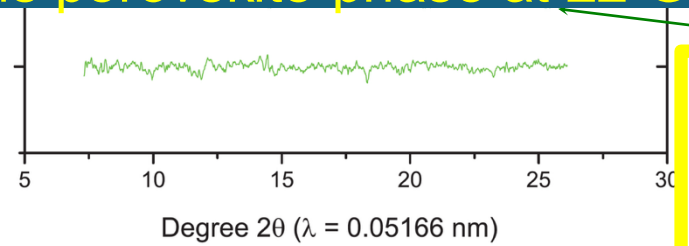
davemaoite: lower mantle host for K-Th-U

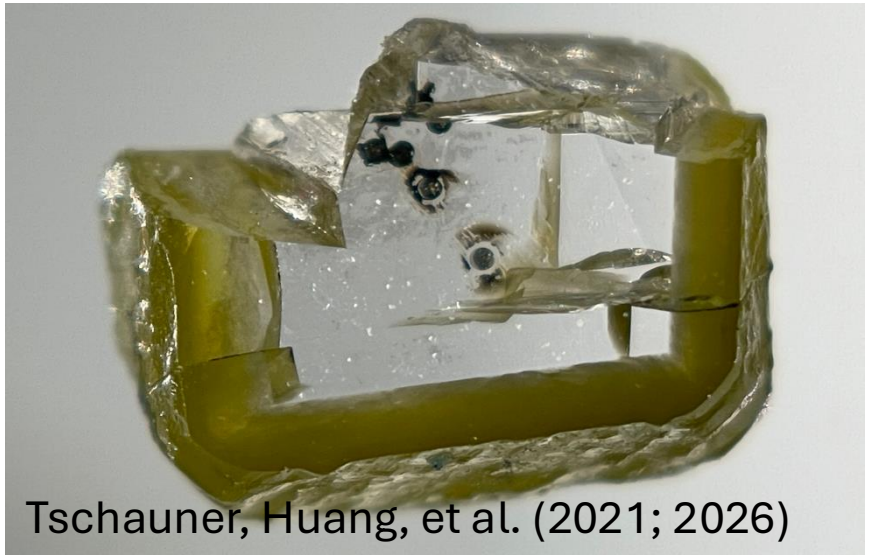
$(Ca_{0.43(1)}K_{0.20(1)}Na_{0.06}Fe_{0.11(1)}Al_{0.08}Mg_{0.06}Cr_{0.04(2)})(Si_{1.0(2)}Al_{0.00(1)})O_3$

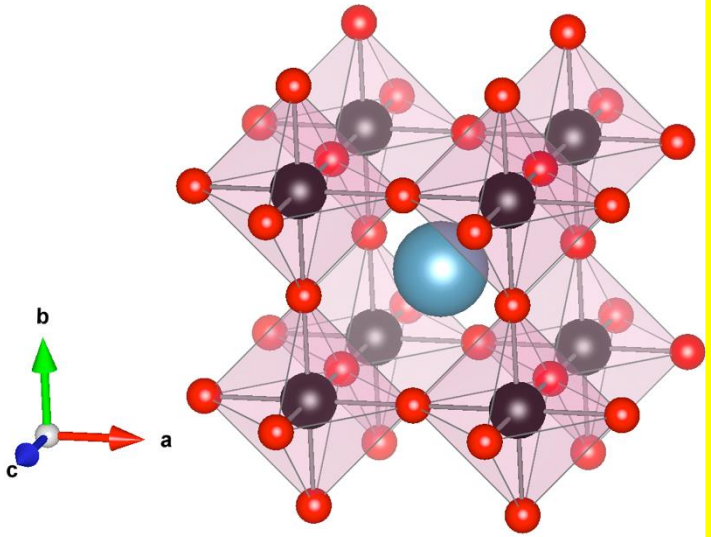
~4 wt% K

Our DAC experiment shows that glass of a composition close to that of type davemaoite transforms to a homogenous perovskite-phase at 22 GPa









Lower mantle "garbage can"

Davemaoite can thus host three of the major heat-producing elements (uranium and thorium were previously shown experimentally) affecting heat generation in Earth's lower mantle. —BG

davemaoite: lower mantle host for K-Th-U

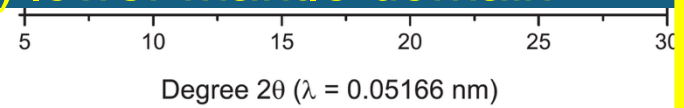
$(Ca_{0.43(1)}K_{0.20(1)}Na_{0.06}Fe_{0.11(1)}Al_{0.08}Mg_{0.06}Cr_{0.04(2)})(Si_{1.0(2)}Al_{0.00(1)})O_3$

~4 wt% K

Our DAC experiment shows that glass of a composition close to that of type davemaoite transforms to a homogenous perovskite-phase at 22 GPa

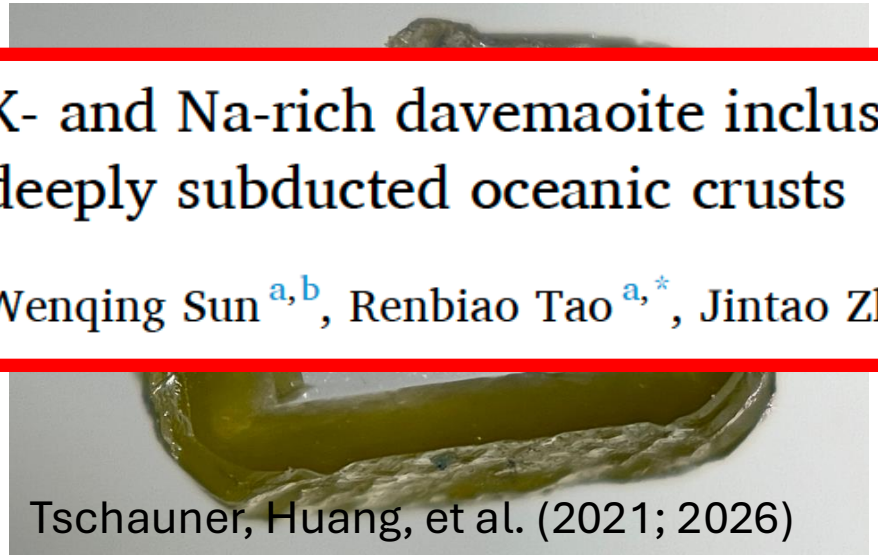
A K-(U-Th)-enriched (higher than HIMU) lower mantle domain



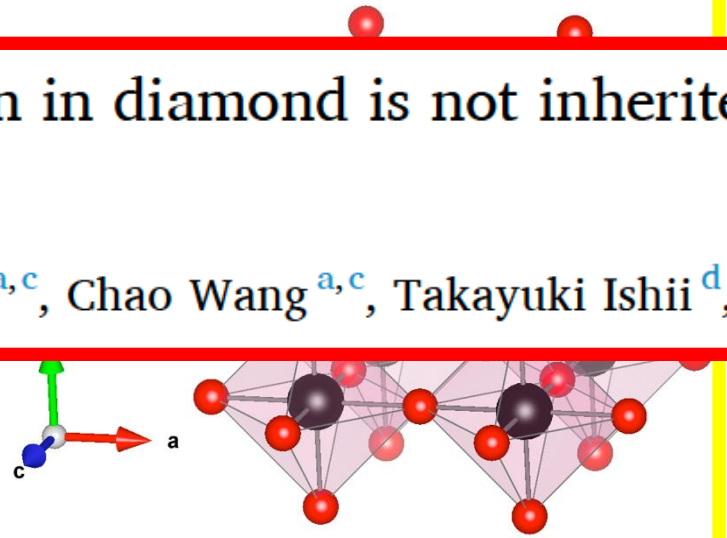


K- and Na-rich davemaoite inclusion in diamond is not inherited from deeply subducted oceanic crusts

Wenqing Sun [a,b], Renbiao Tao [a,*], Jintao Zhu [a,c], Chao Wang [a,c], Takayuki Ishii [d], Yunxiu Li [e]



Tschauner, Huang, et al. (2021; 2026)



Lower mantle "garbage can"

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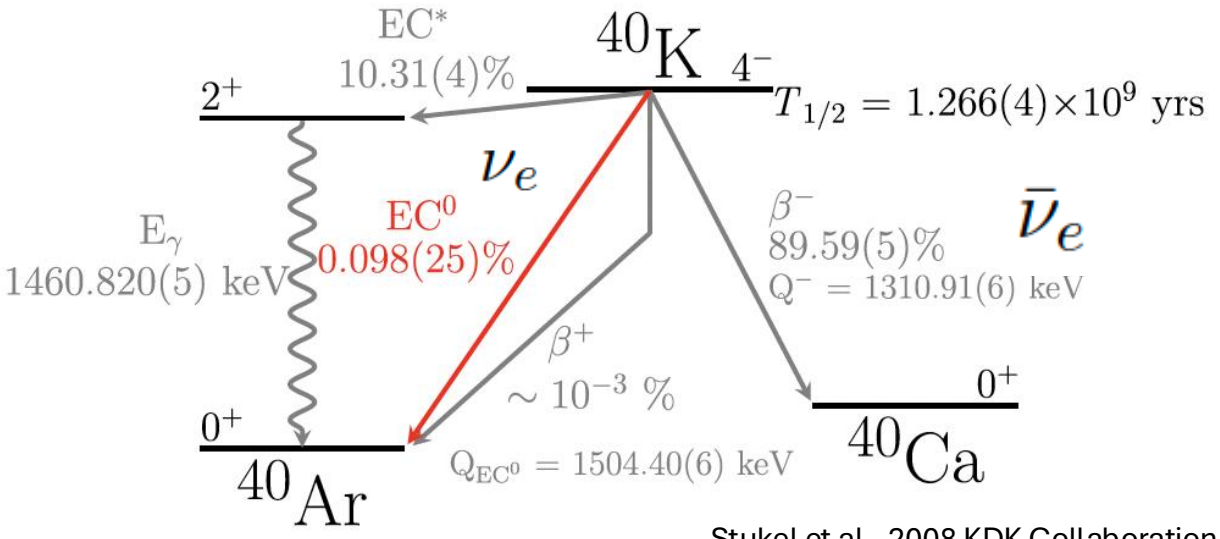
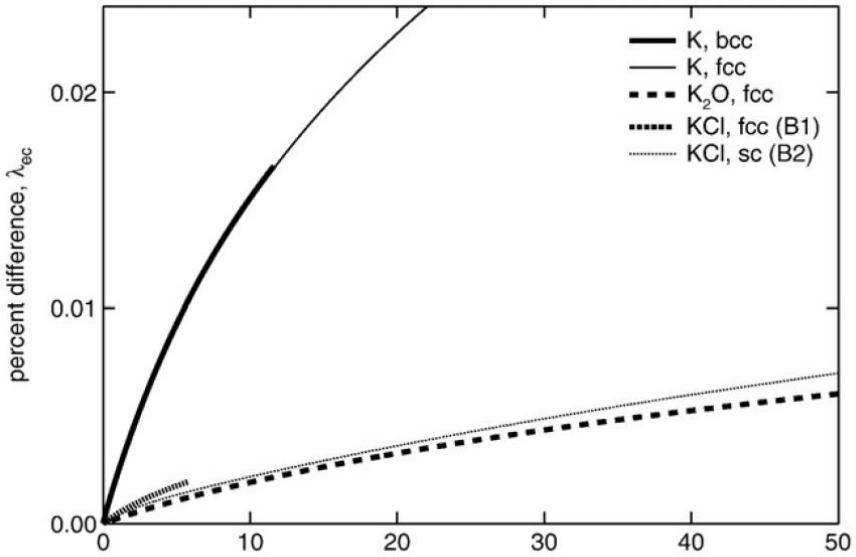
Potassium decay constant is not constant and a possible ^{40}K neutrino barometer



Stukel et al., 2008 KDK Collaboration



Lee and Steinle-Neumann, 2008

- Demonstrated by diamond-anvil experiments (Liu and Huh, 2000) and through chemical shift (Norman et al., 2001) for the ^{7}Be-^{7}Li system with a half-life of ~53 days
- First experiment about the possible pressure effect on ^{40}K EC was conducted ~50 years ago without conclusive result
- Norman et al. (2001) reported no measurable (at ±1% level) chemical effect on ^{40}K EC decay
- A 0.02% increase in ^{40}K EC decay constant at 16 GPa (~450 km depth in the Earth) was predicted (Lee and Steinle-Neumann, 2008)
- ^{40}K EC and beta decay release different types of neutrino, allowing a possible ^{40}K neutrino barometer

Summary

- Estimates of bulk Earth HSE compositions are model dependent
  - U : 10 – 23 ppb
  - Th: 40 – 90 ppb
  - K : 120 - 1872 ppm
  - Their concentrations help understand the internal structure (1D) of the Earth
- HIMU mantle endmember, with U-Th-K ~100 x PM, in the mantle transition zone
- Eastern China basalts have HIMU signature, which may contribute to the observed JUNO geoneutrino signal
- Davemaoite is the major U-Th-K host in the lower mantle
- The type davemaoite contains ~4 wt% K, implying a K-(U-Th)-enriched lower mantle domain
- Possible pressure and chemical effects on the ^{40}K electron capture decay may provide basis for developing a ^{40}K neutrino barometer