Thermal constraints on the ureilite parent body (UPB): Evidence from the refractory spinel in polymict ureilite EET 87720 using *in situ* SIMS

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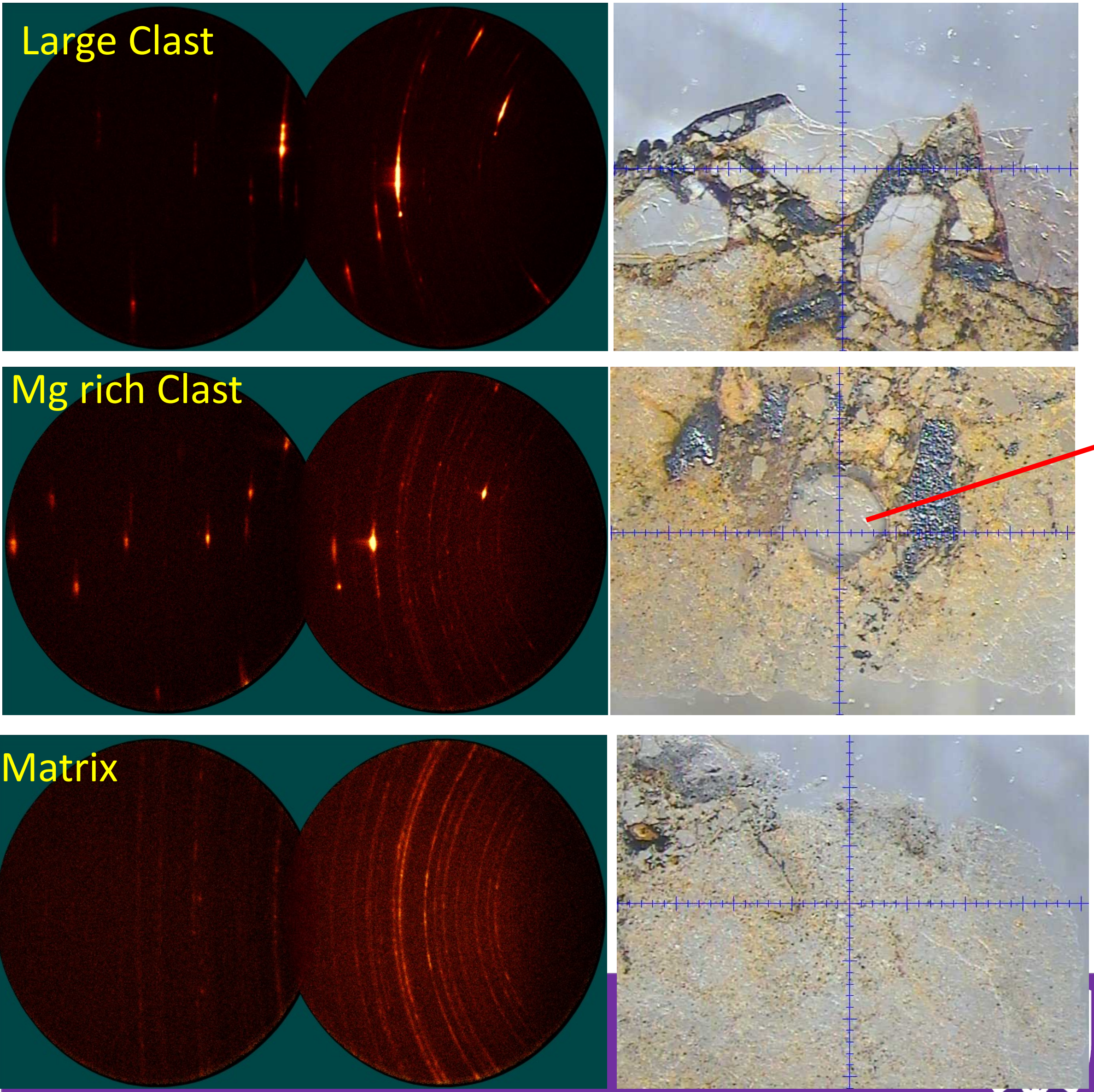
Supplementary Materials

Western Science

Supplementary Material: Olivine Comp. Overview



Olivine Composition

	Fo	Fa	Ca-Ol	Mn-Ol	Mg/(Mg+Fe)	Target Type
EET_87720_grain2_01	78.22	20.3	0.5	0.58	79.50	Clast
EET_87720_grain2_02	90.27	8.78	0.45	0.5	91.14	Clast
EET_87720_grain3_05	95.43	3.84	0.2	0.53	96.13	Matrix
EET_87720_grain3_06	85.52	12.57	1.38	0.54	87.19	Matrix
EET_87720_grain4_01	79.83	19.19	0.51	0.47	80.62	Clast
EET_87720_grain4_02	79.99	19.05	0.49	0.47	80.77	Clast
EET_87720_grain6-9_01	74.2	24.82	0.52	0.46	74.93	Clast
EET_87720_grain6-9_03	79.16	19.81	0.57	0.47	79.99	Clast
EET_87720_grain6-9_05	84.06	14.97	0.43	0.54	84.88	Matrix
EET_87720_grain6-9_06	90	8.93	0.55	0.51	90.97	Matrix
EET_87720_grain6-9_09	77.13	22	0.41	0.45	77.80	Clast
EET_87720_grain10_01	94.76	2.33	0.42	0.51	97.64	Clast
EET_87720_grain10_02	98.05	1.27	0.37	0.3	98.72	Clast
EET_87720_grain10_03	98.79	0.57	0.34	0.3	99.43	Matrix
EET_87720_grain10_04	74.49	18.93	5.76	0.52	79.80	Clast
EET_87720_grain10_05	90.91	8.11	0.42	0.56	91.81	Clast
EET_87720_grain10_06	76.1	22.93	0.52	0.44	76.84	Clast
EET_87720_grain12-13-16-17_02	73.84	25.32	0.35	0.49	74.47	Matrix
EET_87720_grain12-13-16-17_zoomed_01	74.61	24.49	0.42	0.48	75.29	Matrix
EET_87720_grain12-13-16-17_zoomed_03	75.12	23.94	0.47	0.47	75.83	Matrix
EET_87720_grain14-15_01	72.98	26.2	0.33	0.49	73.58	Matrix
EET_87720_grain14-15_03	80.62	18.58	0.31	0.49	81.27	Matrix
EET_87720_grain14-15_05	78.52	20.64	0.33	0.51	79.18	Matrix
EET_87720_matrix1_01	74.3	24.83	0.37	0.51	74.95	Matrix
EET_87720_matrix1_05	87.18	11.85	0.39	0.57	88.03	Matrix

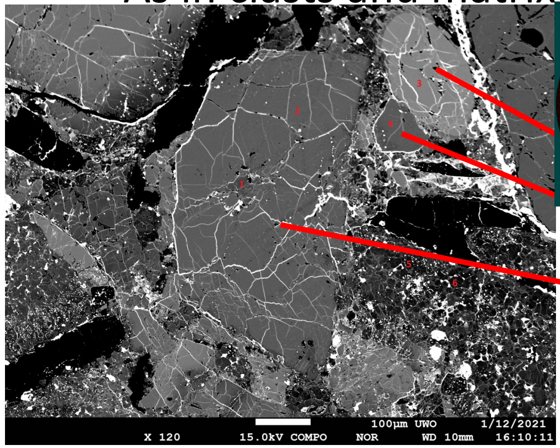
	Max	Min	Ol Ave Mg#	STDEV
Clast	98.72	74.93	84.13	8.33
Matrix	99.43	73.58	83.17	8.69

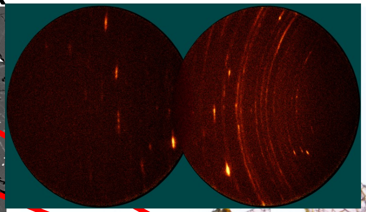
Supplementary Material: Pyroxene Comp. Overview

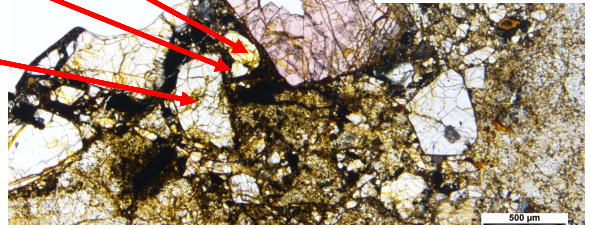
Opx – Pgt Pyroxene

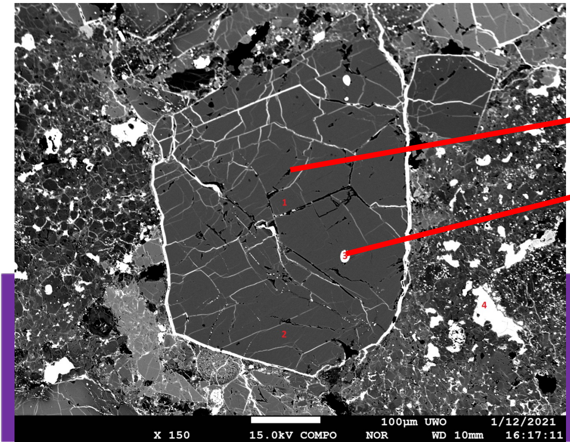
- Dominant by low-Ca pyroxene (Wo < 8.9%), Opx – pgt series
- NO high-Ca CPX found (e.g., augite)
- As in clasts and matrix

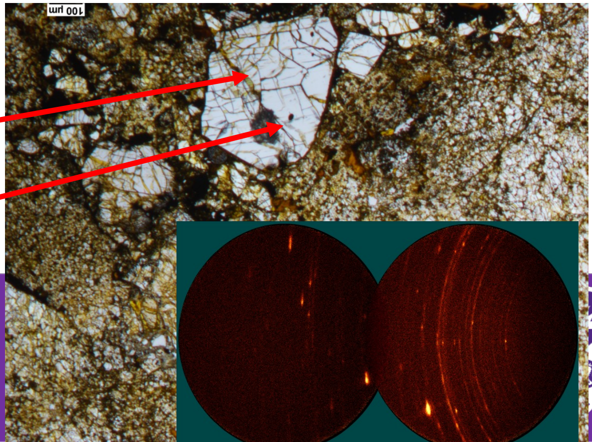
	Clast(N =7)	
	Average	**STDEV**
En	75.20	7.04
Fs	18.08	5.56
Wo	6.72	2.06
	Matrix (N =4)	
	Average	**STDEV**
En	81.19	12.14
Fs	14.11	7.97
Wo	4.66	7.97

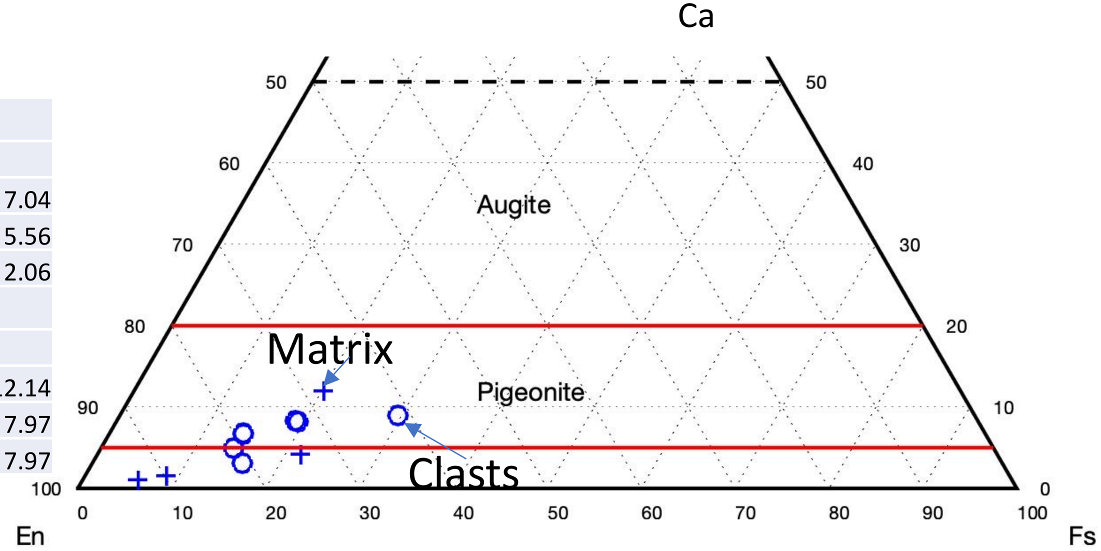








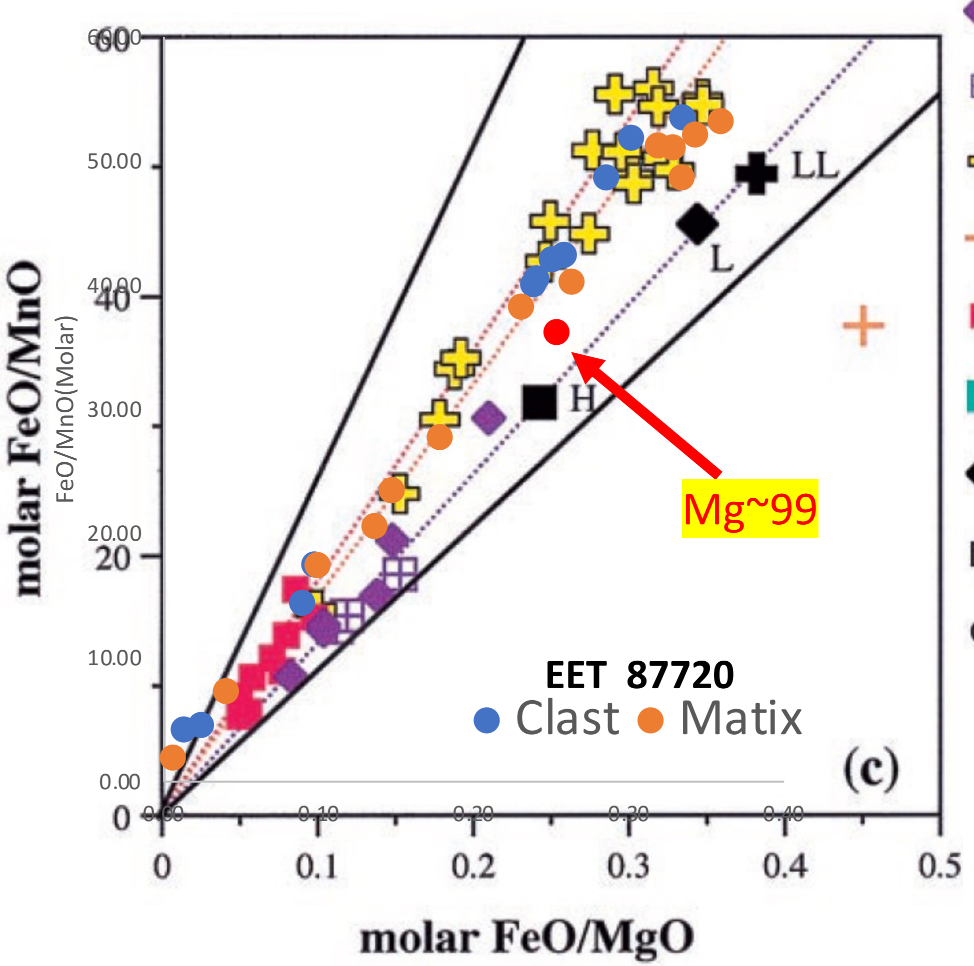


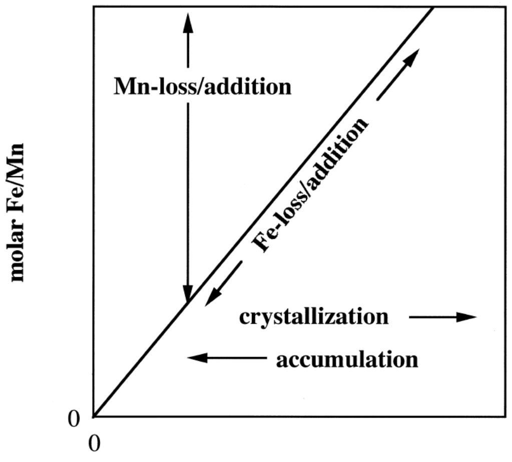


	En	Wo	Fs	Pyroxene Tyepe	Target Type
EET_87720_grain3_01	80.86	3.14	16	Opx	Clast
EET_87720_grain3_02	72.69	8.3	19.01	Pgt	Clast
EET_87720_grain3_03	61.44	8.92	29.64	Pgt	Clast
EET_87720_grain3_04	72.46	8.22	19.32	Pgt	Clast
EET_87720_grain5_01	78.95	6.79	14.25	Opx-Pgt	Clast
EET_87720_grain5_02	79.01	6.7	14.29	OPX – Pgt	Clast
EET_87720_grain6-9_02	80.97	4.98	14.05	OPX-Pgt	Clast
EET_87720_grain6-9_08	93.05	1.04	5.91	Opx	Matrix
EET_87720_grain12-13-16-17_zoomed_02	67.8	11.8	20.24	Pgt	Matrix
EET_87720_grain12-13-16-17_zoomed_04	74.16	4.22	21.62	OPX - Pgt	Matrix
EET_87720_matrix1_02	89.74	1.57	8.68	OPX	Matrix

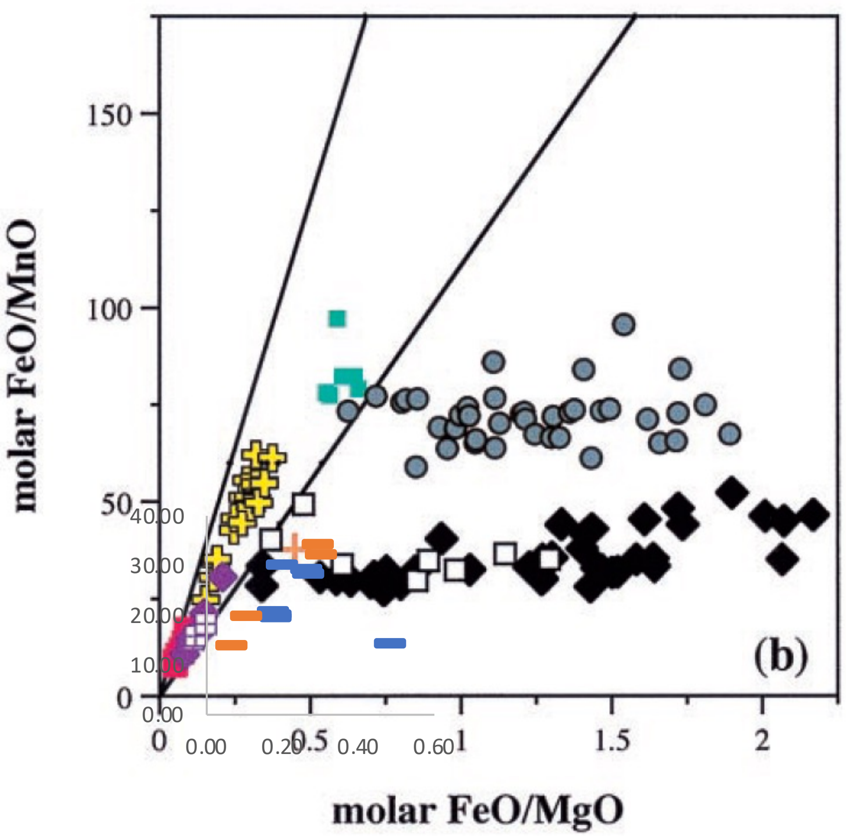
All ureilite materials are primitive origin, unequilibrium

Comparing with other achondrites and primitive achon.





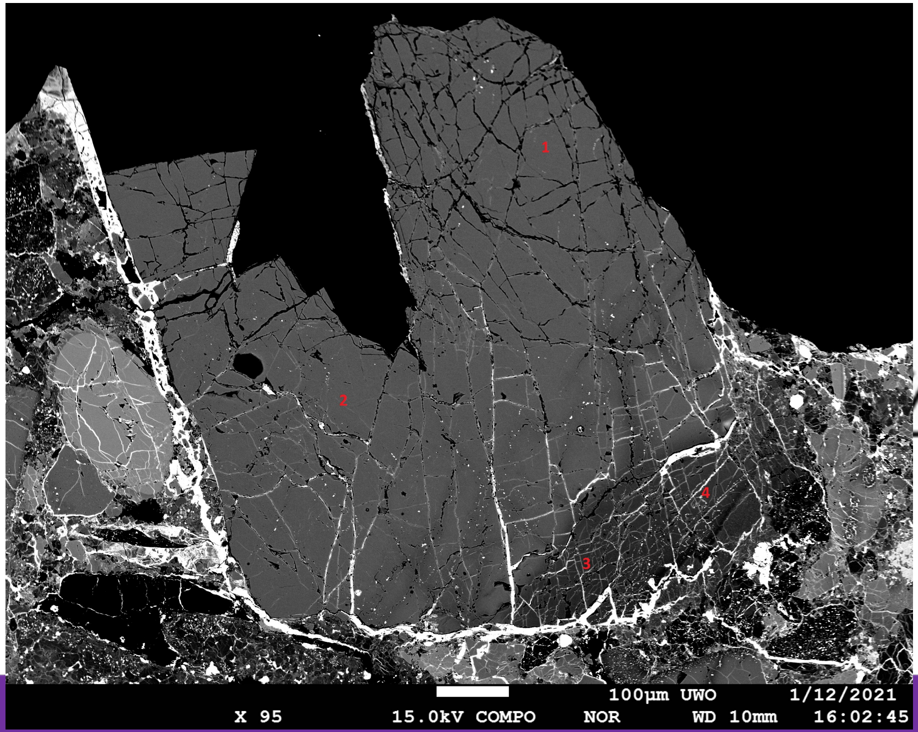
Goodrich and Delaney 2000

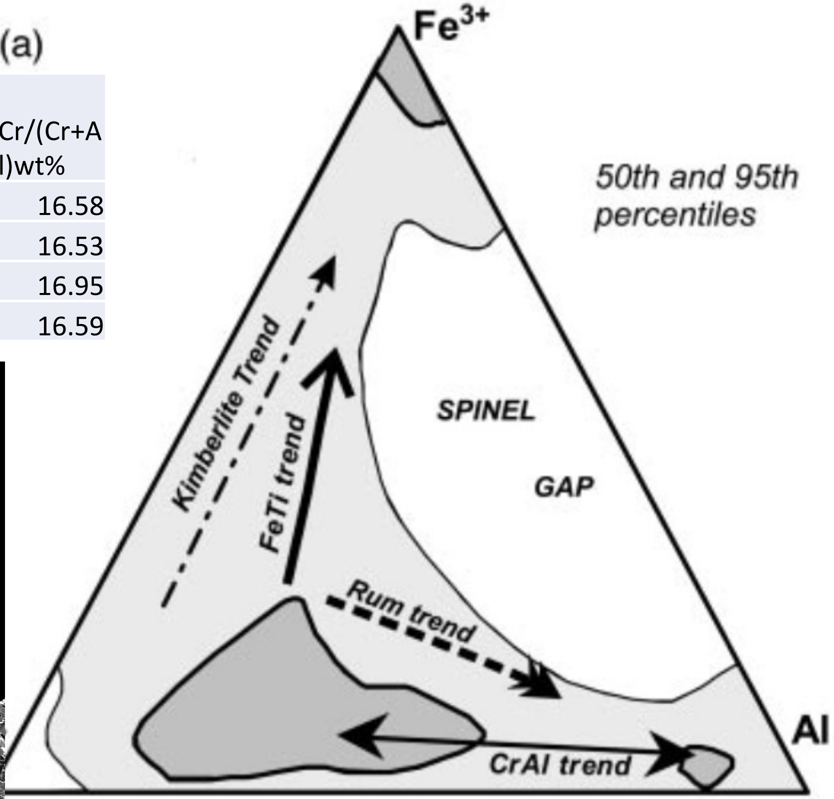


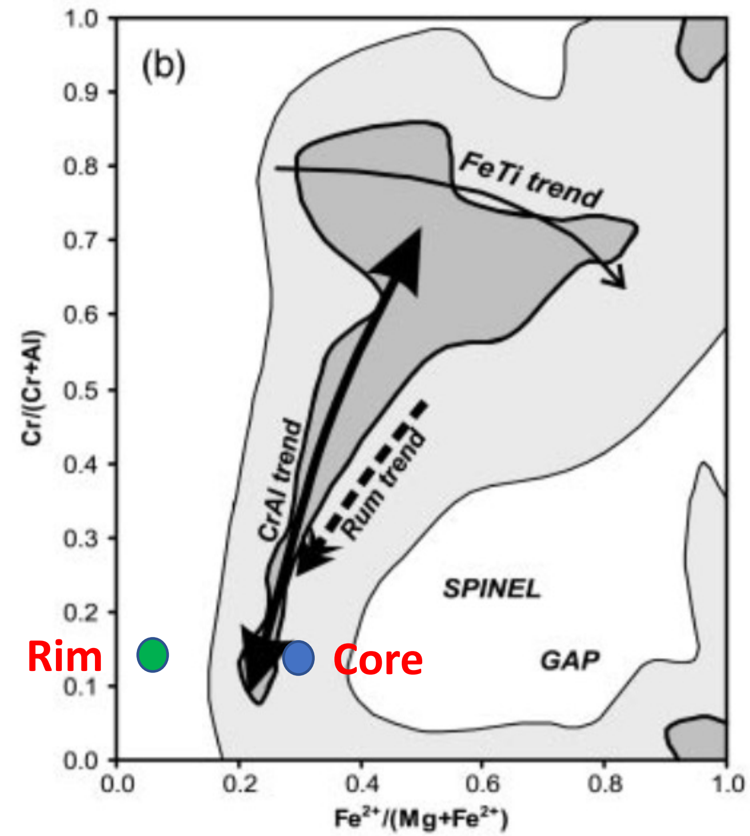
Supplementary Material: it's also rare on Earth

Spinel Composition

	Spinel	Mg-Chromite	Mg/(Mg+Fe)	Fe/(Fe+Mg)		Mg(Mg+Fe)wt%	Fe(Mg+Fe)wt%	Cr/(Cr+Al)wt%
1	88.22	11.78	81.71	18.29		71.49	28.51	16.58
2	88.29	11.71	81.74	18.26		71.53	28.47	16.53
3	87.95	12.05	95.29	4.71		91.91	8.09	16.95
4	88.24	11.76	97.22	2.78		95.15	4.85	16.59







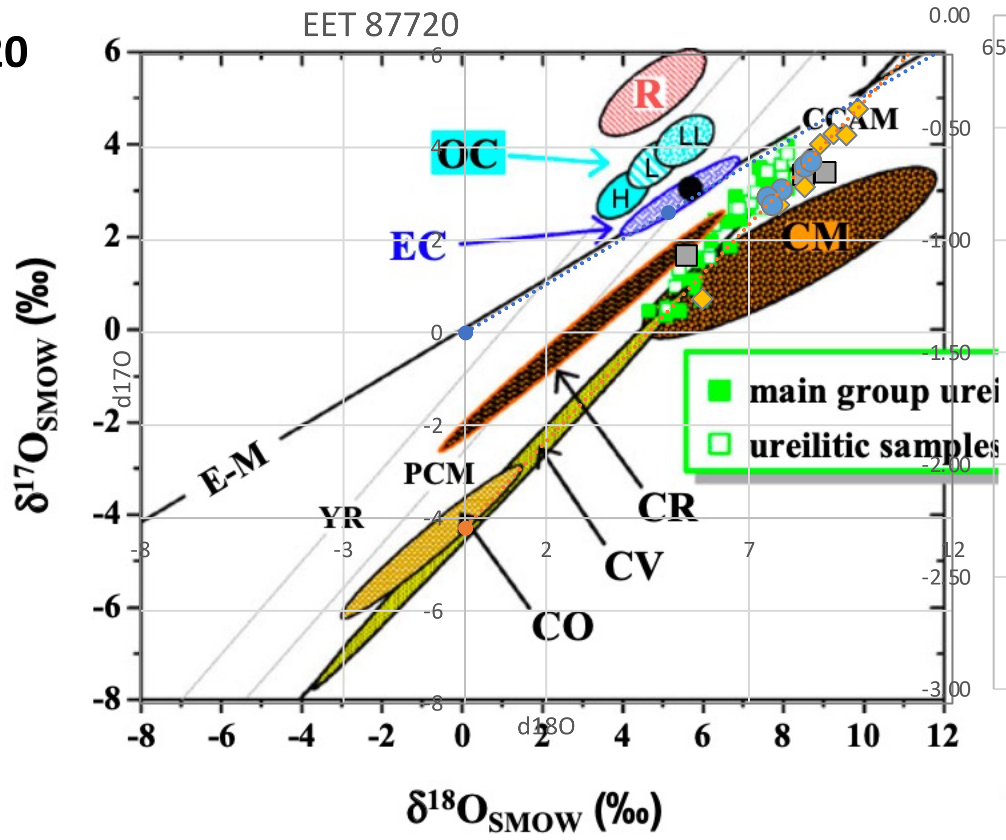
"Thus one might expect that the chromite that crystallizes from the most primi
basalt, that closest to being in equilibrium with the mantle peridotite from whi
it was derived, will have the lowest $Fe^{2+}(Fe^{2+} + Mg)$" ---- Roeder 1994

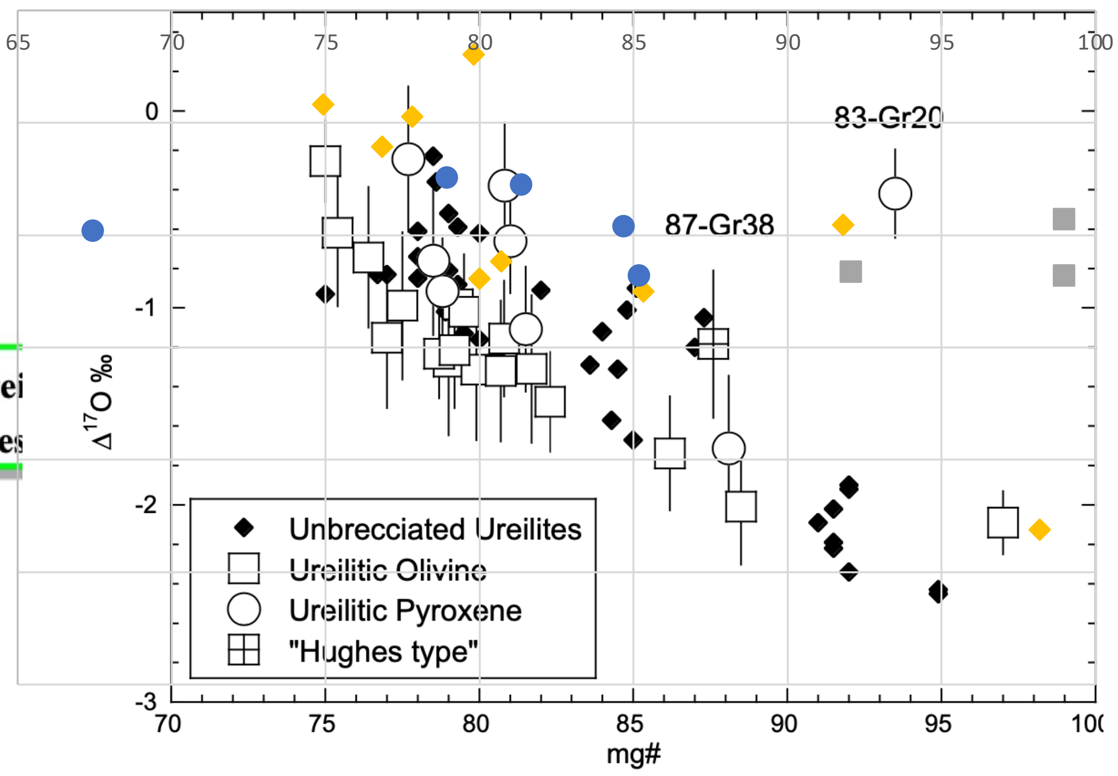
Barnes and Roeder 2001

Supplementary Material: Oxygen Isotopes by SIMS

Legend for EET 87720

- TFL
- CCAM
- spinel
- olivine
- pyroxene
- Linear (TFL)
- Linear (CCAM)





Delta 17O VS mg#

- The oxygen isotopes of EET 87720 are plotted overlay with Downes et al., 2008
- All targets, including spinels, are plotted within the common ureilitic area.
- Despite spinel grain 2 shows the lose of O17 and O18.

Figure overlay with Downes et al., 2008

Supplementary Material: Ol-Sp thermal constrain

- Close relationship of spinel crystallization with forsterite and pyroxene
- Chromite and Spinel have been considered as useful geothermal indicator for igneous rocks (e.g., Irvine 1965, Roeder et al 1979, and Barnes and Roeder 2001).
- It may also help us here.

Revised T formula by Roeder et al 1979
From simplified func:

1/2Fa + Mg-Sp -> 1/2Fo + Fe-Sp

Est. Kd = 0. 7 with Average Fo 0.83, Mg-Sp 0.85

T core ~ 1378K,
T rim ~ 1380K,
Est. T Average 1379K → Zoning due to reduction

Consistent with other study (smelting, e.g. Chikami et al., 1997 Goodrich 2004, Goodrich et al., 2015)

$$K_d = \left(\frac{X_{Mg}}{X_{Fe^{2+}}}\right)_{olivine} \left(\frac{X_{Fe^{2+}}}{X_{Mg}}\right)_{spinel}$$

$$t(°K) = \frac{\alpha\, 3480 + \beta\, 1018 - \gamma\, 1720 + 2400}{\alpha\, 2.23 + \beta\, 2.56 - \gamma\, 3.08 - 1.47 + 1.987 \ln K_D} \quad (3)$$

where

$$\alpha = \frac{Cr}{Cr + Al + Fe^{3+}}, \quad \beta = \frac{Al}{Cr + Al + Fe^{3+}}$$

and

$$\gamma = \frac{Fe^{3+}}{Cr + Al + Fe^{3+}}$$

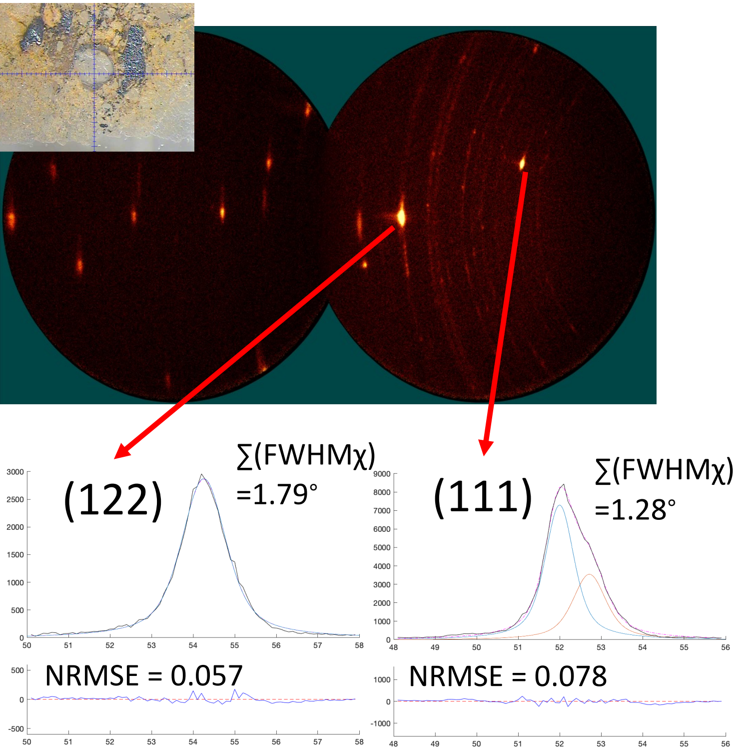
Roeder et al 1979

Hey, Goodrich (2004) also est. UPB is hot and T must > 1100 C ~ 1373K!

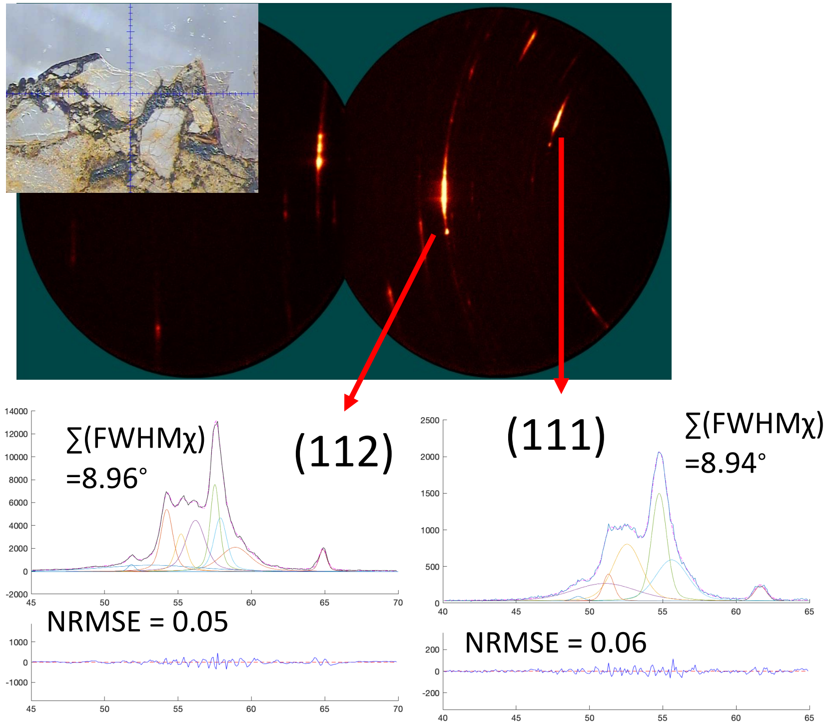
Supplementary Material: Shock Assessment- Olivine

Shock Heterogeneity observed by 2D in-situ XRD, revealing a complex shock history for the near surface in the UPB

Bulk shock history was estimated to S5 by Li et al., 2021

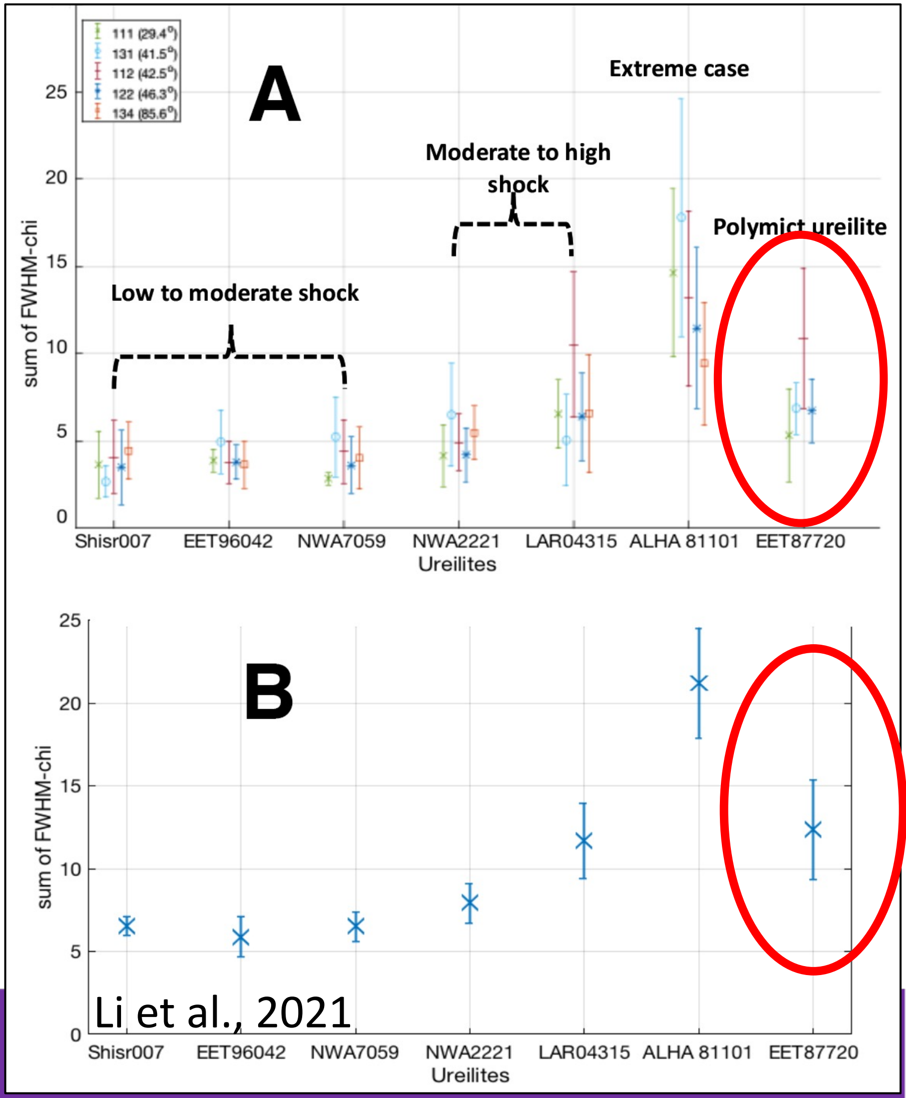


Annealed olivine clast that is nearly strain free



Shock strained olivine

Peak Fitting by BestFit (BFCP, software coded by Li et al., 2020)



Proposed Stratigraphy for UPB

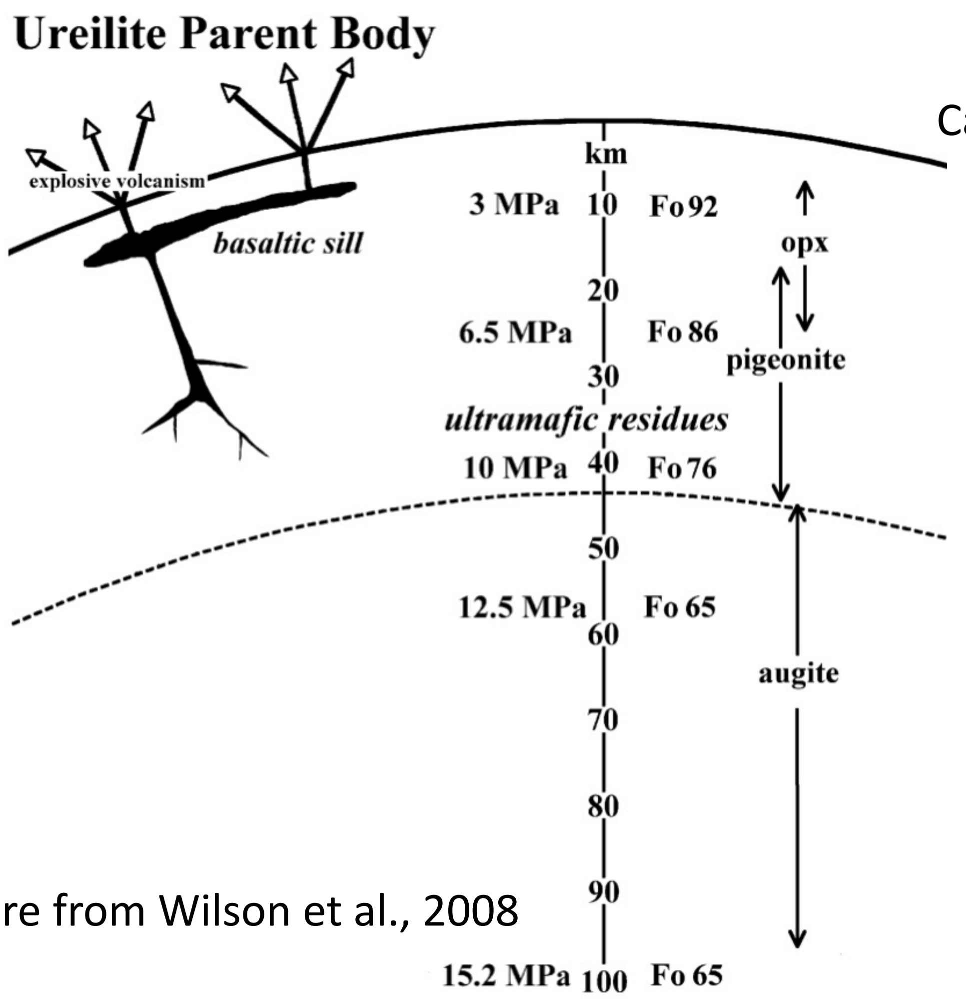


Figure from Wilson et al., 2008

CaO is consumed by two-stage process

Surface

High Mg olivine (up to Fo 74- 99)

Low Ca Pyroxene (Wo 1.04 to 11. 8)

High Al Spinel (Cr_2O_3 ~11.5, Al_2O_3 ~57)

EET 87720
Opx bearing

Ureilitic Ol (76 – 92)

Ureilitic Pgt (Wo 7-13)

Spinel is not common (no data yet)

Most of monomict ureilites
Pigeonite

Low Mg olivine (Fo~75)

High Ca Pyroxene (Wo 4.4 to 33.5)

High Cr Spinel (Cr_2O_3 ~ 55; Al_2O_3~14.5)

LEW 88774
Augite bearing

Deeper

Li et al., 2023B, in prep

Hypothetical Two-Stage Formation for Oldhamite

Desulfurization:

FeS (troilite) + CaO - > FeO + CaS	$\Delta G° = -4615 - 0.205T$ J	Exo

Smelting/reduction in the UPB:

FeO + C -> Fe + CO(g)	$\Delta G° = +111\,500 - 147.93T$ J	Endo
And/ Or		
FeO + CO -> Fe + CO_2(g)	$\Delta G° = -12615 + 20.40T$ J	Endo, giving the high T

- FeO consumption to Fe facilitates the reaction to proceed to the right-hand side on UPB
- Heat budget could be maintained if UPB was hot.
- On the other hand, smelting process has been established by previous research (e.g., Warren and Rubin 2010; Janots et al. 2011; Horstmann and Bischoff 2014; Goodrich et al. 2004, 2015).

Further experimental work is needed to simulate the condition in the UPB

Energy calculation is estimated from Amini et al., 2019