Aqueous activity on chondrite parent asteroids

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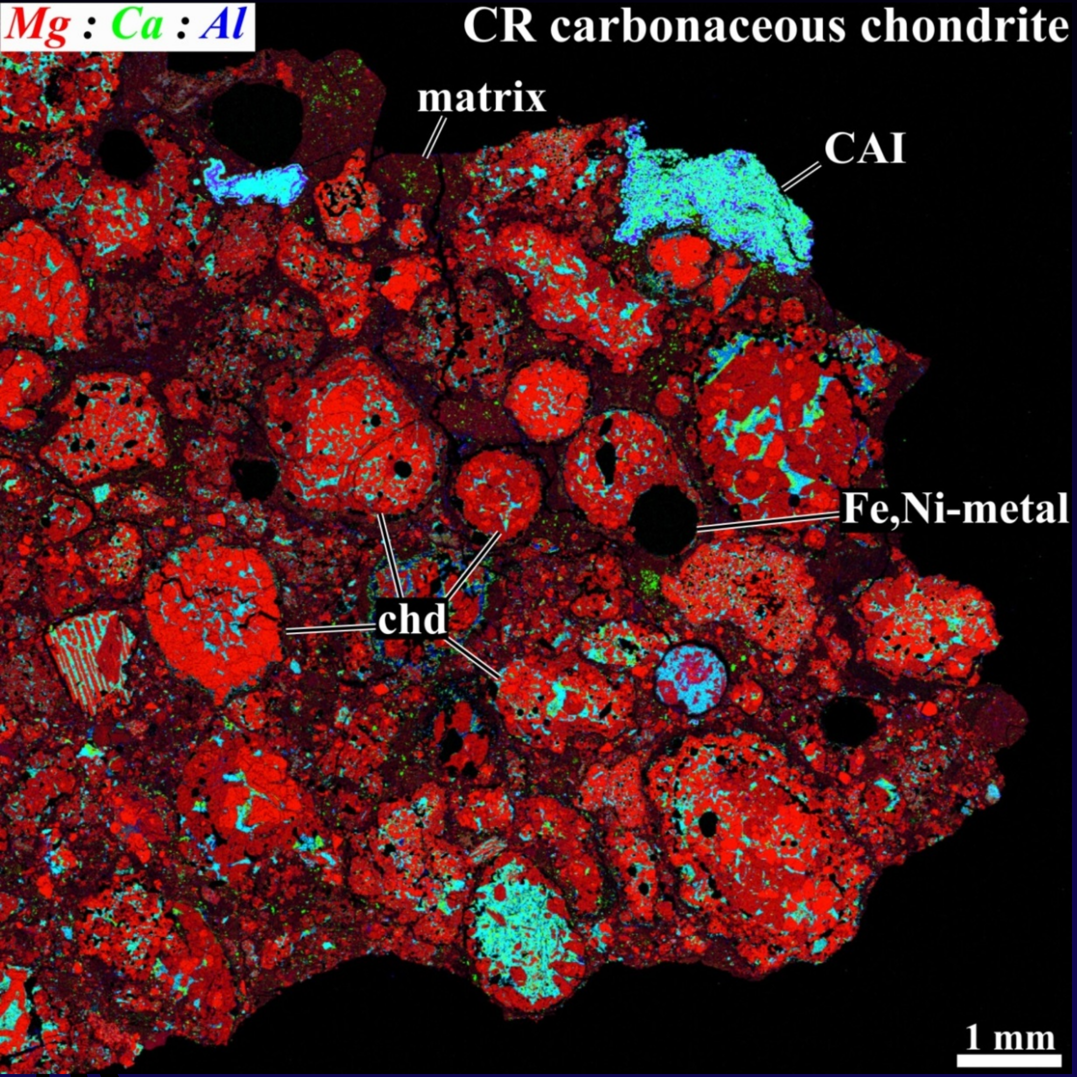
Outline

- Chondritic meteorites & their classification
- Aqueously-formed minerals & conditions (temperature & water/rock ratio) of chondrite aqueous alteration
- Dating of aqueous alteration
  - ^{53}Mn-^{53}Cr ages of fayalite in CV, CO, & ordinary chondrites
  - ^{53}Mn-^{53}Cr ages of carbonates in CI, CM, & CR chondrites
- Oxygen-isotope compositions of aqueously-formed minerals & estimated D/H values of asteroidal water: Constraints on the origin of asteroidal water

Major chondritic components: Chondrules, matrix, & CAIs



- chondrules + Fe,Ni-metal (30–98 vol%)
- Ca,Al-rich inclusions (CAIs) (<1–5 vol%)
- matrix (<2–70 vol%)

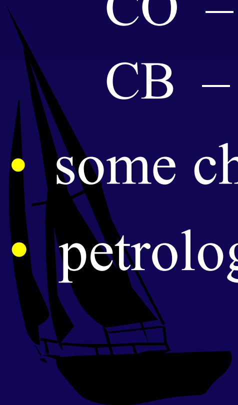
In contrast to ISM, chondrites are dominated by crystalline material → thermal processing in PPD

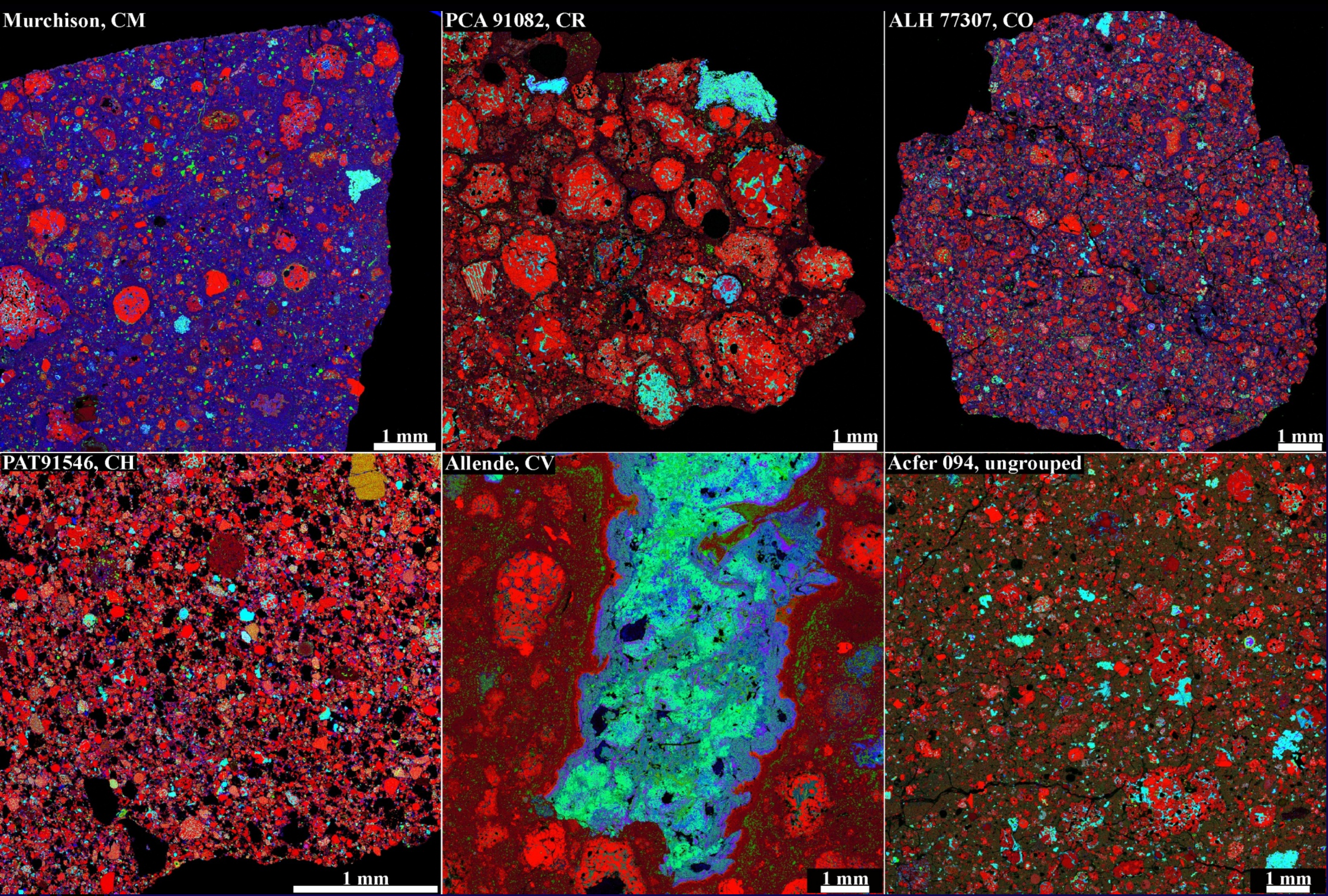
Classification of chondritic meteorites (chondrites)

- based on mineralogy, petrography, bulk oxygen-isotope & chemical compositions, chondrites are divided into 15 groups & 3 major classes

Carbonaceous								*Enstatite*		*Ordinary*			Other	
CI	CM	CR	CV	CK	CO	CB	CH	EH	EL	H	L	LL	K	R
1	2–3	2–3	3	3–6	3	3	3	3–6		3–6			3	3–6

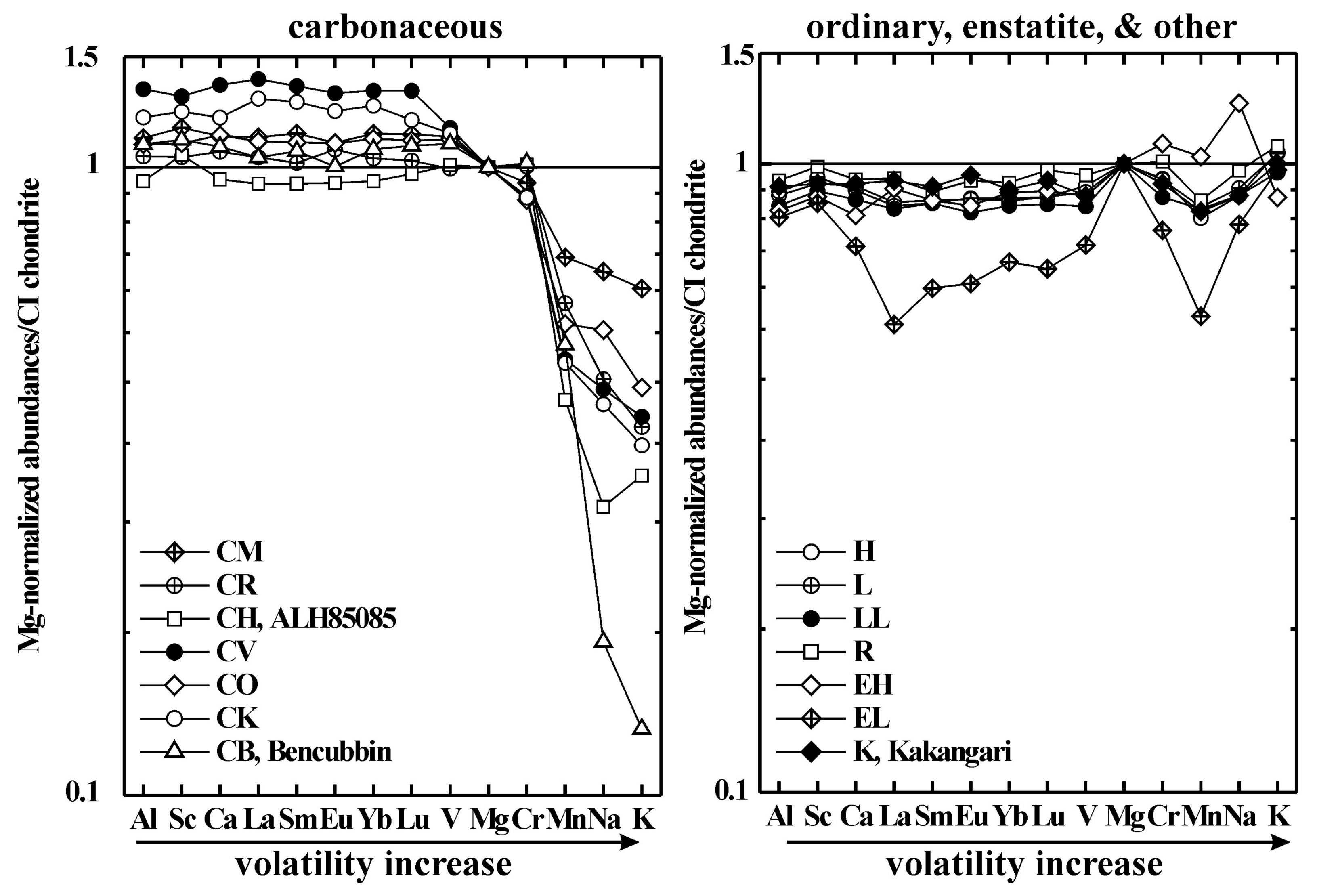
- letters designating groups refer to a typical meteorite in a group:
  - CI – Ivuna type
  - CM – Mighei type
  - CR – Renazzo type
  - CV – Vigarano type
  - CK – Karoonda type
  - CO – Ornans type
  - CB – Bencubbin type
- some chondrites are ungrouped (e.g., Tagish Lake)
- petrologic types: 1 2 3 4 5 6





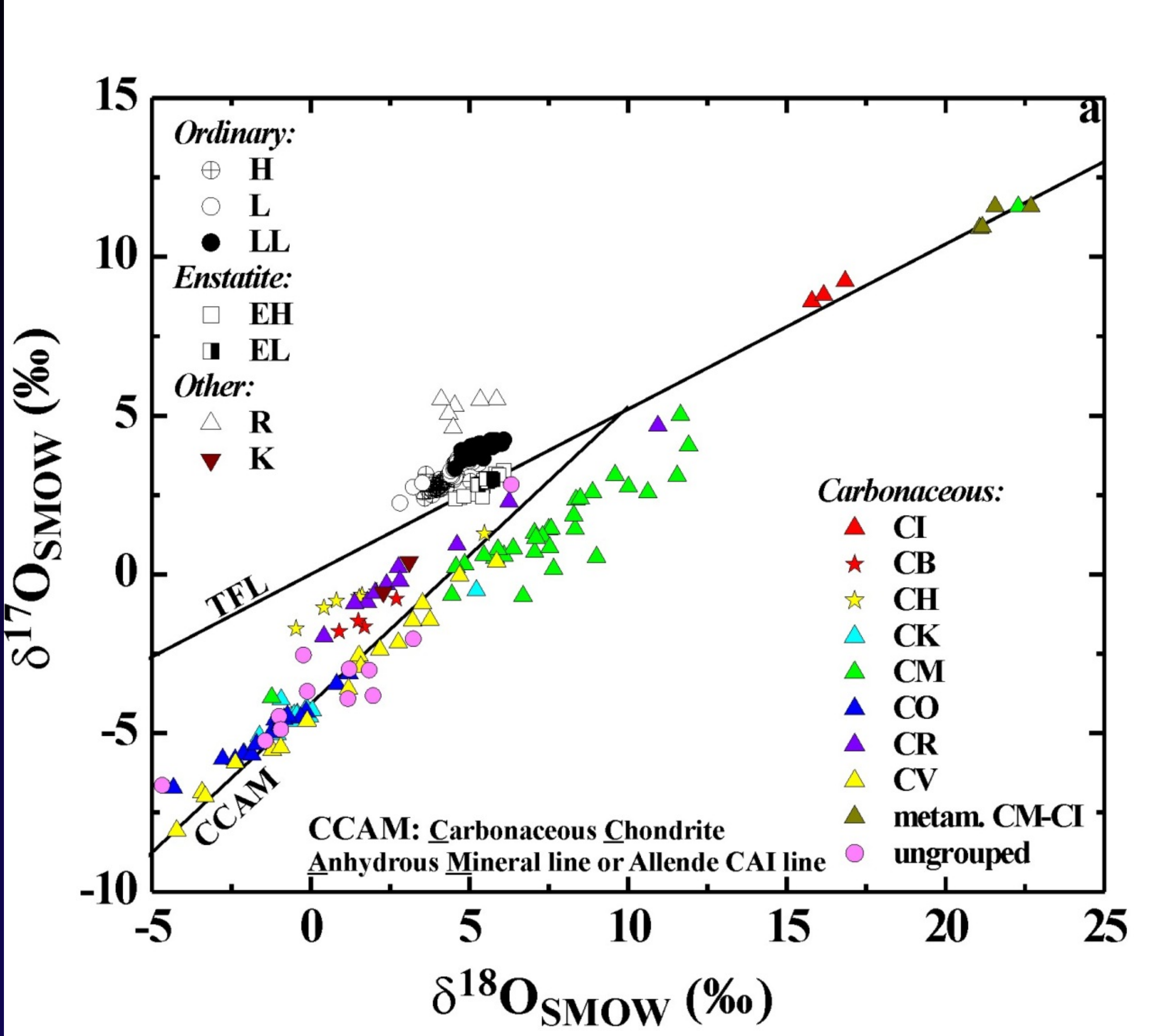
- variations in mineralogy, sizes & abundances of chondritic components among the groups

Bulk chemical compositions



- chondrite groups have distinct bulk chemical compositions

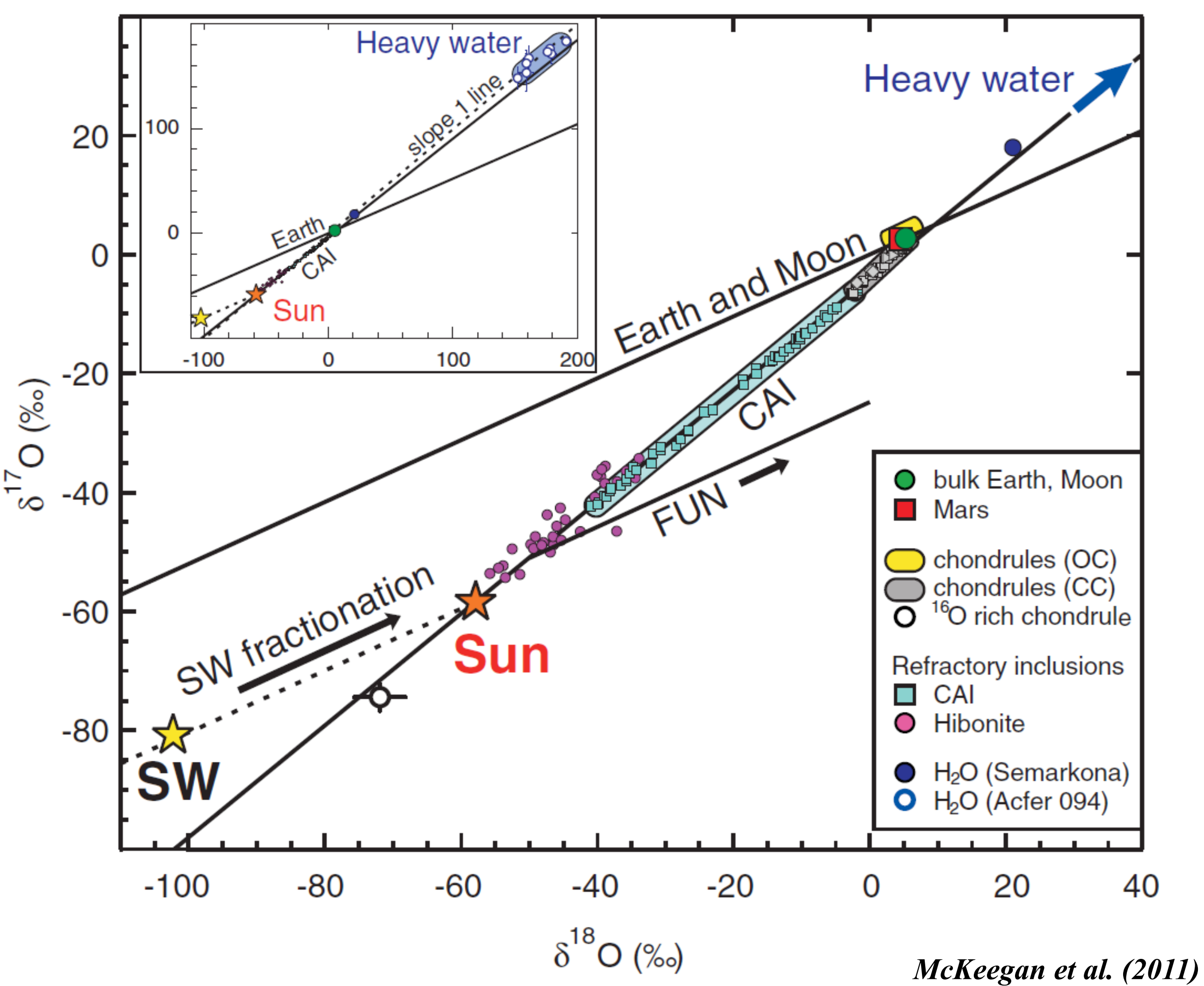
Bulk oxygen-isotope compositions



$\delta^{17,18}O = [({}^{17,18}O/{}^{16}O)_{sample}/({}^{17,18}O/{}^{16}O)_{SMOW} - 1] \times 1000$, Standard Mean Ocean Water

- chondrite groups occupy distinct regions on three-oxygen isotope diagram
- chondrite O-isotope compositions very different from Sun, $\delta^{17,18}O \approx -50‰$

Bulk oxygen-isotope compositions



McKeegan et al. (2011)

$$\delta^{17,18}O = [(^{17,18}O/^{16}O)_{sample}/(^{17,18}O/^{16}O)_{SMOW} - 1] \times 1000, \text{ Standard Mean Ocean Water}$$

- chondrite groups occupy distinct regions on three-oxygen isotope diagram
- chondrite O-isotope compositions very different from Sun, $\delta^{17,18}O \approx -60‰$

Aqueously-altered chondrites

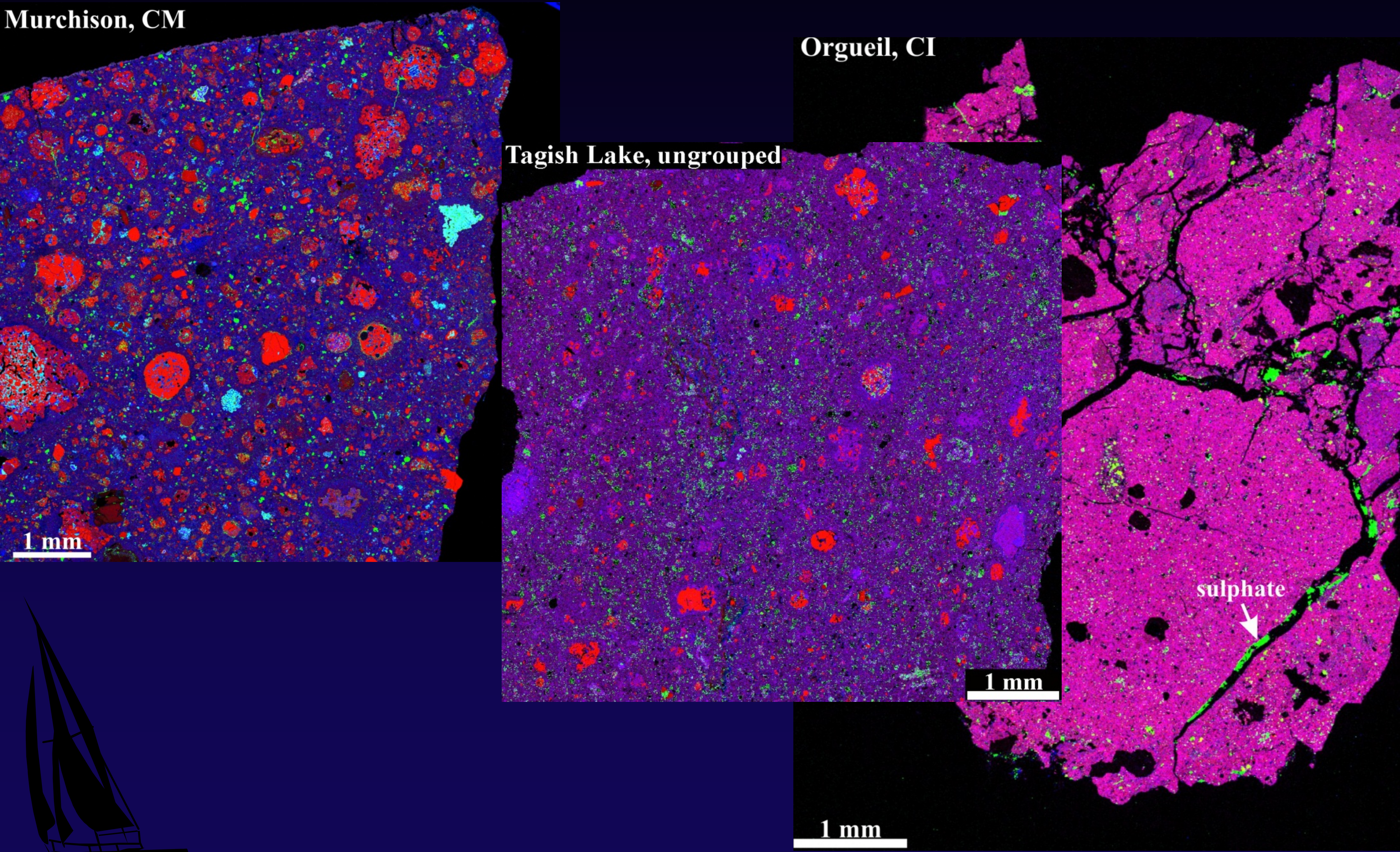
Carbonaceous
CI CM CO CV CK CR CH CB

Enstatite
EH EL

Ordinary
H L LL

Other
K R

Ungrouped
Tagish Lake

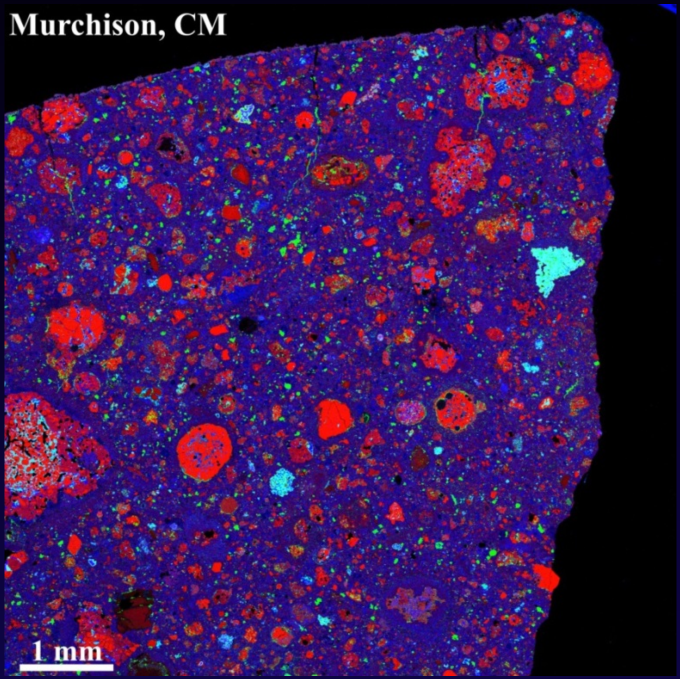


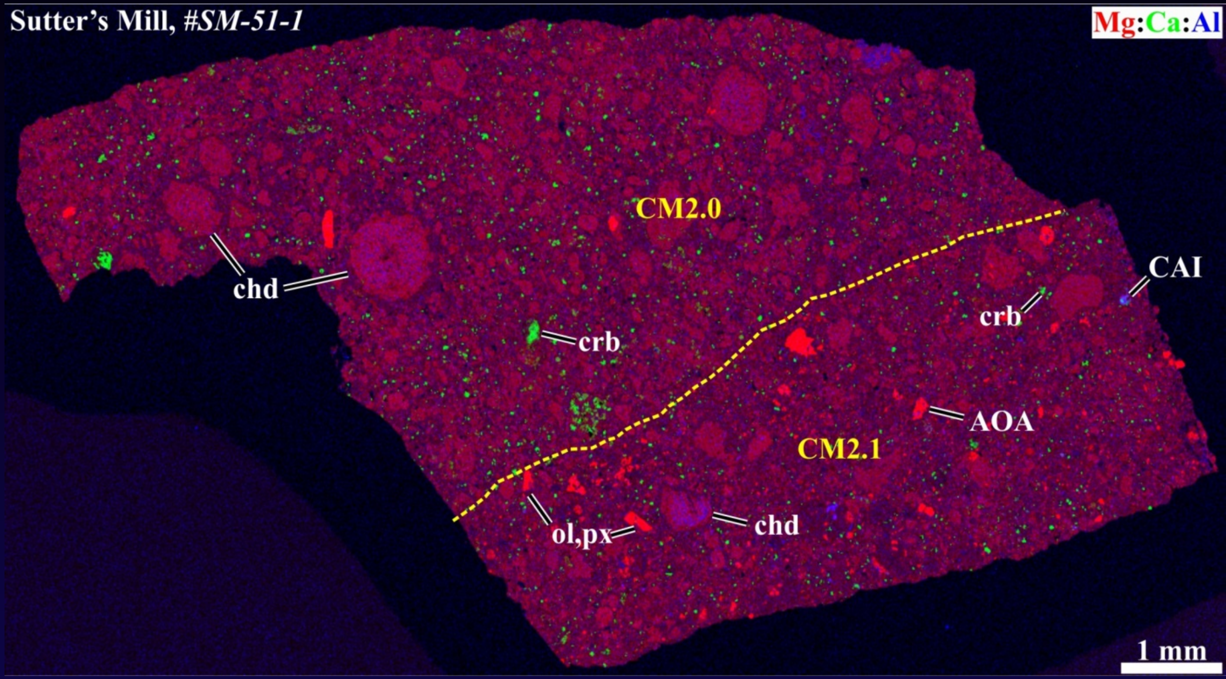
Aqueously produced minerals in CI, CM, & CR chondrites

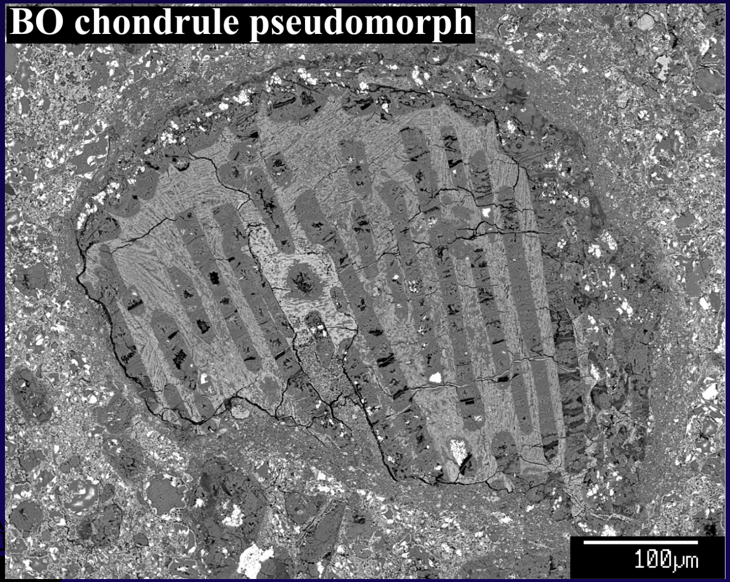
- CM, CI & CR chondrites experienced low-T (< 100°C) aqueous alteration at high water/rock (W/R) ratio (0.2–1)

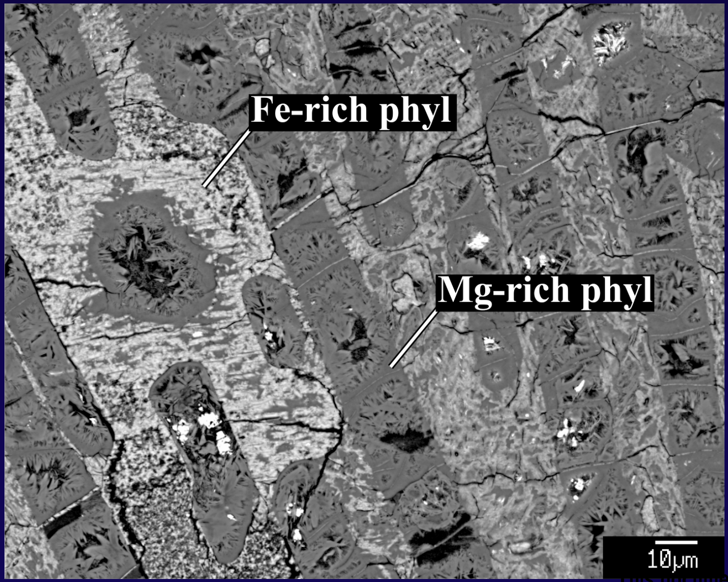
- phyllosilicates
  - serpentine $Mg_3Si_2O_5(OH)_4$
  - cronstedtite $Fe_2^{2+}Fe^{3+}(Si,Fe^{3+})_2O_5(OH)_4$
- tochilinite $2[Fe,Mg,Cu,Ni[])S\bullet 1.57–1.85[(Mg,Fe,Ni,Al,Ca)(OH)_2]$
- carbonates
  - calcite $CaCO_3$ (trigonal)
  - dolomite $(Ca,Mg,Fe,Mn)CO_3$
  - breunnerite $Mg(Fe,Mn)(CO_3)_2$
  - aragonite $CaCO_3$ (hexagonal)
- sulfides
  - troilite FeS
  - pyrrhotite $Fe_{1\text{-}x}S$
  - pentlandite $(Fe,Ni)_9S_8$
- magnetite Fe_3O_4
- sulfates $(Mg,Na,Ca,Ni)SO_4\bullet nH_2O$
- cohenite $(Fe,Ni)_3C$

Mineralogy & petrography of Sutter's Mill (CM)

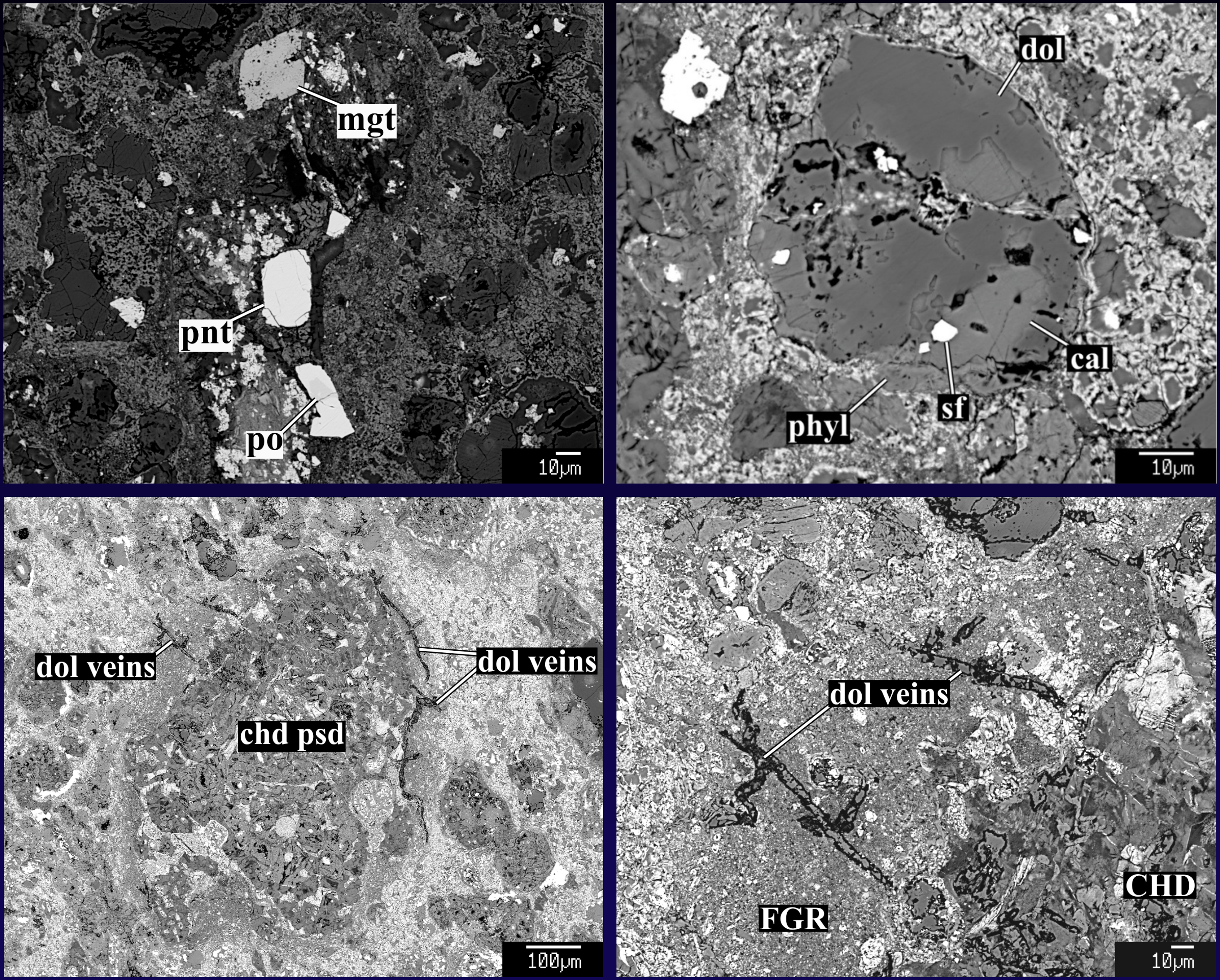

Murchison, CM


Sutter's Mill, #*SM-51-1*


BO chondrule pseudomorph



Mineralogy & petrography of Sutter’s Mill (CM)

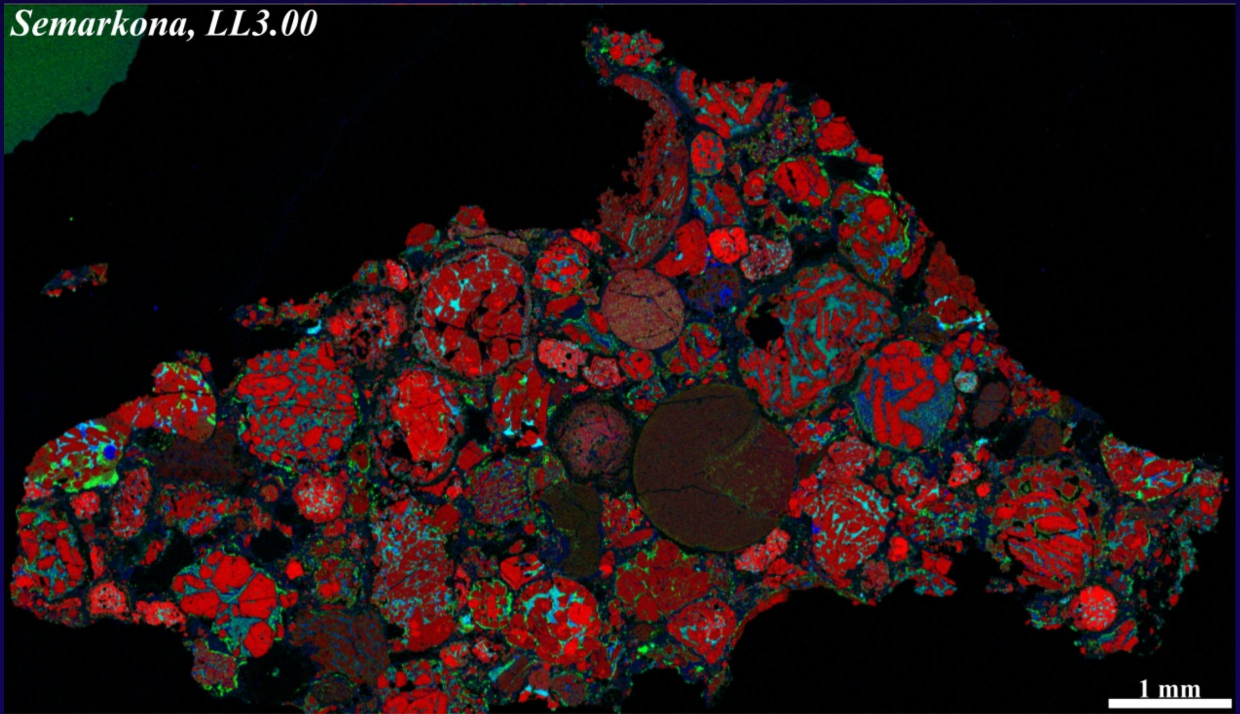


- pseudomorphic replacement of chondrules by phyllosilicates & presence of carbonate veins are clear evidence for *in situ* aqueous alteration

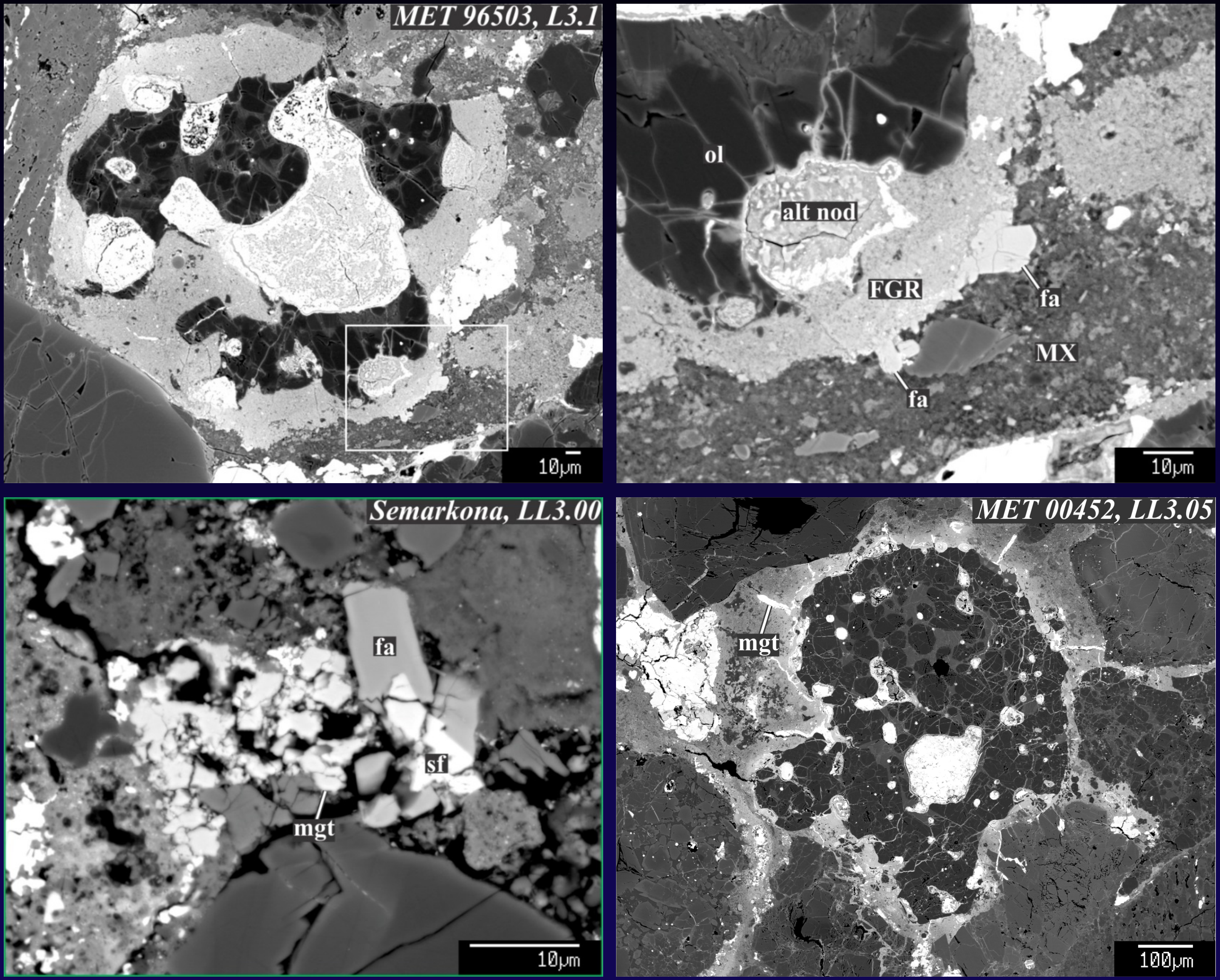
Aqueously produced minerals in ordinary chondrites

- ordinary chondrites experienced aqueous alteration at ~100–200°C & low W/R ratio (<0.2) & were subsequently metamorphosed at higher temperature

saponite	$Ca_{0.25}(Mg,Fe)_3(Si_4O_{10})(OH)_2 \bullet nH_2O$
magnetite	Fe_3O_4
fayalite	Fe_2SiO_4
Fe,Ni-carbides	$(Fe,Ni)_3C$, $(Fe,Ni)_{23}C_6$
pentlandite	$(Fe,Ni)_9S_8$
Ni-rich metal	FeNi, $FeNi_3$
nepheline	$NaAlSiO_4$



Aqueously produced minerals in ordinary chondrites

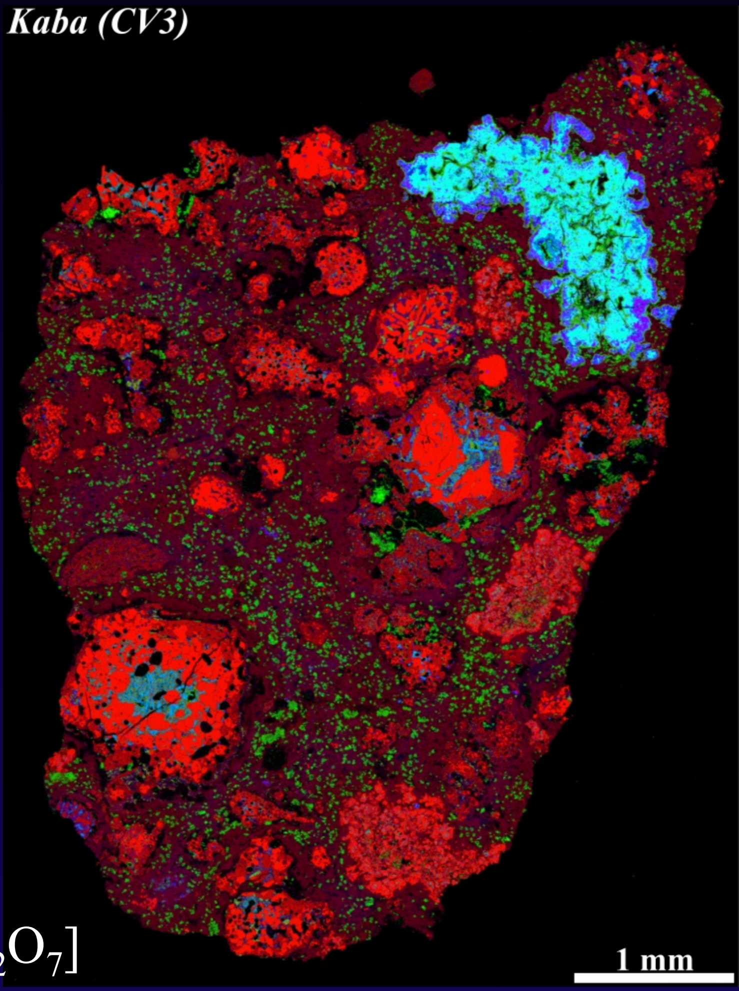


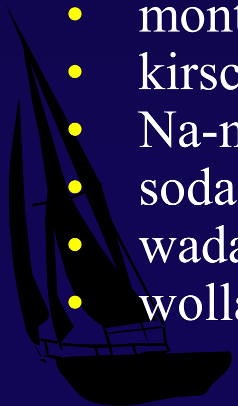
- *in situ* growth of fayalite & magnetite

Aqueously produced minerals in CV & CO chondrites

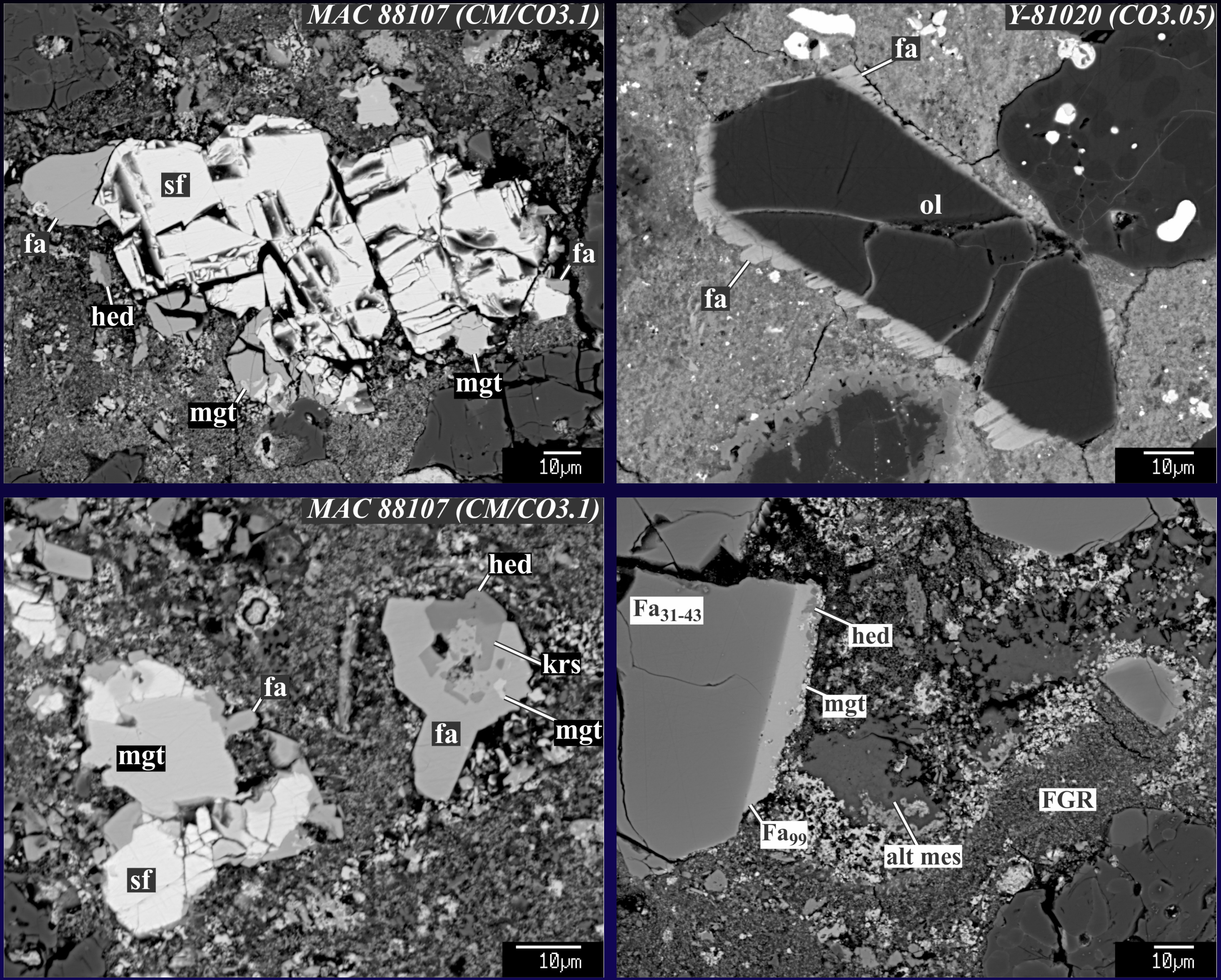
- CV & CO chondrites experienced aqueous alteration ~100–200°C & low W/R ratio (<0.2) & were subsequently metamorphosed at higher temperature

fayalite	Fe_2SiO_4
magnetite	Fe_3O_4
phyllosilicates	
pentlandite	$(Fe,Ni)_9S_8$
hedenbergite	$CaFeSi_2O_6$
andradite	$Ca_3Fe_2Si_3O_{12}$
Fe,Ni-carbides	$(Fe,Ni)_3C$, $(Fe,Ni)_{23}C_6$
Ni-rich metal	FeNi, $FeNi_3$
nepheline	$NaAlSiO_4$
anorthite	$CaAl_2Si_2O_8$
corundum	Al_2O_3
forsterite	Mg_2SiO_4
grossular	$Ca_3Al_2Si_3O_{12}$
kushiroite	$CaAl_2SiO_6$
monticellite	$CaMgSiO_4$
kirschsteinite	$CaFeSiO_4$
Na-melilite	$(CaNa)_2(Al,Mg)[(AlSi)_2O_7]$
sodalite	$Na_8Al_6Si_6O_{24}Cl_{12}$
wadalite	$Ca_6(Al,Si,Mg)_7O_{16}Cl_3$
wollastonite	$CaSiO_3$



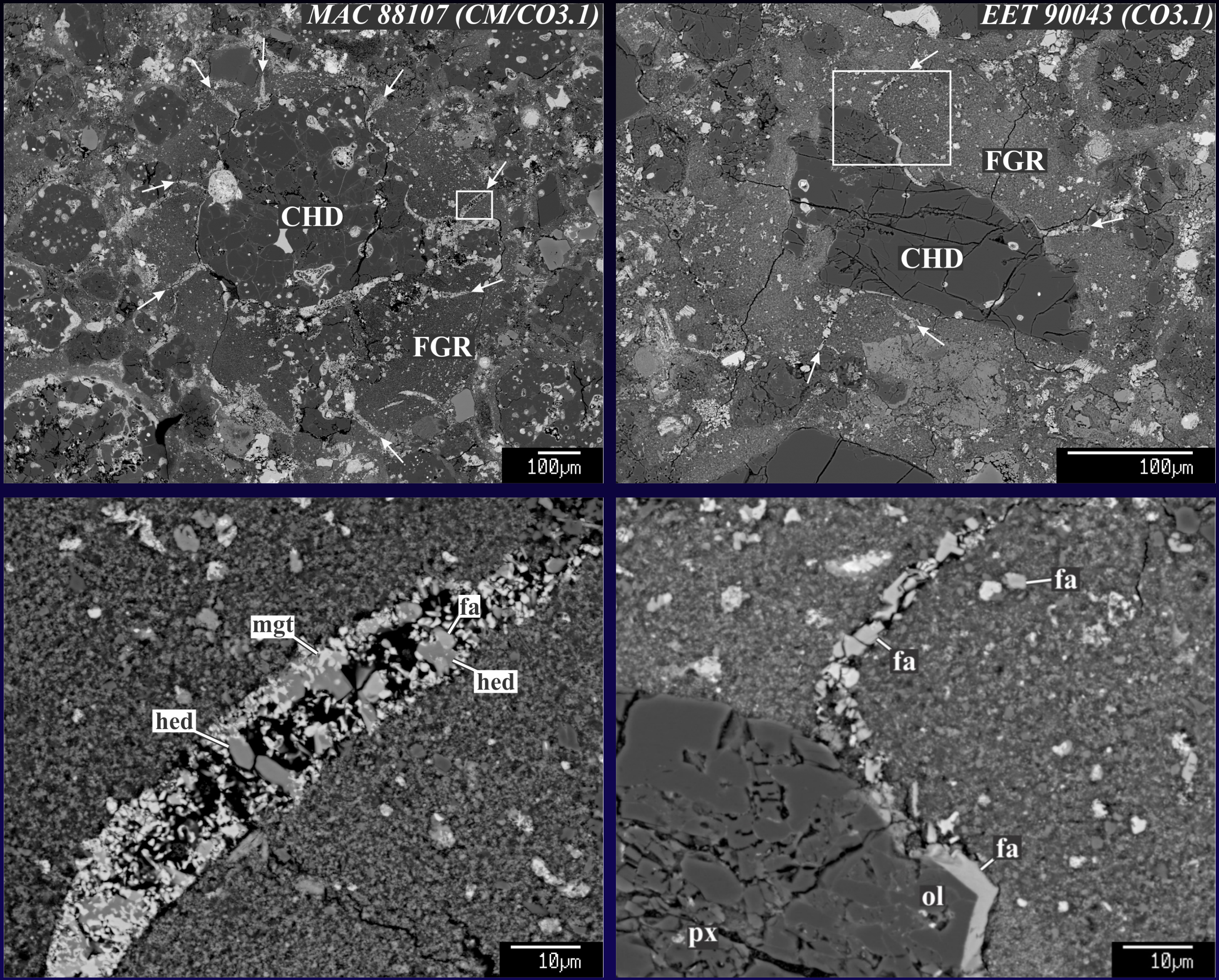


Aqueously produced minerals in CV & CO chondrites



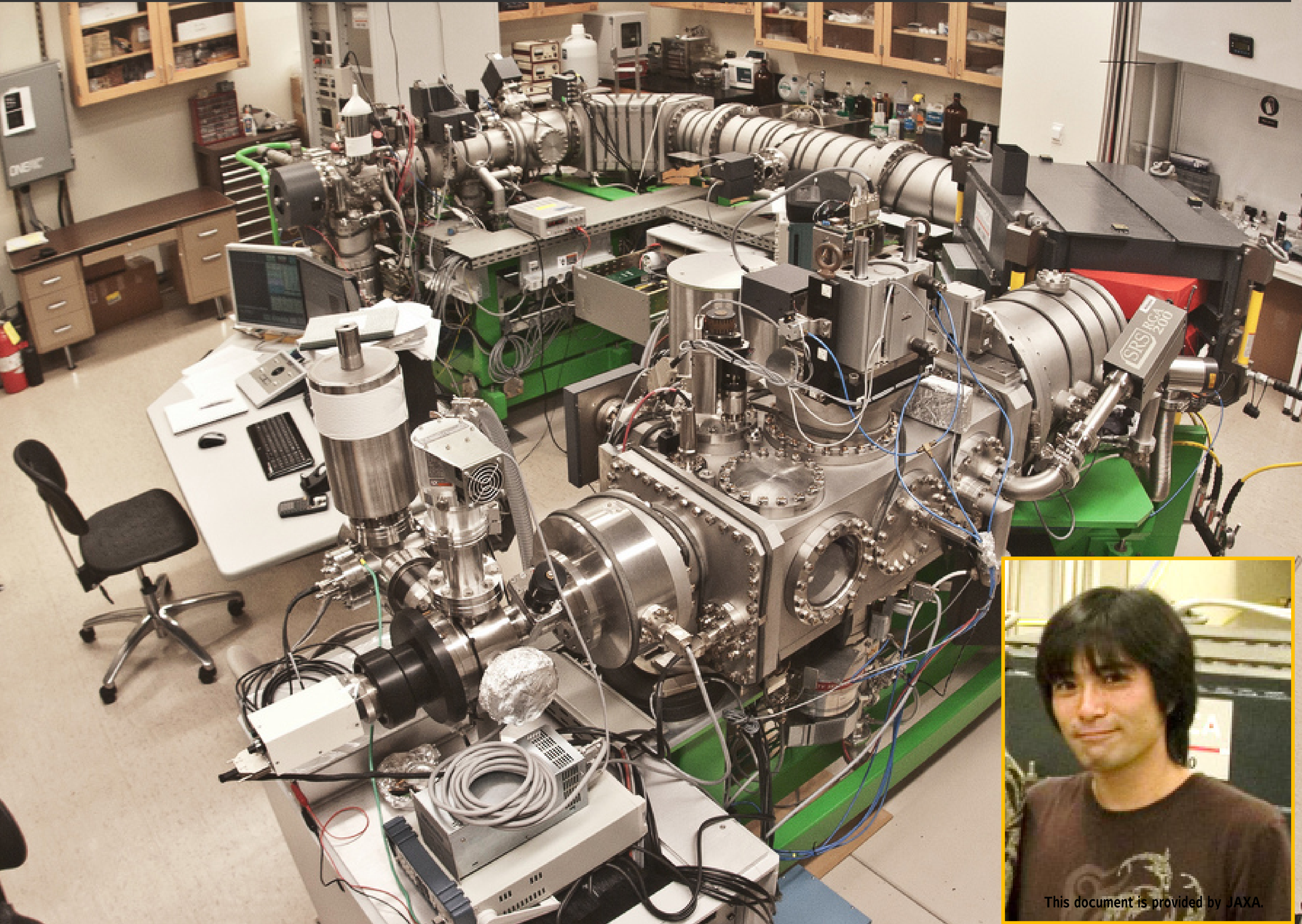
- fayalite associated with magnetite, hedenbergite, kirschsteinite, & Fe,Ni-sulfides in hydrated matrices; no corrosion by phyllosilicates

Aqueously produced minerals in CV & CO chondrites

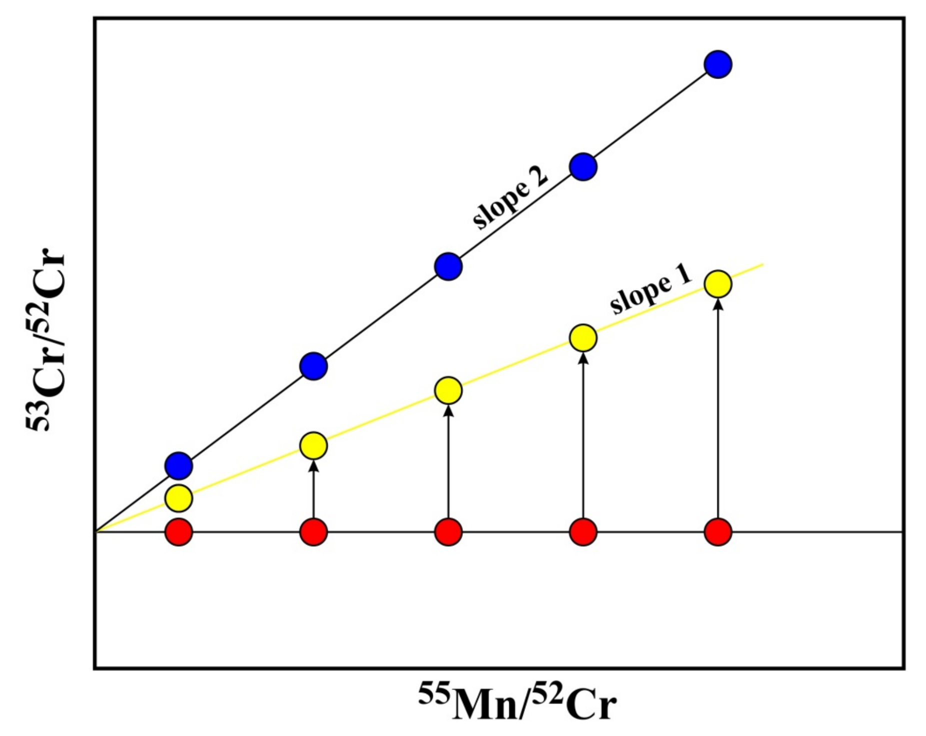


- fayalite-hedenbergite-magnetite veins, indicative for *in situ* growth

Isotope measurements of aqueously-altered meteorites by SIMS



Dating of aqueous alteration using Mn-Cr isotope system



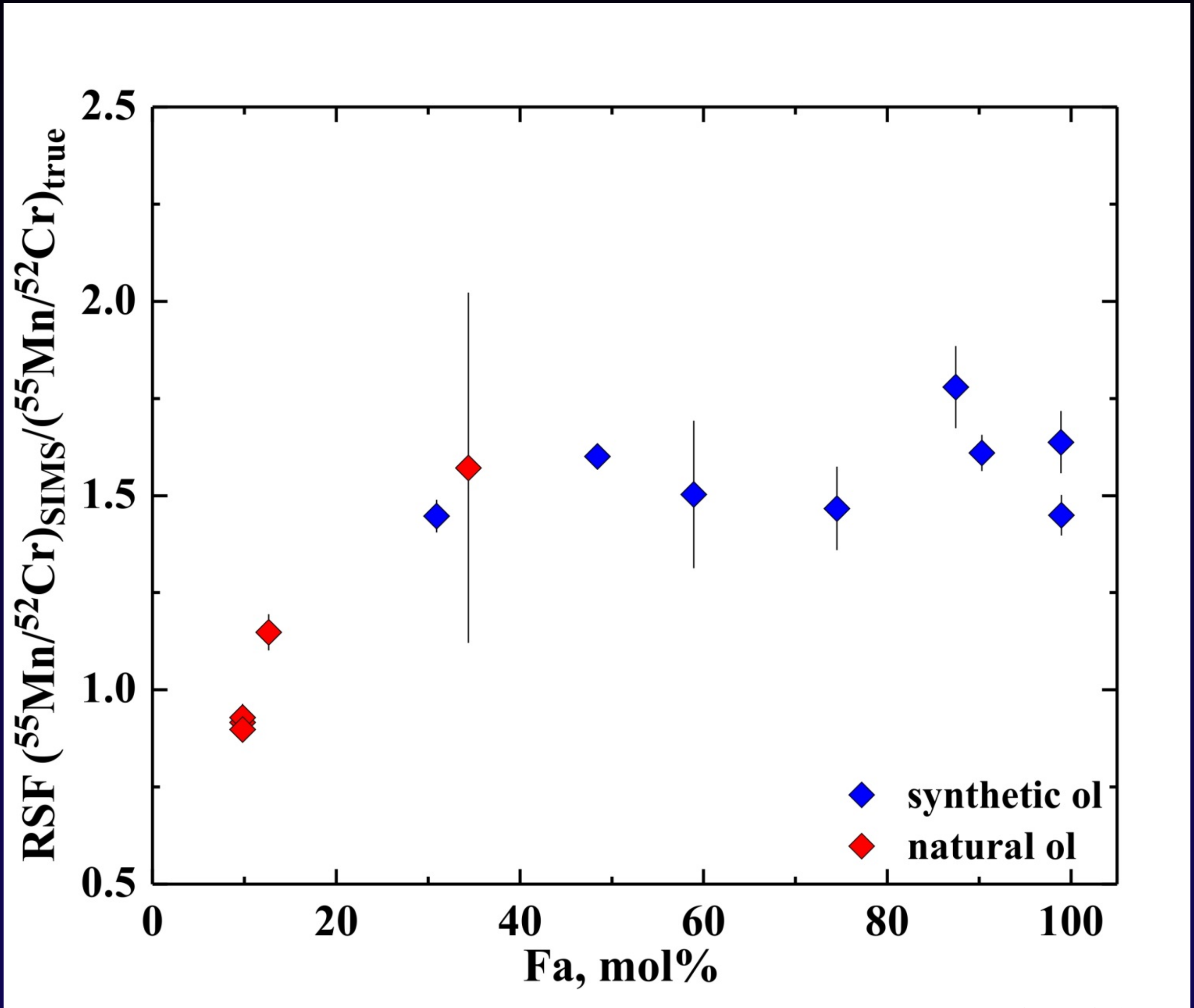
- ^{53}Mn → ^{53}Cr, $t_{1/2}$ ~ 3.7 Myr
- ^{53}Mn was present & uniformly distributed in the early Solar System
- can be used for chronology of the early Solar System processes, including aqueous alteration

- ^{53}Mn-^{53}Cr is a relative chronometer
- $\Delta t_{\text{slope-1} - \text{slope-2}} = 1/\lambda \times \ln[(^{53}\text{Mn}/^{55}\text{Mn})_{\text{slope-1}}/(^{53}\text{Mn}/^{55}\text{Mn})_{\text{slope-2}}]$, where λ is a decay constant of ^{53}Mn (= $\ln(2)/t_{1/2}$)
- ^{53}Mn-^{53}Cr chronology can be anchored to absolute U-Pb chronology, e.g., D'Orbigny angrite with $(^{53}\text{Mn}/^{55}\text{Mn})_0 = (3.24\pm0.04)\times10^{-6}$ & U-corrected Pb-Pb age of 4563.4±0.3 Ma *(Glavin et al. 2008; Brennecka et al. 2012)* & compared with U-corrected Pb-Pb ages of CV CAIs 4567.30±0.16 Ma *(Connelly et al. 2012)*

Dating aqueous alteration: ^{53}Mn-^{53}Cr ages of carbonates & fayalite

- Relative Sensitivity Factor (RSF) = $(^{55}\text{Mn}^{+}/^{53}\text{Cr}^{+})_{\text{SIMS}}$ / $(^{55}\text{Mn}/^{53}\text{Cr})_{\text{EPMA}}$; it depends on a number of factors *(Hoppe et al. 2007; Sugiura et al. 2010; McKibbin et al. 2013; Doyle et al. 2013)*
    - mineral composition
    - analytical conditions
- proper standards for Mn-Cr isotope measurements of carbonates & fayalite are required
- San Carlos olivine (Fa_{10}) was used a standard for $\text{Fa}_{95\text{–}100}$ & carbonates
    - Mn- & Cr-bearing calcite *(Sugiura et al. 2010)*
    - Mn- & Cr-bearing fayalite *(Doyle et al. 2013)*

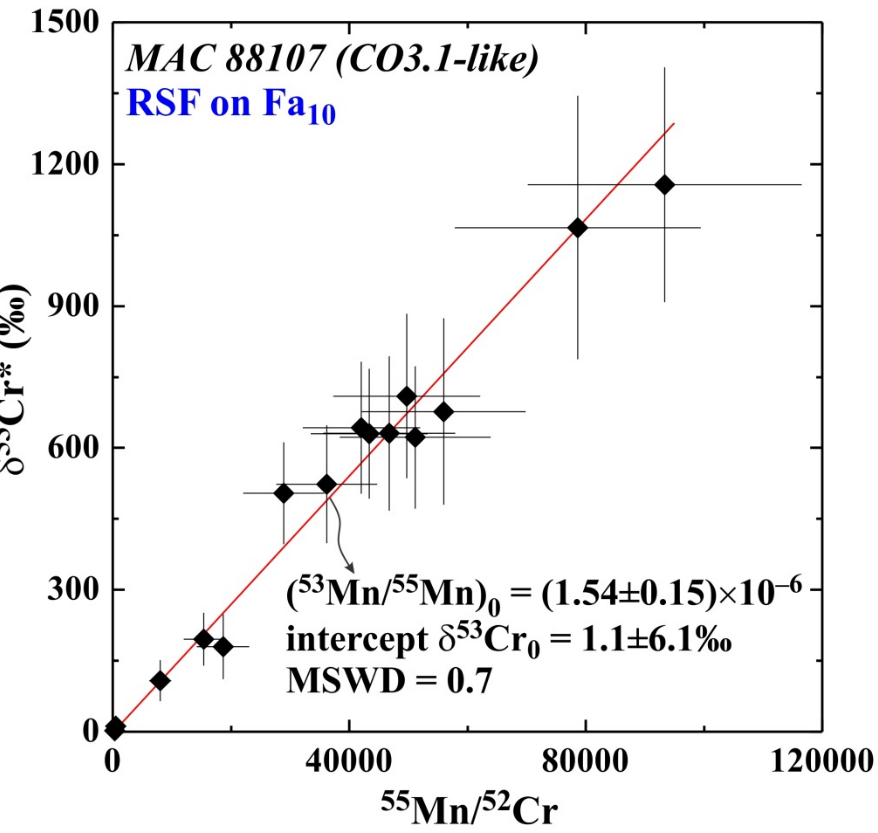
Mn-Cr relative sensitivity factors (RSF) in ferromagnesian olivine

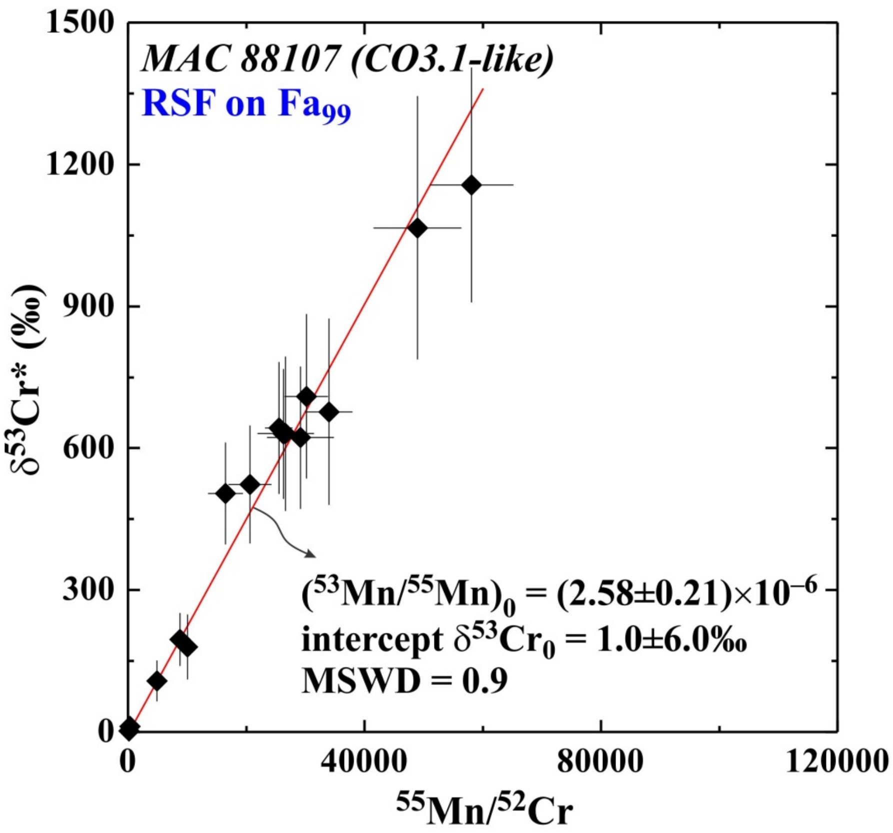


Doyle et al. (2013)

- San Carlos olivine is not a proper standard for ^{53}Mn-^{53}Cr systematics of fayalite

^{53}Mn-^{53}Cr dating of fayalite formation: RSF effect

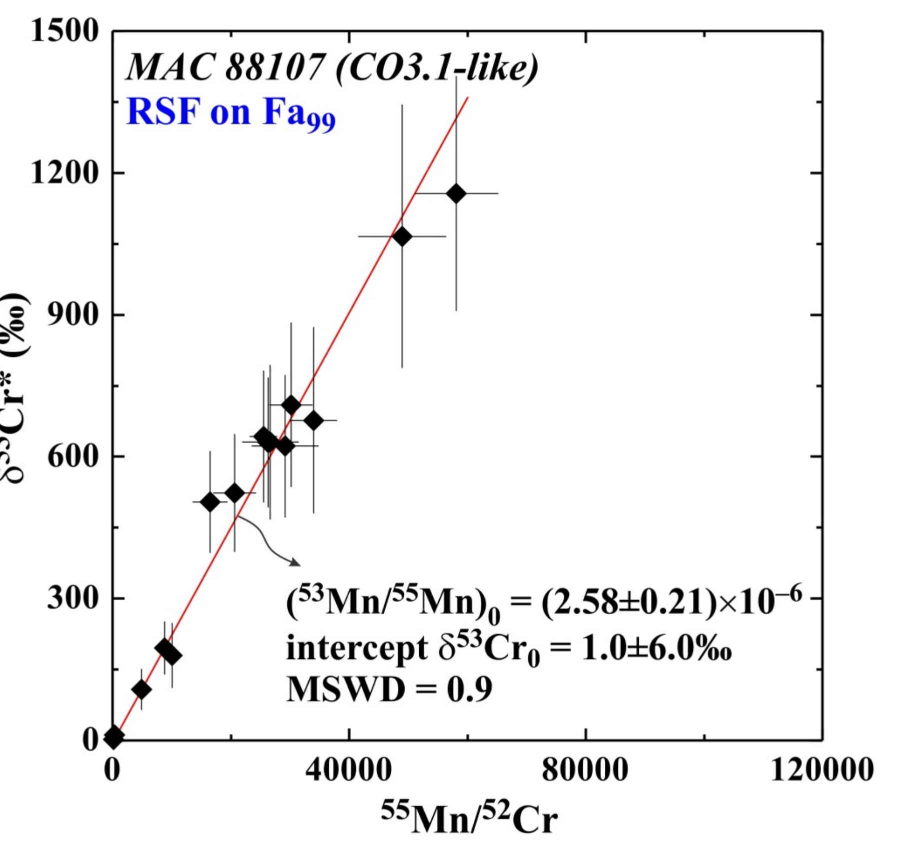


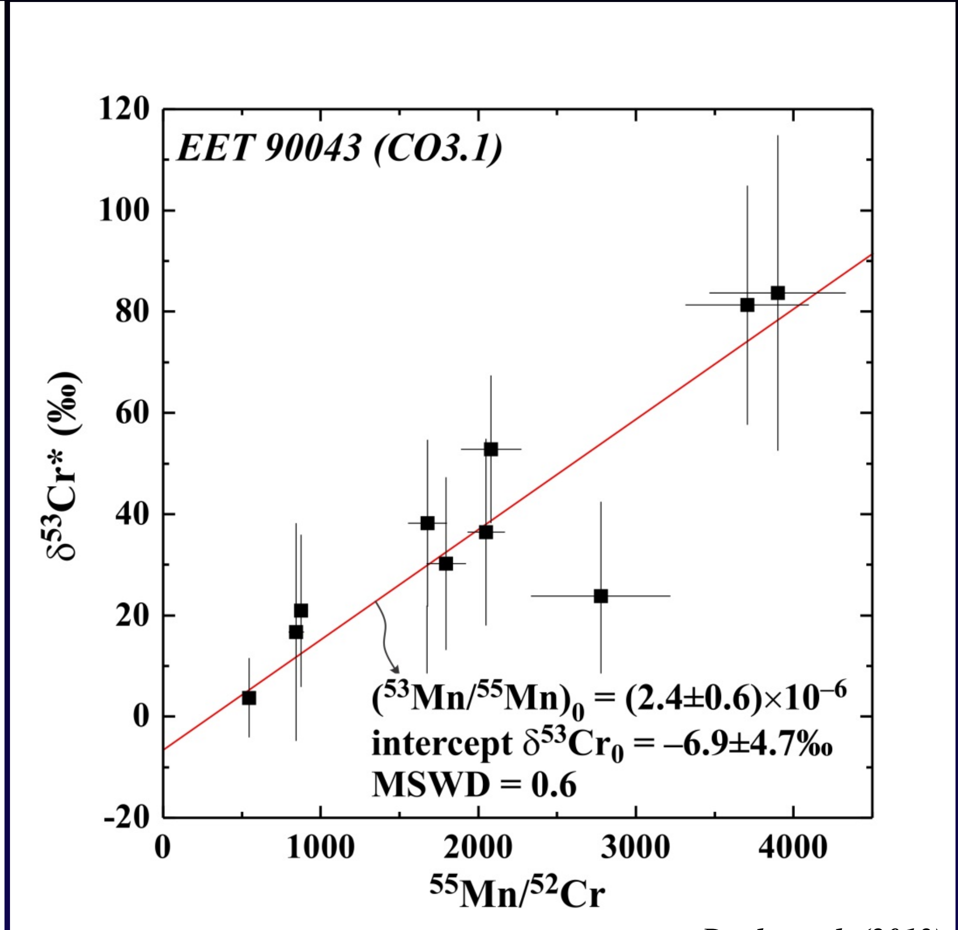


Doyle et al. (2013)

- $7.9^{+0.6}_{-0.5}$ Myr after CV CAIs
- $5.1^{+0.5}_{-0.4}$ Myr after CV CAIs
- San Carlos olivine is not a proper standard for Mn-Cr isotope measurements of fayalite → ^{53}Mn-^{53}Cr ages of fayalite published prior to 2013 are incorrect *(Hutcheon et al. 1998; Krot et al. 2000; Hua et al. 2005; Jogo et al. 2009 etc.)*

^{53}Mn-^{53}Cr dating of fayalite formation in CO & CO-like chondrites

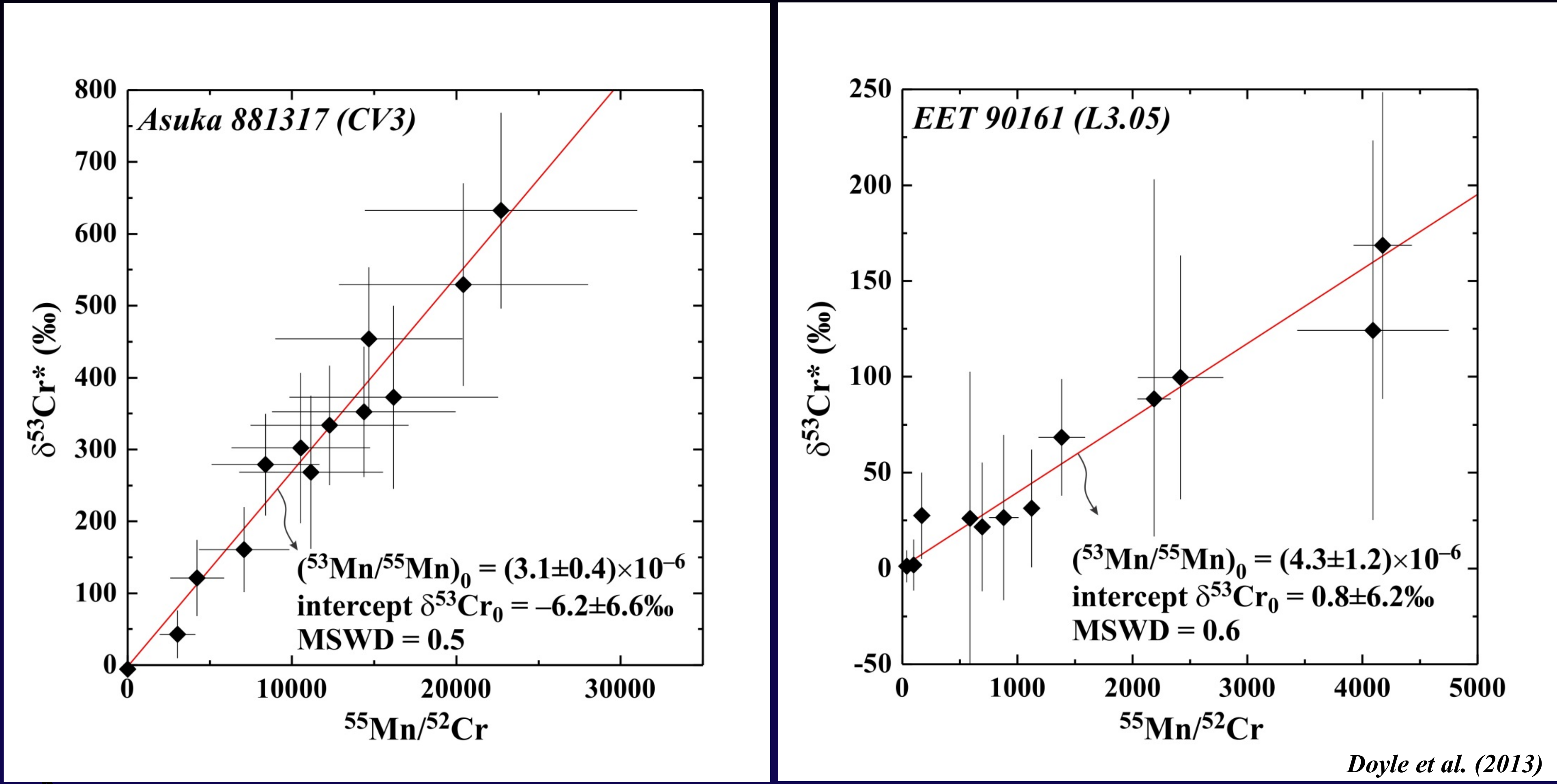




Doyle et al. (2013)

- $5.1^{+0.5}_{-0.4}$ Myr after CV CAIs
- $5.5^{+1.5}_{-1.2}$ Myr after CV CAIs

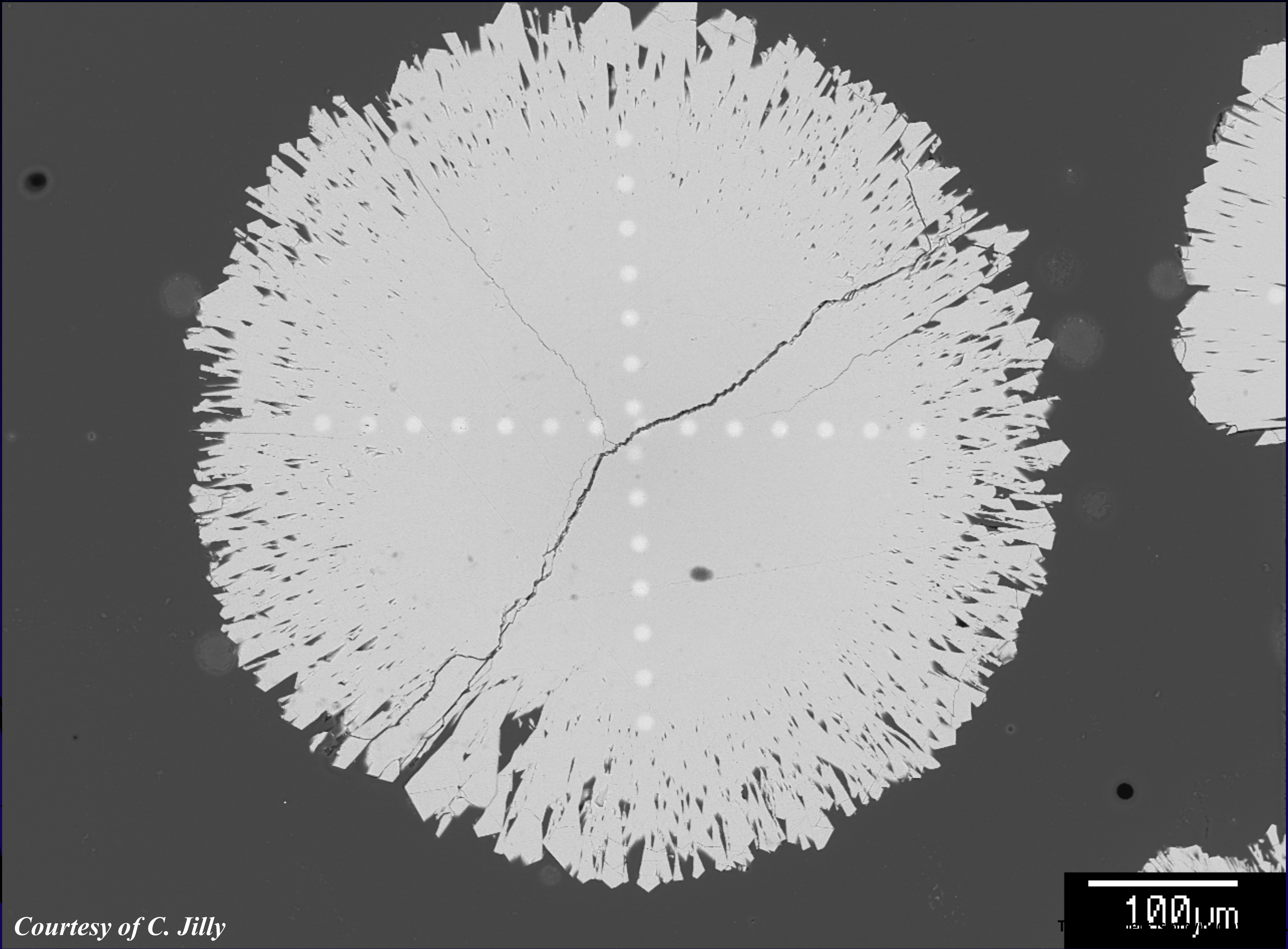
^{53}Mn-^{53}Cr dating of fayalite formation in CV & ordinary chondrites



Doyle et al. (2013)

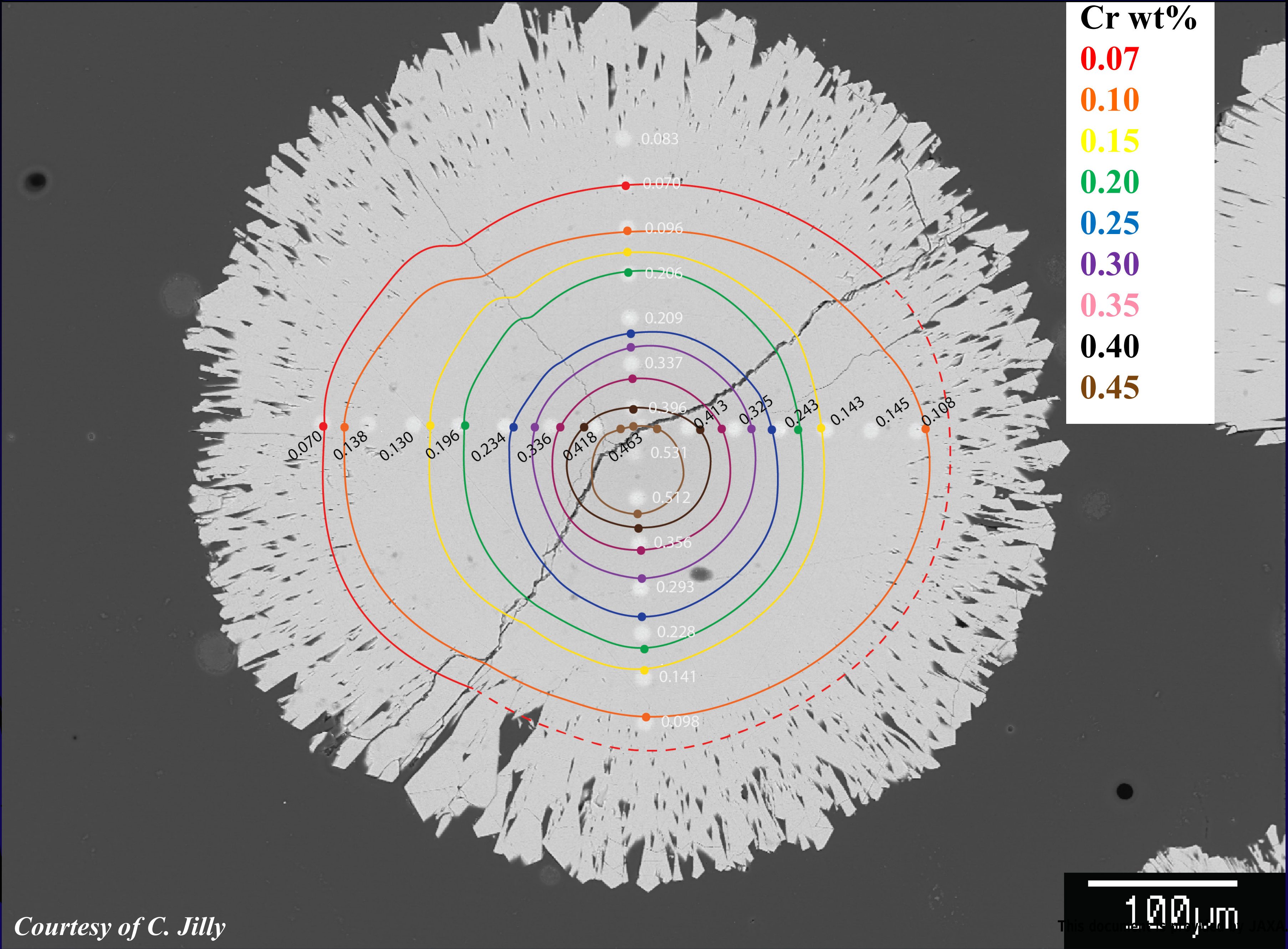
- $4.2^{+0.8}_{-0.7}$ Myr after CV CAIs
- $2.4^{+1.8}_{-1.3}$ Myr after CV CAIs

Synthetic Mn- & Cr-bearing calcite *(N. Sugiura, U. Tokyo)*



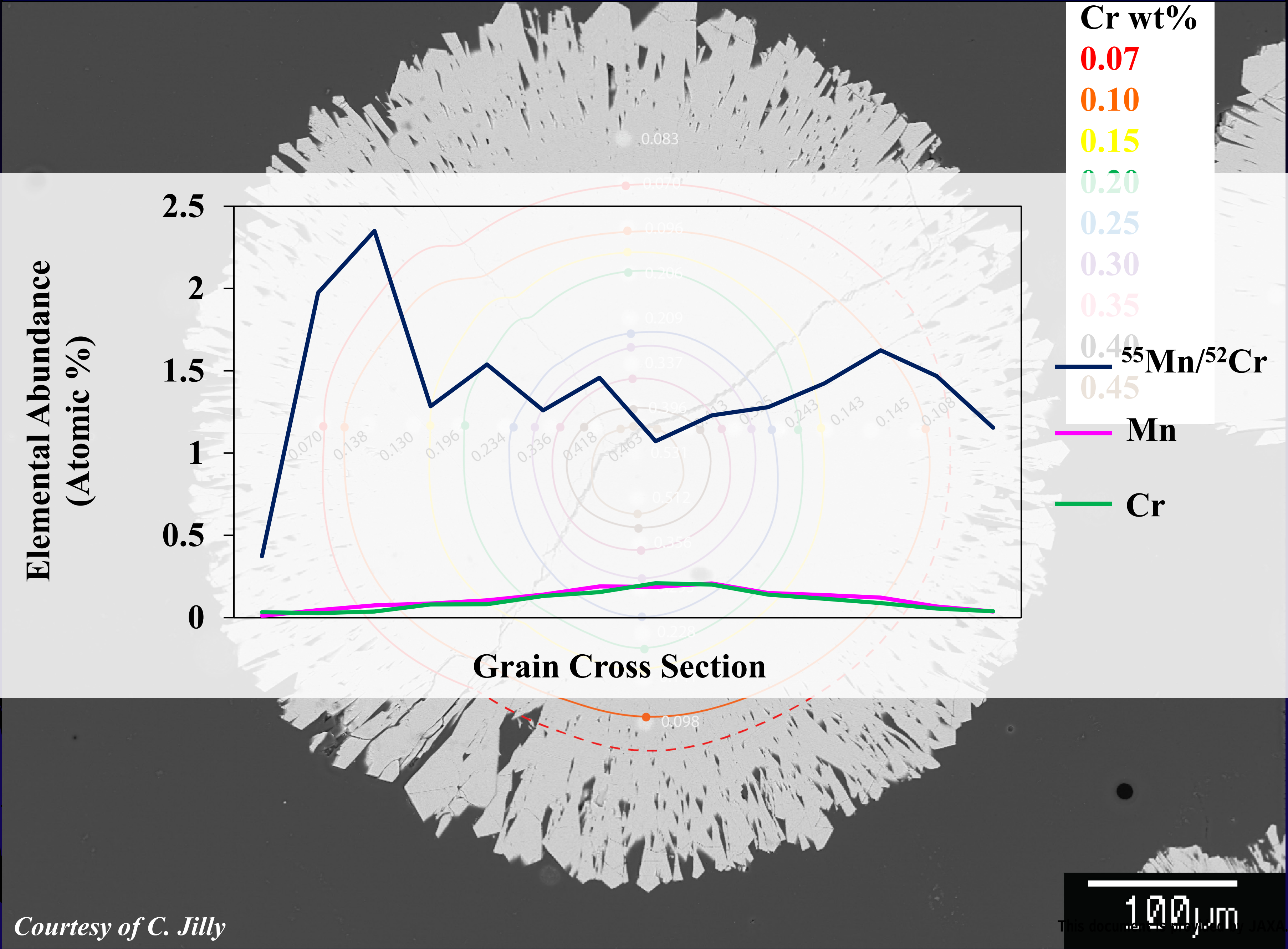
Courtesy of C. Jilly

Synthetic Mn- & Cr-bearing calcite *(N. Sugiura, U. Tokyo)*



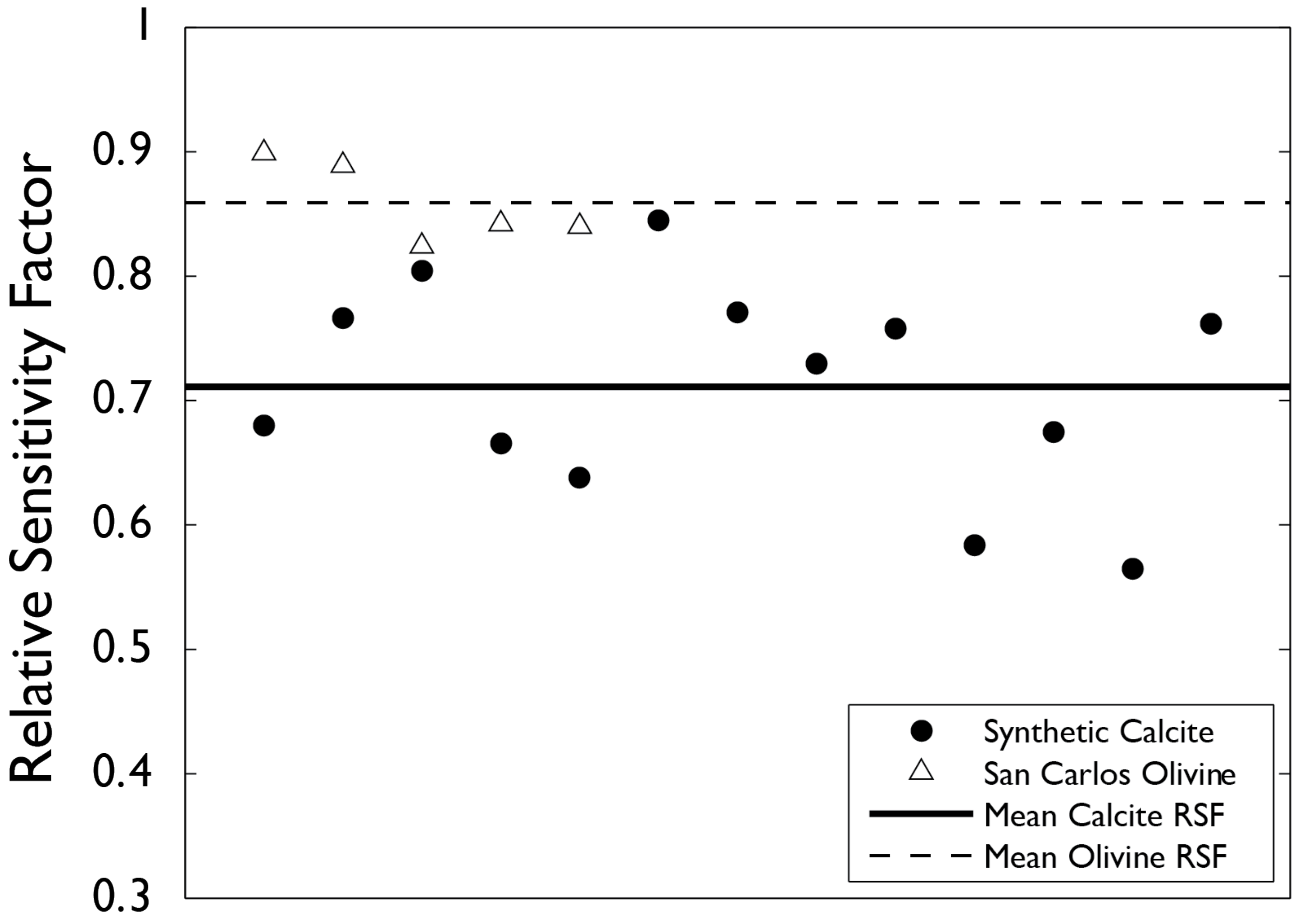
Courtesy of C. Jilly

Synthetic Mn- & Cr-bearing calcite *(N. Sugiura, U. Tokyo)*



Courtesy of C. Jilly

Mn-Cr relative sensitivity factors in SC olivine *vs.* synthetic calcite



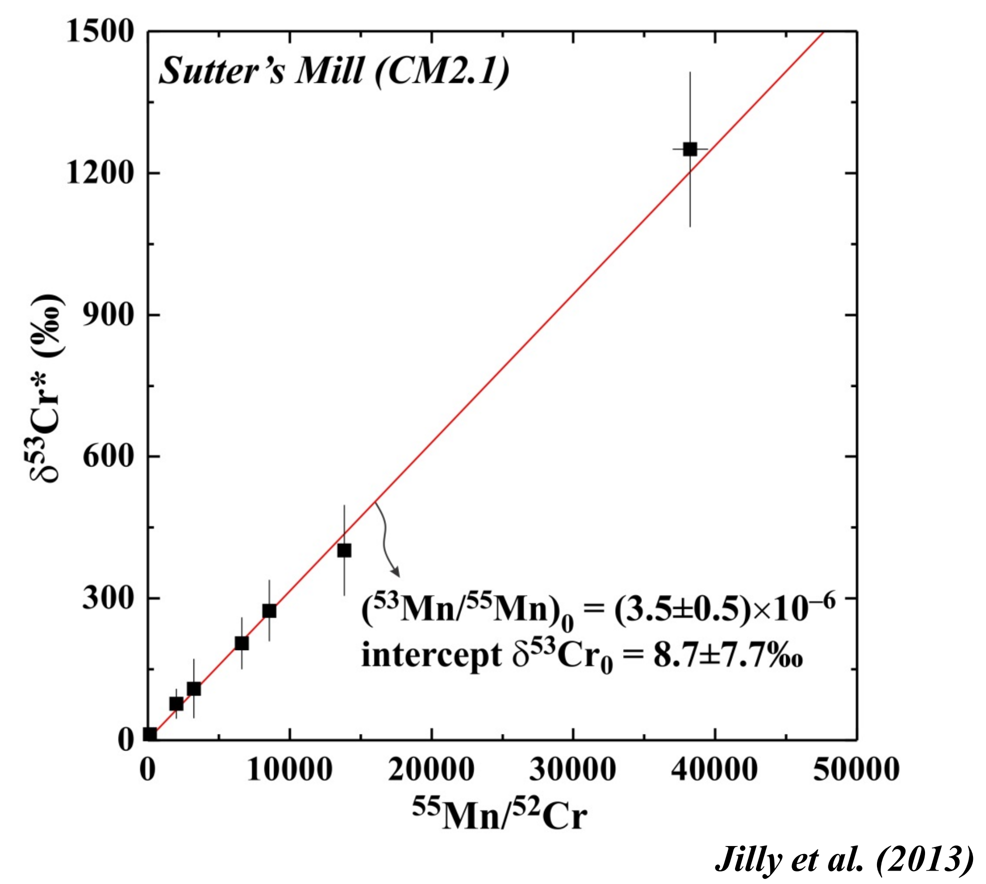
RSF SC olivine ~ 0.86

RSF synth calcite ~ 0.71

Courtesy of C. Jilly

- ^{53}Mn-^{53}Cr dating of carbonates by SIMS requires proper standards
- ^{53}Mn-^{53}Cr ages of carbonates published prior to 2012 are incorrect
- ^{53}Mn-^{53}Cr ages of dolomite [*Fujiya et al. (2012, 2013)*] were measured using calcite standard & should be considered as preliminary

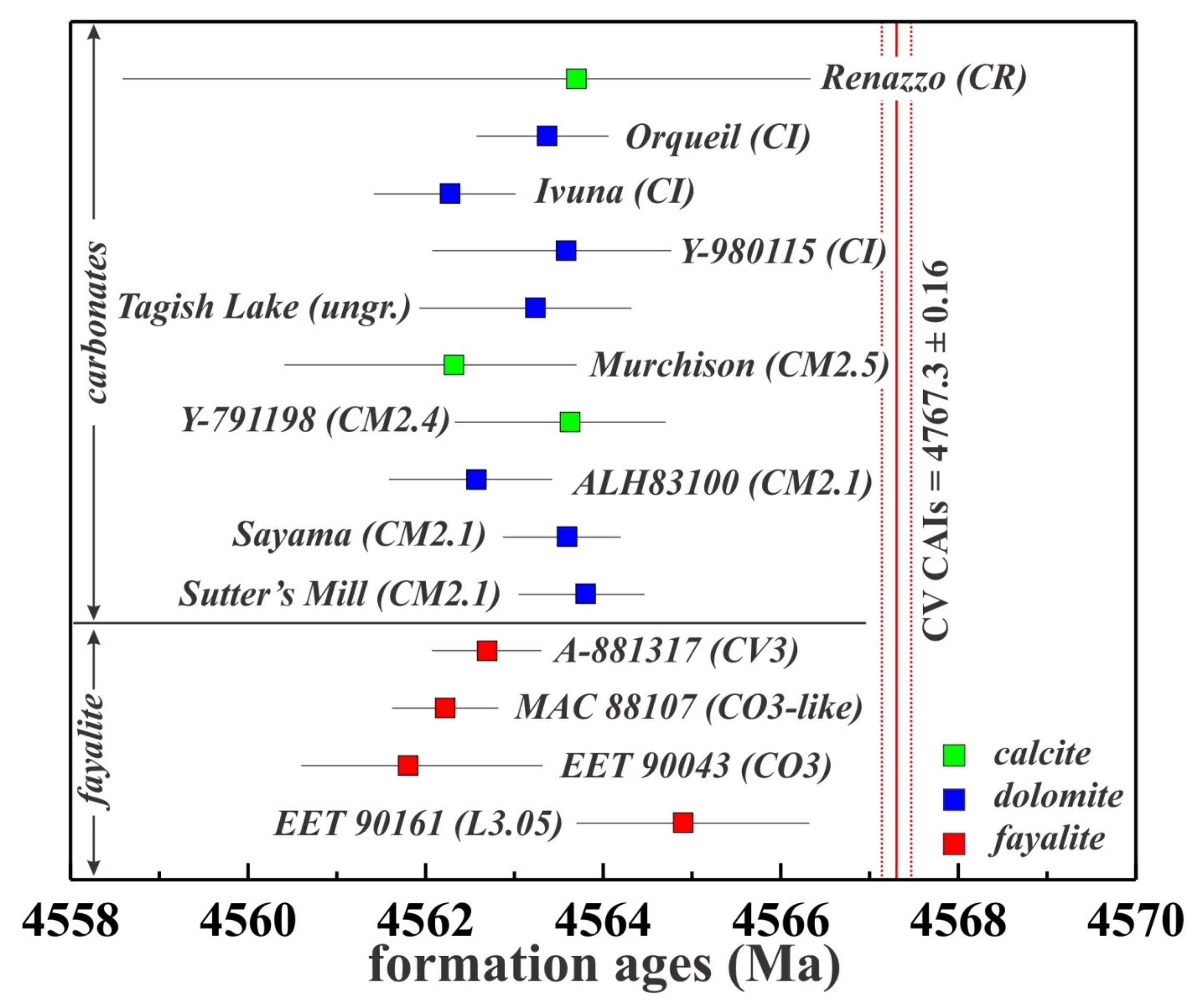
^{53}Mn-^{53}Cr dating of dolomite in CO chondrites



Jilly et al. (2013)

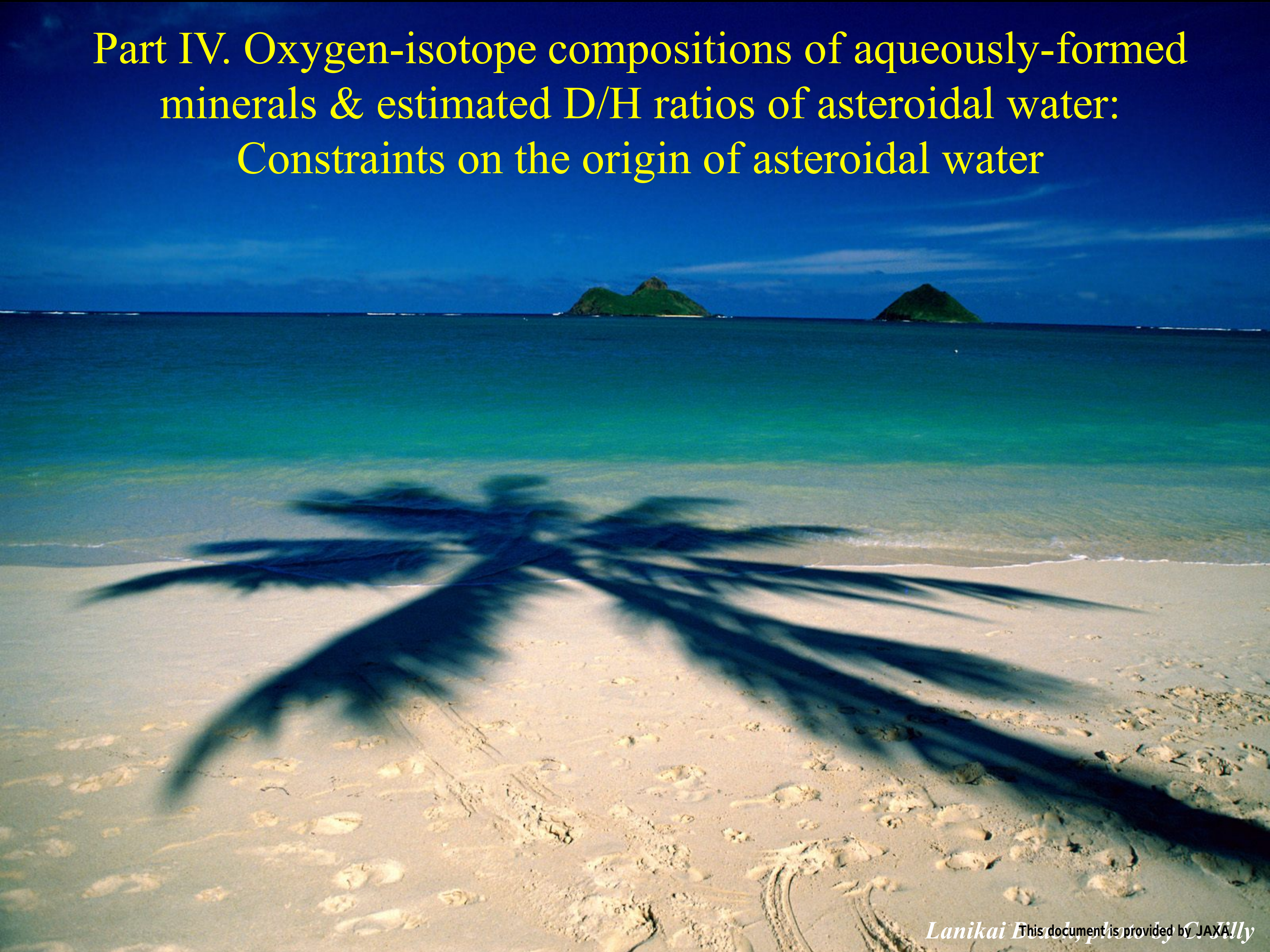
- $3.5^{+0.7}_{-0.8}$ Myr after CV CAIs

^{53}Mn-^{53}Cr ages of fayalite & carbonates in UOCs & CCs



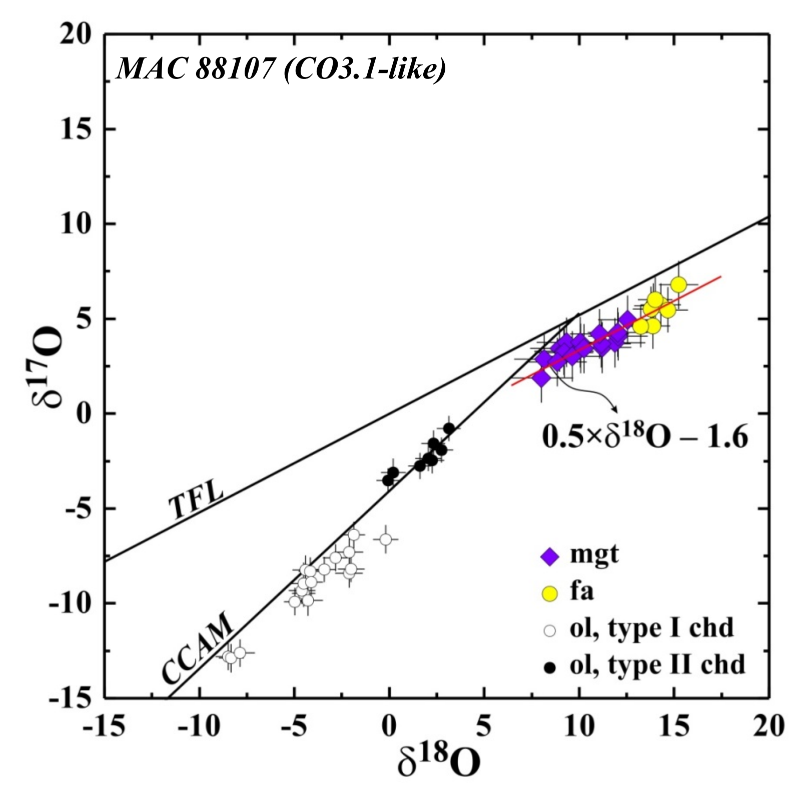
Fujiya et al. (2012, 213); Jilly et al. (2013); Doyle et al. (2013)

Part IV. Oxygen-isotope compositions of aqueously-formed minerals & estimated D/H ratios of asteroidal water: Constraints on the origin of asteroidal water



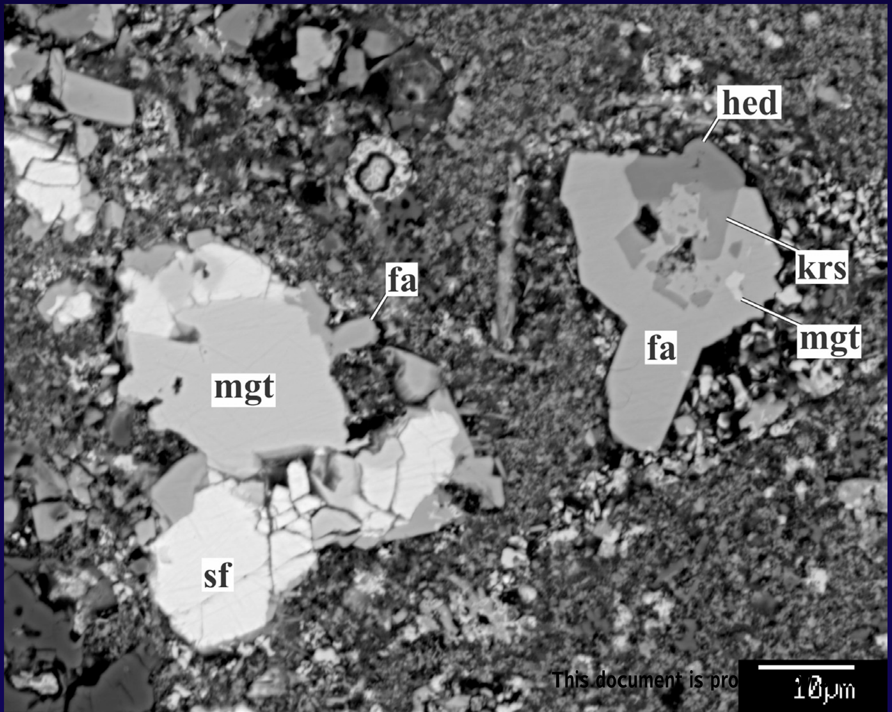
Lanikai Beach, photo by C. Jilly

O-isotope compositions of fayalite & magnetite in MAC 88107

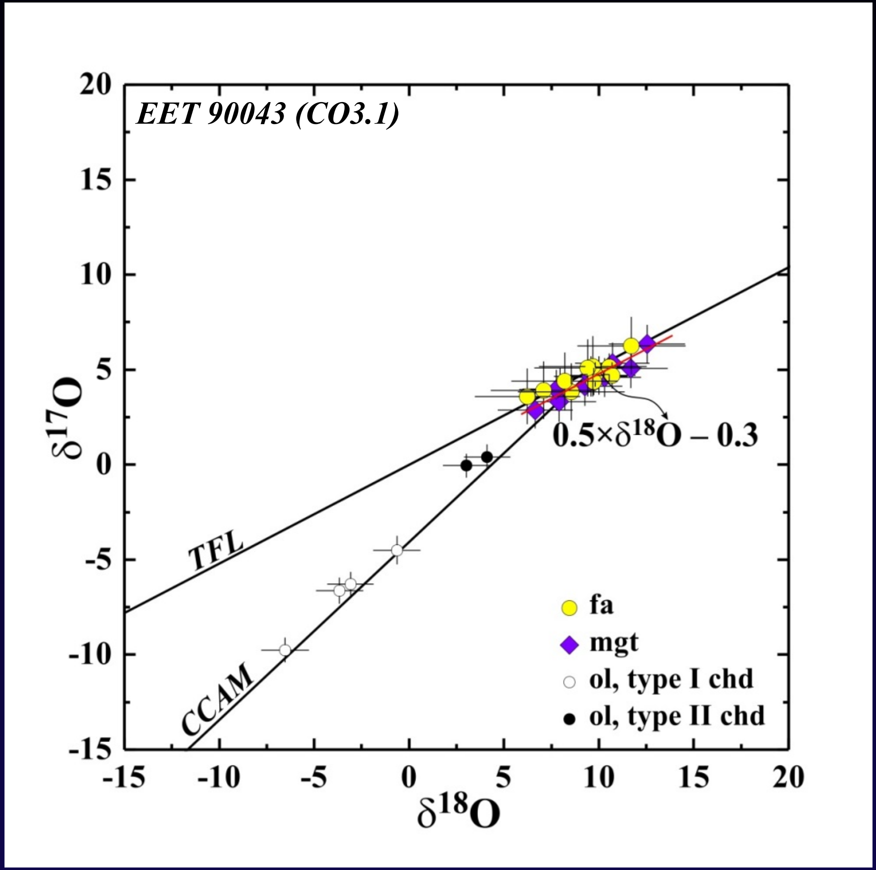


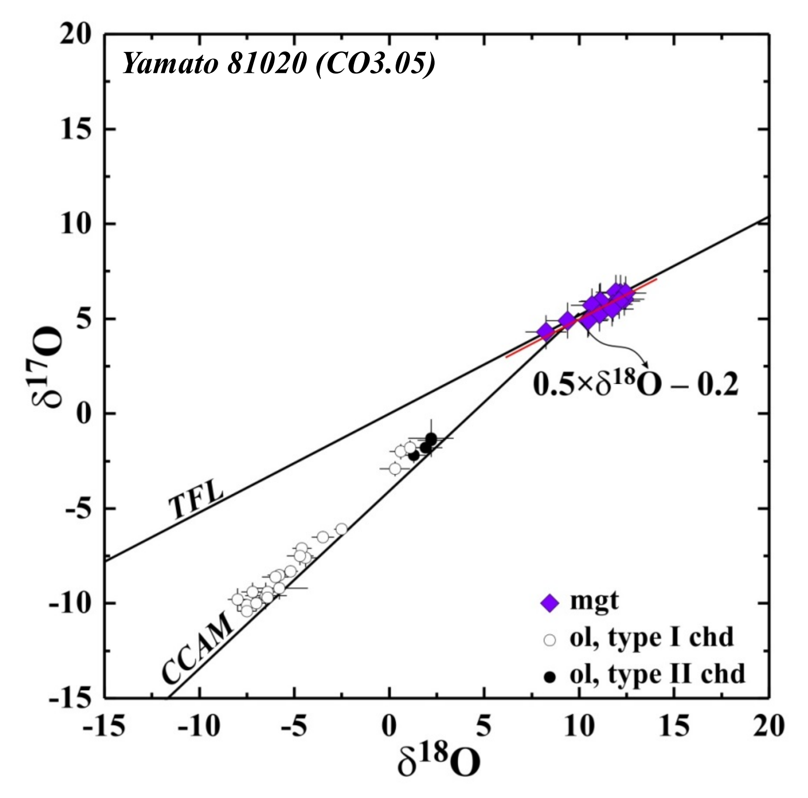
Krot et al. (2013)

- *fa* & *mgt* along slope-0.5 line
  - $\Delta^{17}O \sim -1.6\pm0.9‰$, where $\Delta^{17}O = \delta^{17}O - 0.52\times\delta^{18}O$
- chondrule *ol*
  - type I: $\Delta^{17}O \sim -6.9\pm1.8‰$
  - type II: $\Delta^{17}O = -3.2\pm0.8‰$
- *fa* & *mgt* are in oxygen isotopic disequilibrium with chondrule *ol*



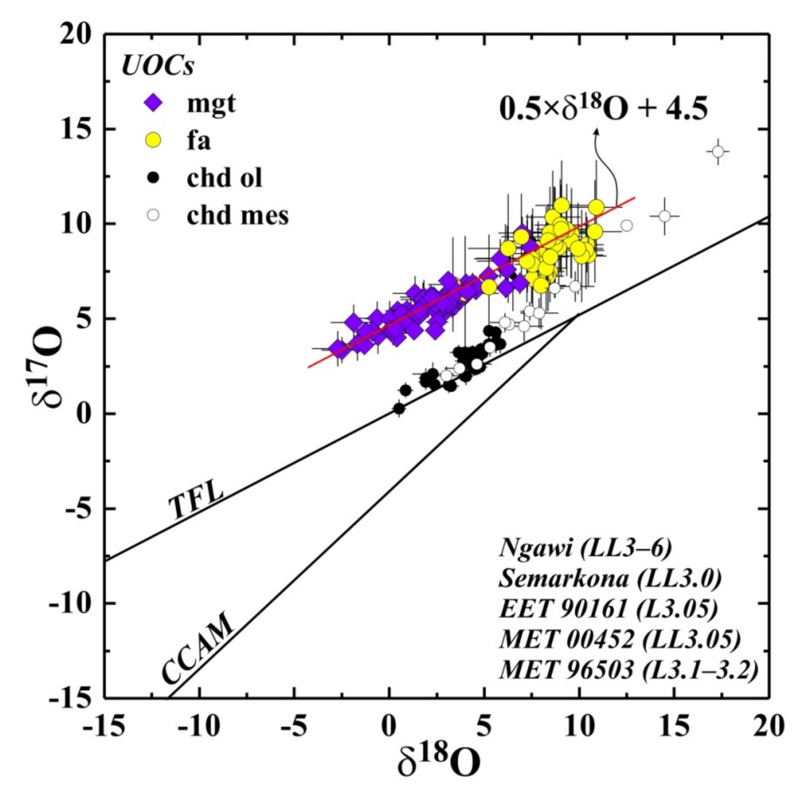
O-isotope compositions of fayalite & magnetite in CO chondrites





- *fa* & *mgt* along slope-0.5 line
  - $\Delta^{17}O \sim -0.3 \pm 0.4‰$
- chondrule *ol*
  - type I: $\Delta^{17}O \sim -5‰$
  - type II: $\Delta^{17}O \sim -2‰$
- *fa* & *mgt* are in oxygen isotopic disequilibrium with chondrule *ol*

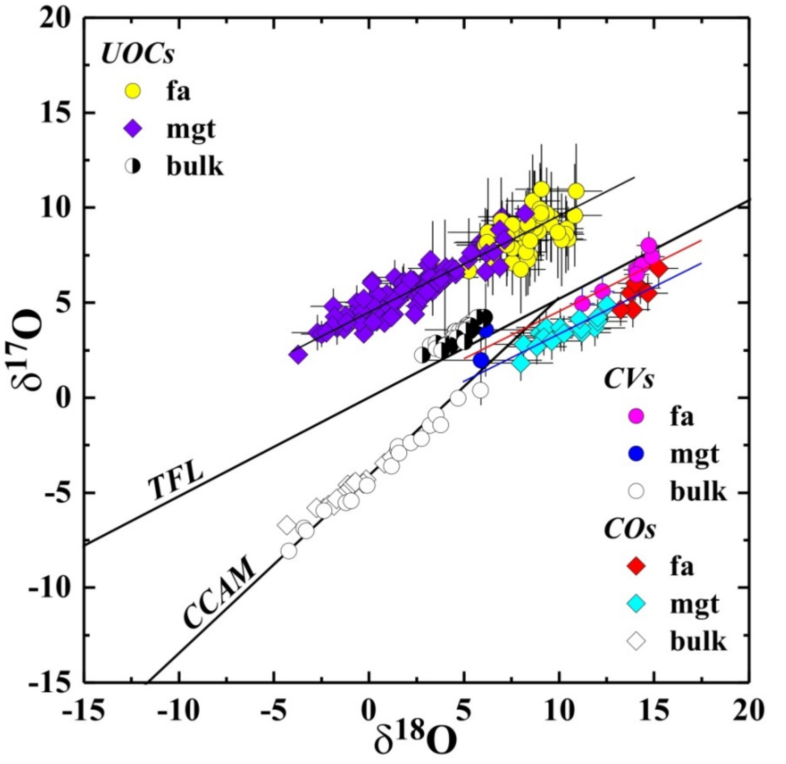
O-isotope compositions of fayalite & magnetite in UOCs

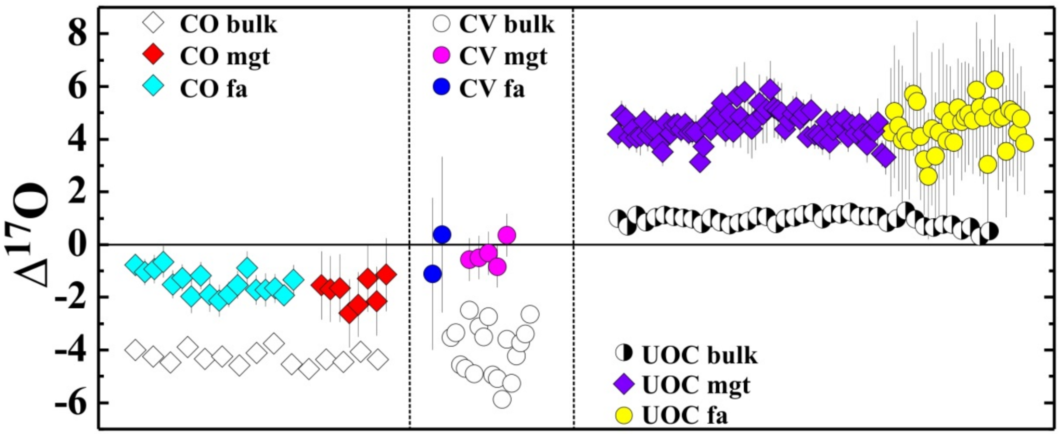


Kita et al. (2010); Krot et al. (2012); Doyle et al. (2013)

- *fa* & *mgt* along slope-0.5 line
  - Δ^{17}O ~ +4.5‰
- chondrule silicates
  - *ol*: Δ^{17}O ~ +0.6±0.5‰
  - *mes*: Δ^{17}O +1 to +4.5‰
- *fa* & *mgt* in oxygen isotopic disequilibrium with chondrule *ol*
- chondrule *mes* experienced O-isotope exchange with a fluid

Oxygen-isotope compositions of aqueous solutions

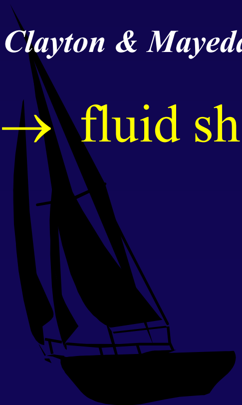




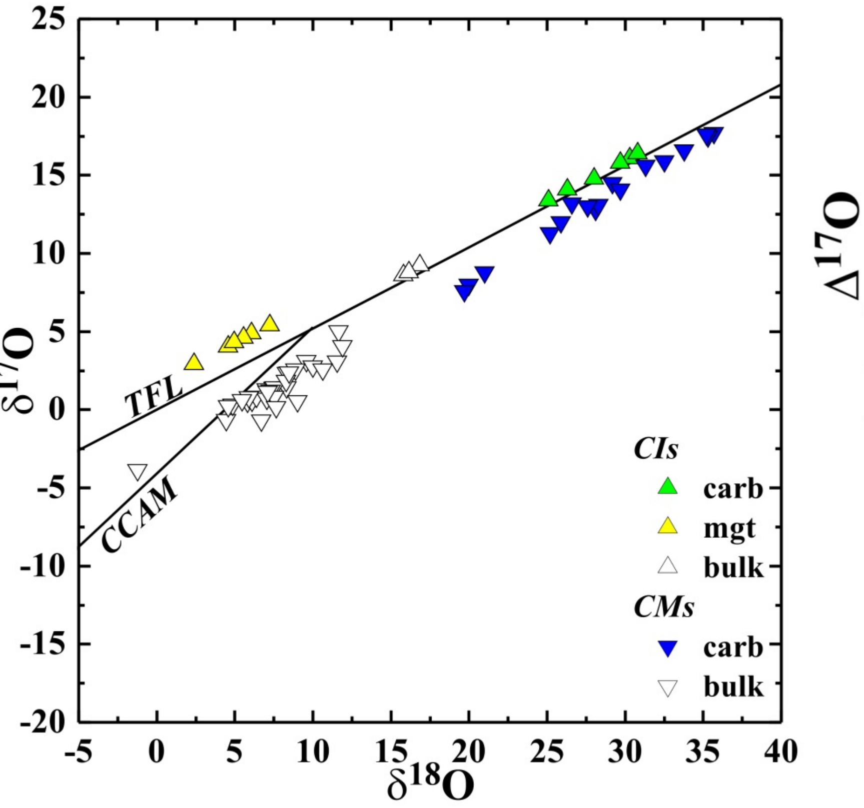
- in UOC, CV & CO:
  - Δ^{17}O of *fa & mgt* differ from chondrule silicates & bulk chondrites
  - plot along slope-0.5 line
  - $\Delta^{17}O_{fa\ \&\ mgt} = \Delta^{17}O_{fluid}$

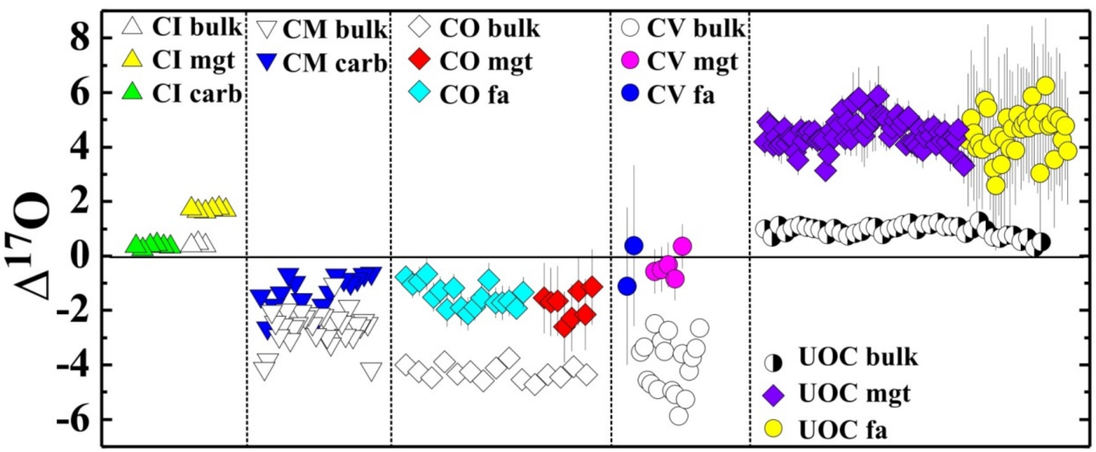
Clayton & Mayeda (1999); Krot et al. (2013); Doyle et al. (2013)

→ fluid shows no evidence for exchange with ^{16}O-enriched anhydrous silicates



Oxygen-isotope compositions of aqueous solutions & water ices





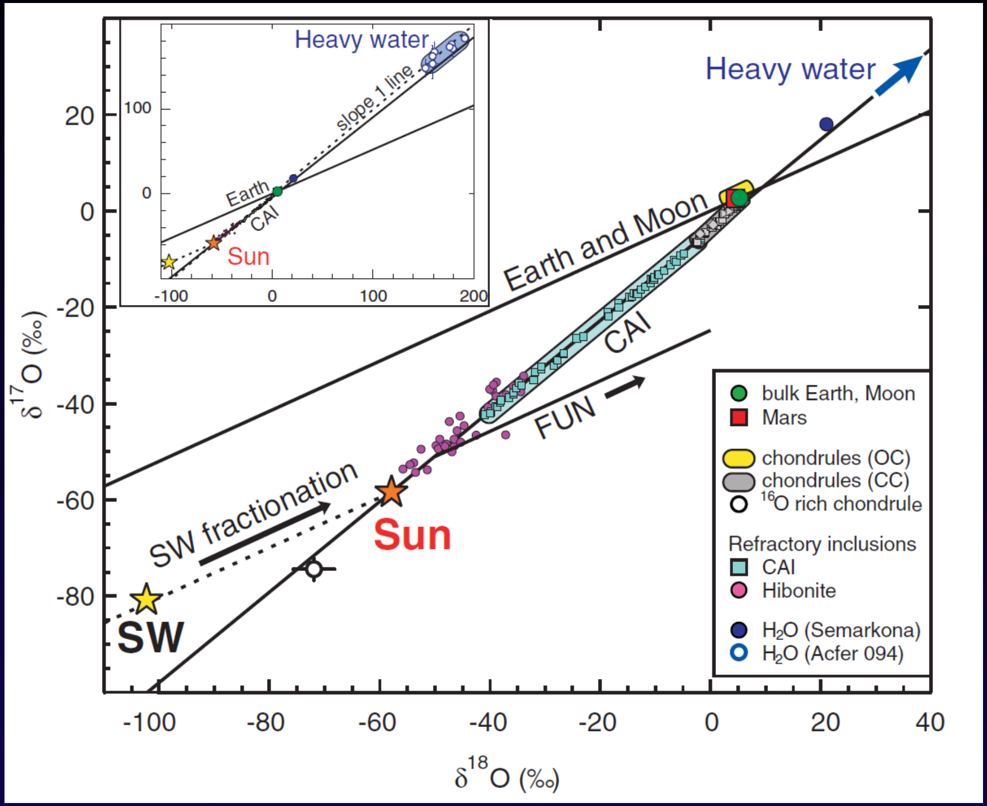
Clayton & Mayeda (1999), Rowe et al. (1994), Benedix et al. (2003)
Leshin et al. (1997, 2011)

- in CM & CI chondrites:
  - $\Delta^{17}O$ of *carb* approach $\Delta^{17}O$ of whole-rock meteorites
  - small changes in $\Delta^{17}O$ value of a fluid with increasing degree of aqueous alteration

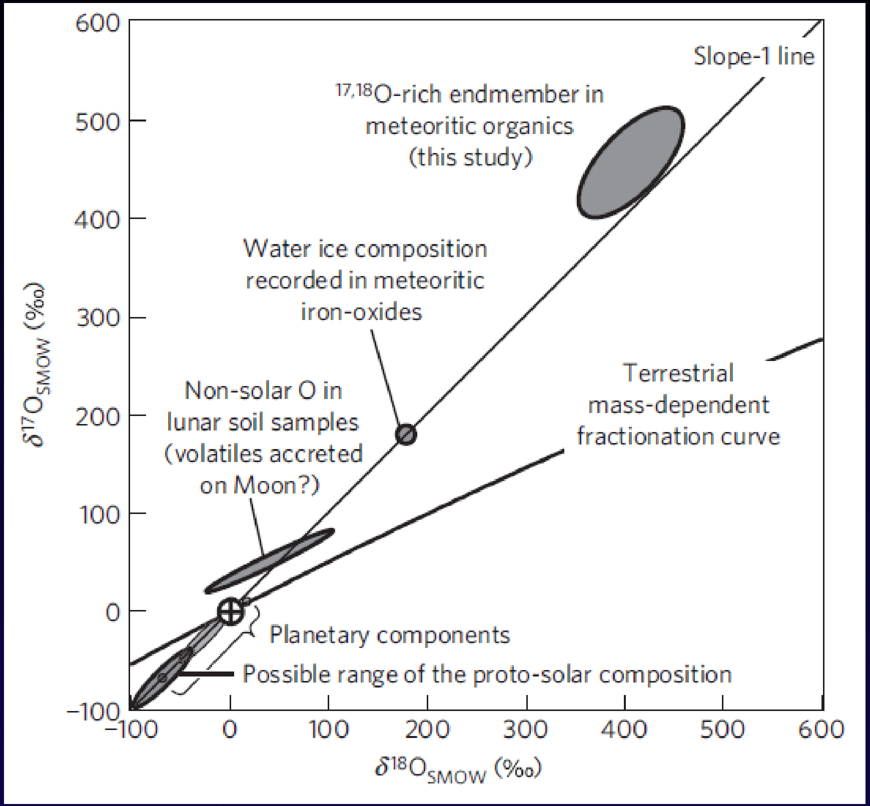
$\Delta^{17}O$ of *fa & mgt* in ordinary, CO & CV, & of *mgt & carb* in CI & CM chondrotes can be used as a proxy* for $\Delta^{17}O$ values of water ices that accreted into their parent bodies

*$\Delta^{17}O$ of water prior to formation of *mgt*, *fa*, & *carb* is not known

Sources of water ices on chondrite asteroids



McKeegan et al. (2011)

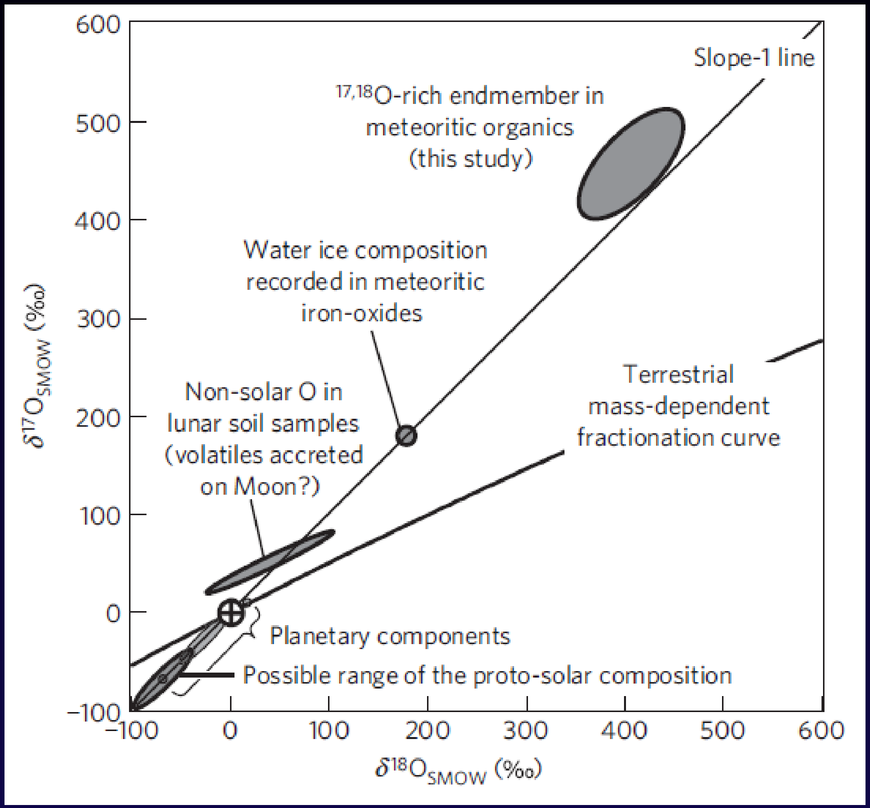


Hashizume et al. (2011)

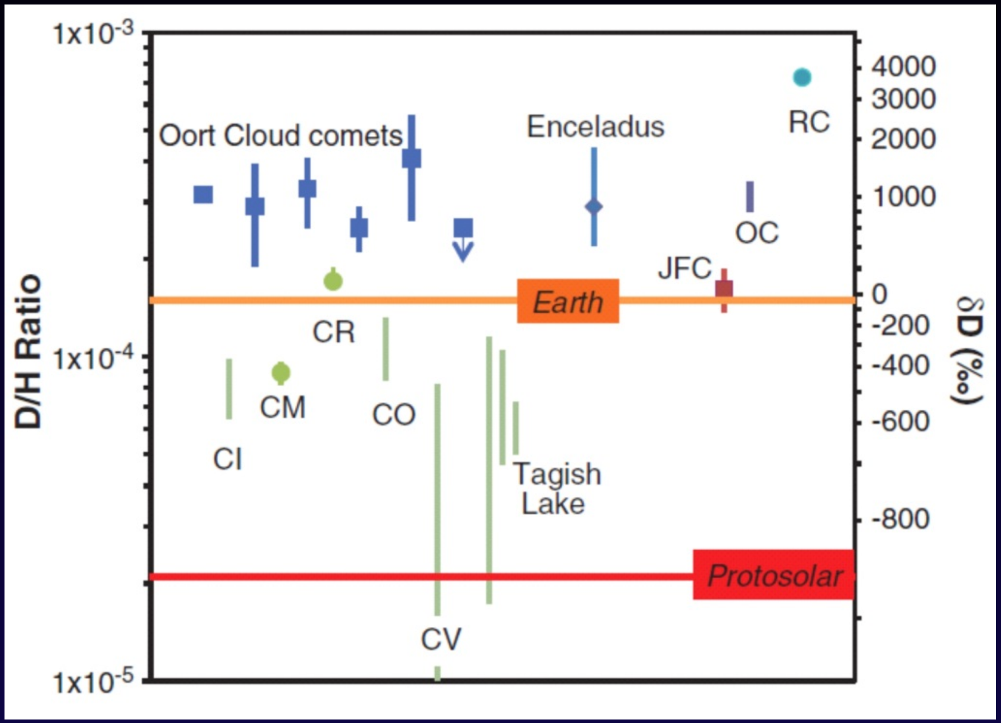
- in the CO self-shielding models *(Yurimoto & Kuramoto, 2004; Lyons & Young, 2005)*, water ices in the outer disk is highly ^{17}O & ^{18}O-enriched relative to gas & solids in inner disk
  - iron oxides in Acfer 094 (ungrouped): $\Delta^{17}O$ ~ +90‰ *(Sakamoto et al., 2007)*
  - grains in IOM from Y-793495 (CR): $\Delta^{17}O$ ~ +500‰ *(Hashizume et al., 2007)*

- water ices on OC & CC asteroids were not anomalously ^{17}O- & ^{18}O-enriched, suggesting a local origin

Sources of water ices on chondrite asteroids



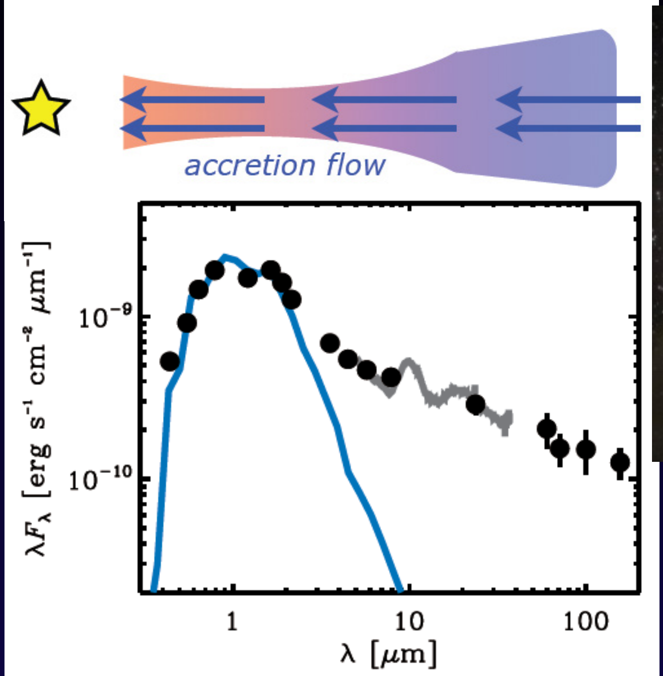
Hashizume et al. (2011)



Alexander et al. (2012)

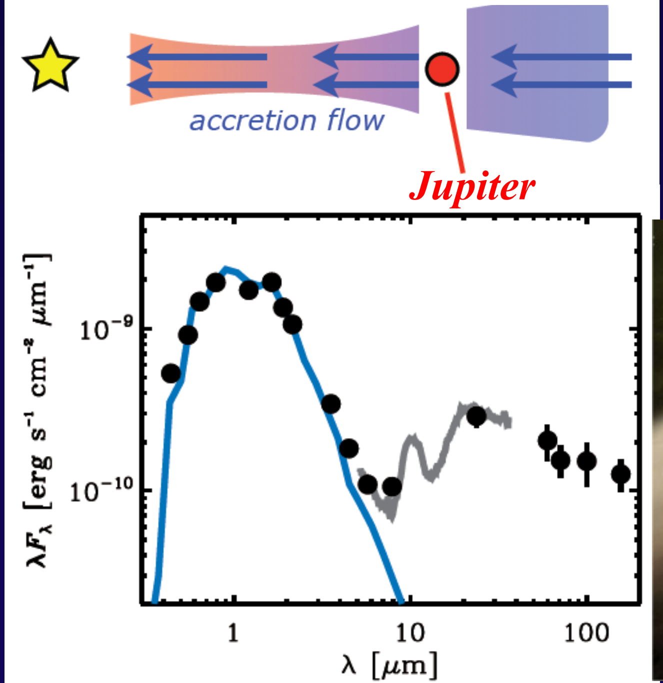
- local, inner Solar System origin of asteroidal water ices is consistent with the inferred D/H ratios of chondritic water *(Alexander et al. 2012)*, which are very different from D/H ratios in Oort Cloud Comets measured

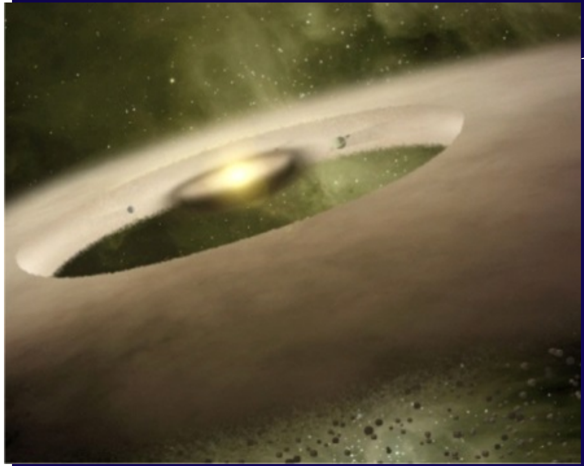
Role of Jupiter in isolating inner disk from the outer Solar System



full, optically thick disk

- low influx of water from the outer Solar System $\geq$2.5 Myr after CAI formation could be due to an early growth of Jupiter that opened a gap in the disk & prevented significant radial transport of dust from outside its orbit





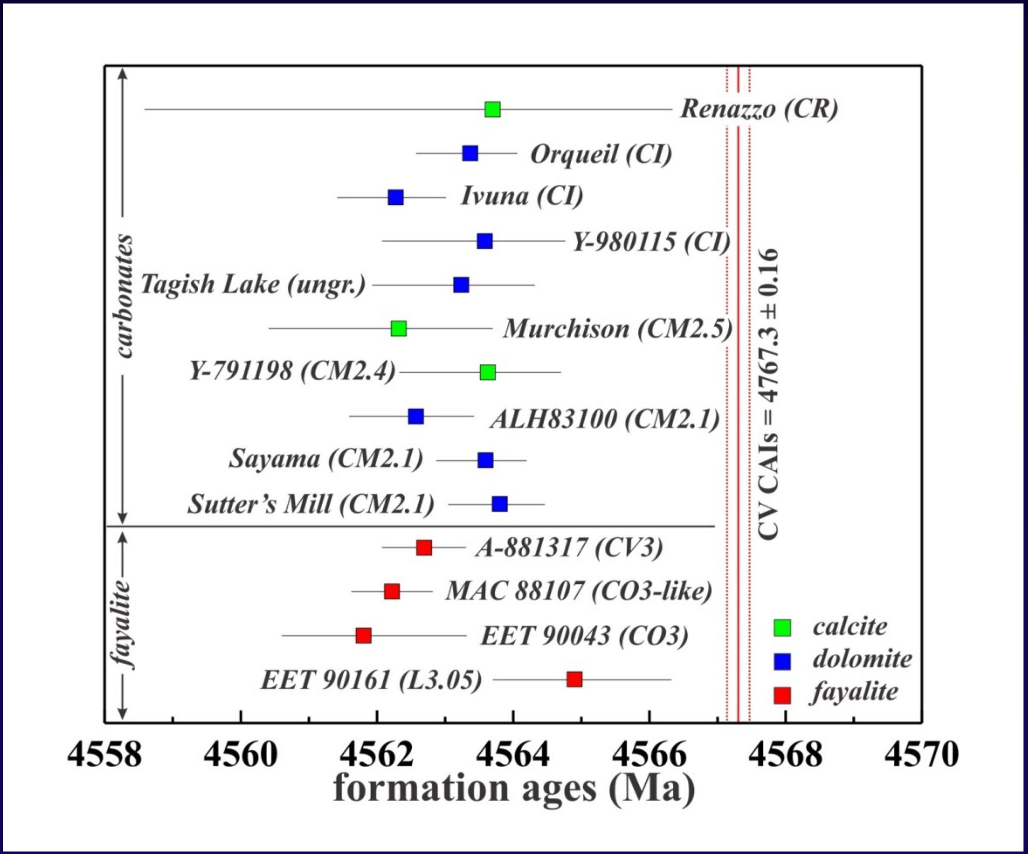
pre-transitional disk with a gap

Conclusions (I)

- CI, CM, CR, CV, CO, & UOCs experienced various degrees of aqueous alteration

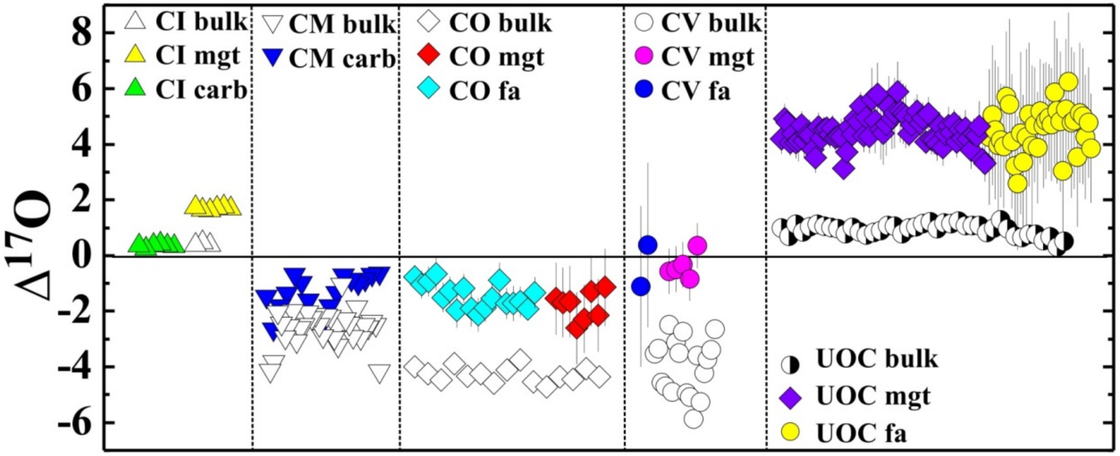
- ^{53}Mn-^{53}Cr dating of carbonates in CI, CM, & CR chondrites, & fayalite in CV, CO, & UOCs indicate aqueous activity occurred ~3–5 Myr after CV CAIs

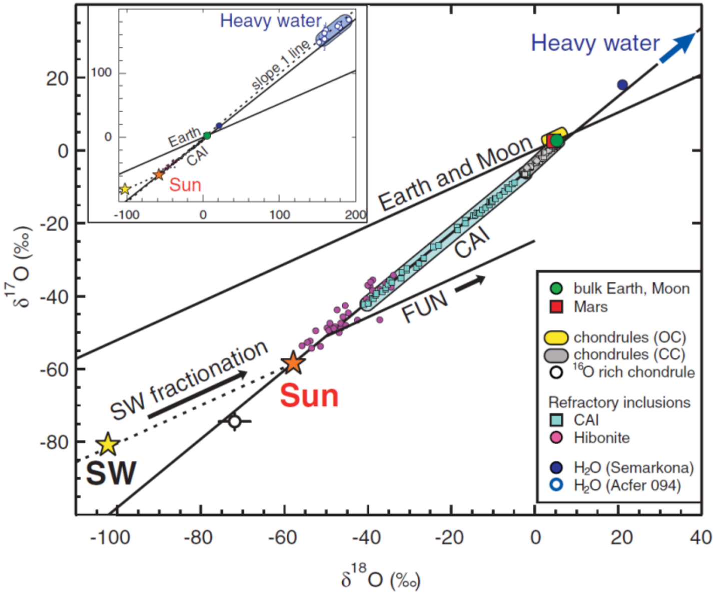
- old ages of aqueous alteration & their narrow range are consistent with heating of chondrite asteroids by ^{26}Al, & inconsistent with a significant role of impact heating



Conclusions (II)

- near the terrestrial O-isotope compositions of fayalite, magnetite, & carbonates in UOCs & CCs imply that asteroidal water had preferentially a local, inner Solar System origin, consistent with the inferred D/H ratio of chondritic water *(Alexander et al. 2012)*





- ordinary chondrites accreted isotopically heavier water than CCs & may have had a higher proportion of the outer Solar System water

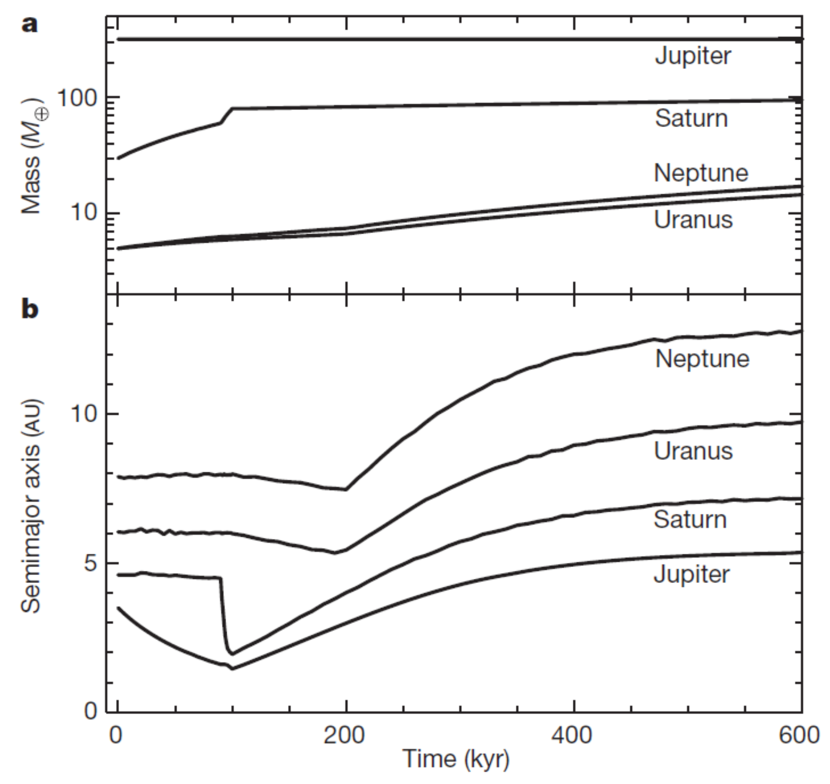
- low influx of water from the outer SS during accretion of CC asteroids could be due to an early growth of Jupiter that opened a gap in the disk & prevented significant radial transport of dust from outside its orbit

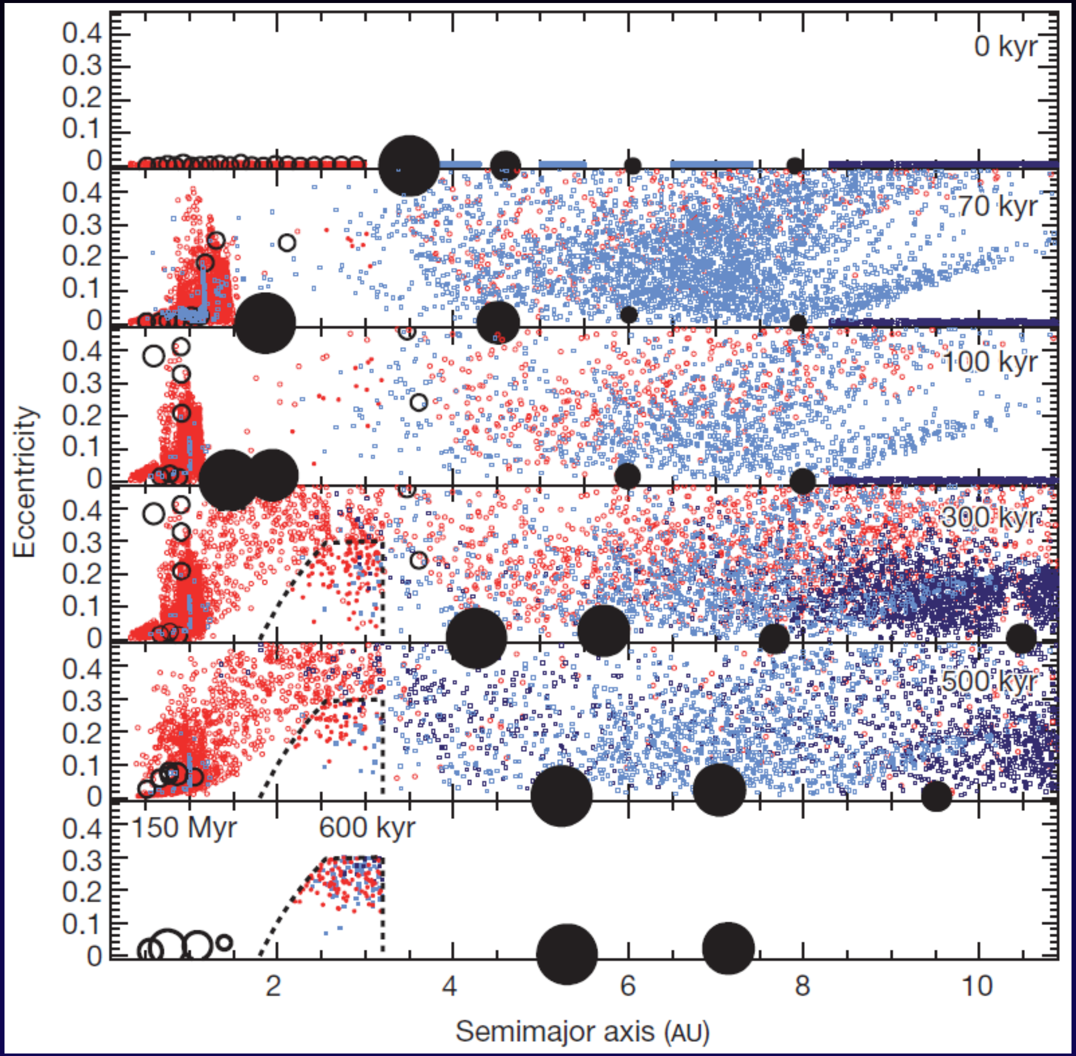
Extra slides

A low mass for Mars from Jupiter's early gas-driven migration

Kevin J. Walsh[1,2], Alessandro Morbidelli[1], Sean N. Raymond[3,4], David P. O'Brien[5] & Avi M. Mandell[6]

Nature (2011)





Sources of water on asteroids: Insights from H & N isotopes

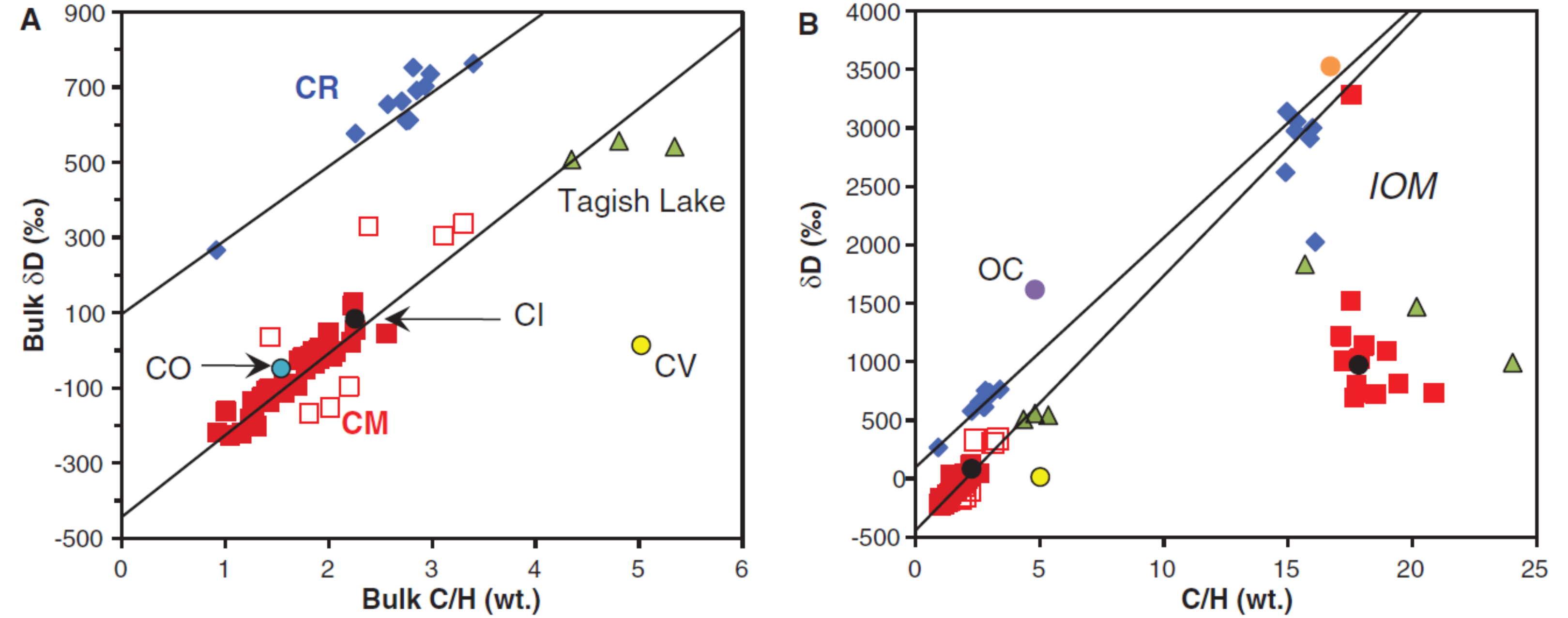
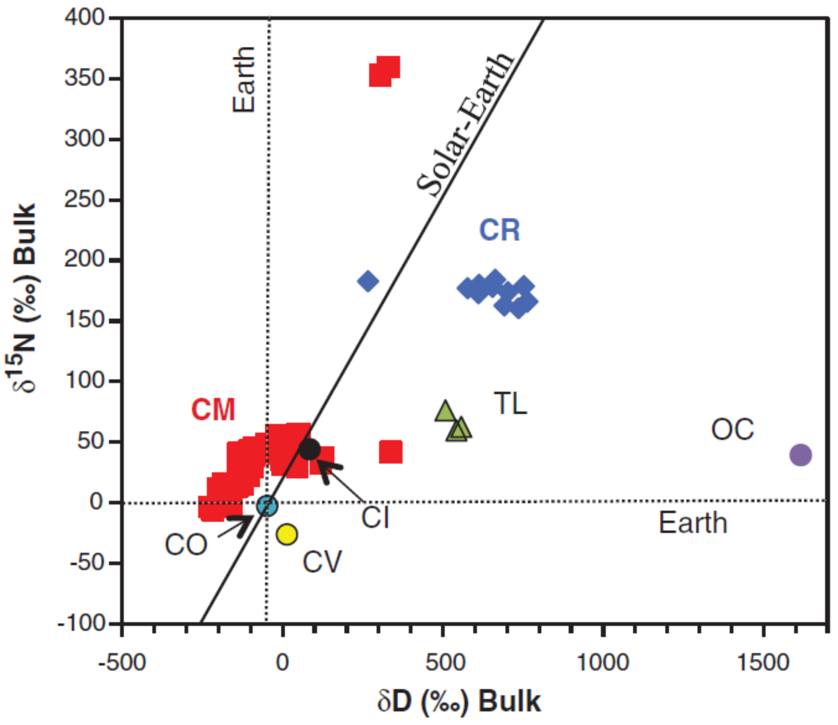


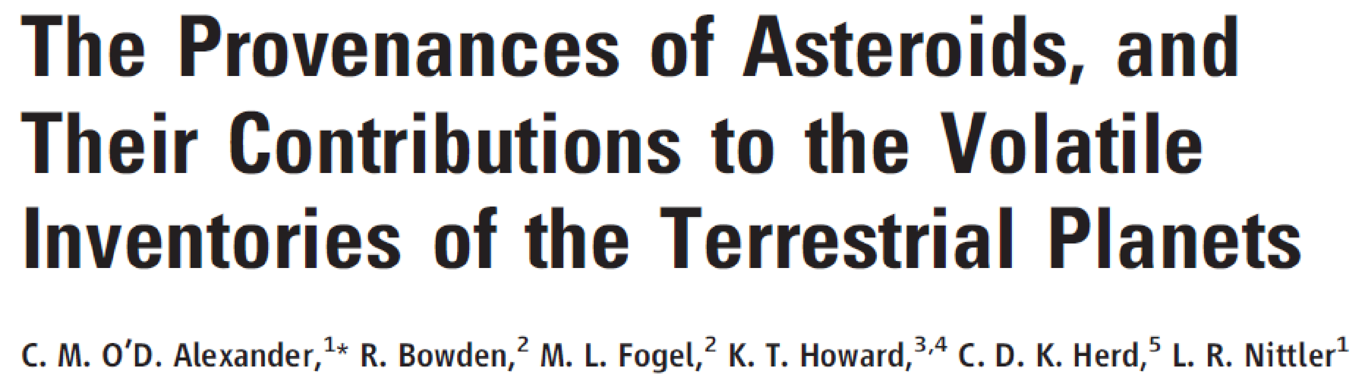
Fig. 1. (**A**) The bulk compositions of the carbonaceous chondrites analyzed here. The lines are fits to the CR and CM data. Open red squares are CMs that were not included in the CM fit. (**B**) An expanded scale to show that the CR and CM lines pass through the compositions of the most primitive chondritic insoluble organic matter (IOM) (*11*, *14*). The bulk composition of the OC Semarkona is also included.

- CM & CR chondrites experienced different degrees of aqueous alteration
- bulk H-isotopic compositions of a chondrite = hydrated silicates + organics
- δD *vs.* C/H → isotopic composition of water; $\delta D = (D/H_{sample}/D/H_{SMOW} - 1)\times 1000$
- CM & CR trends converge on the region where the most primitive insoluble organic matter (IOM) plots → share a common primitive organic component

Fig. 3. The bulk hydrogen and nitrogen isotopic compositions of chondrites (TL, Tagish Lake). The line connects the solar and terrestrial isotopic compositions. Bodies similar to chondrites are potential sources of Earth's volatiles. For reasons discussed in the text, CI-like material with ~10% contributions of material with isotopically solar compositions, but a roughly chondritic H/N value, can most simply explain Earth's bulk hydrogen and nitrogen isotopic compositions (*3*).



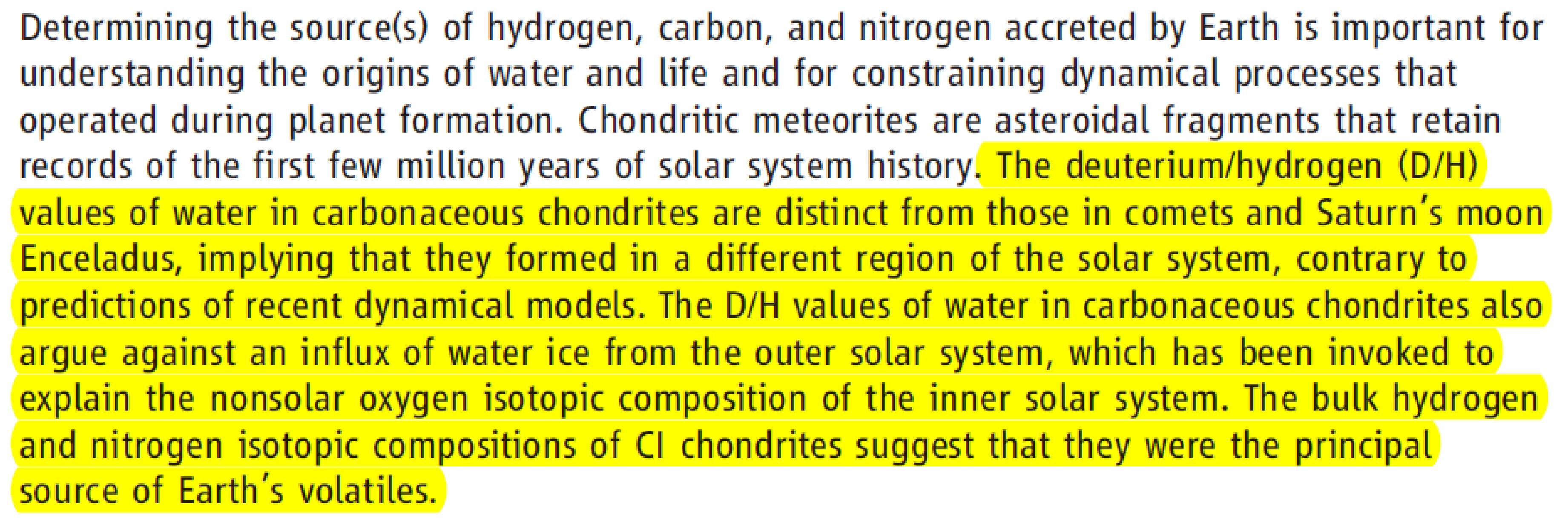
- if comets were not the sources of Earth's water, asteroids become the most likely candidates, along with some nebular gas
- most of H & N (as well as other volatiles) accreted in CI-like material along with ~10% contribution to both elements from material with a solar isotopically solar compositions



The Provenances of Asteroids, and Their Contributions to the Volatile Inventories of the Terrestrial Planets

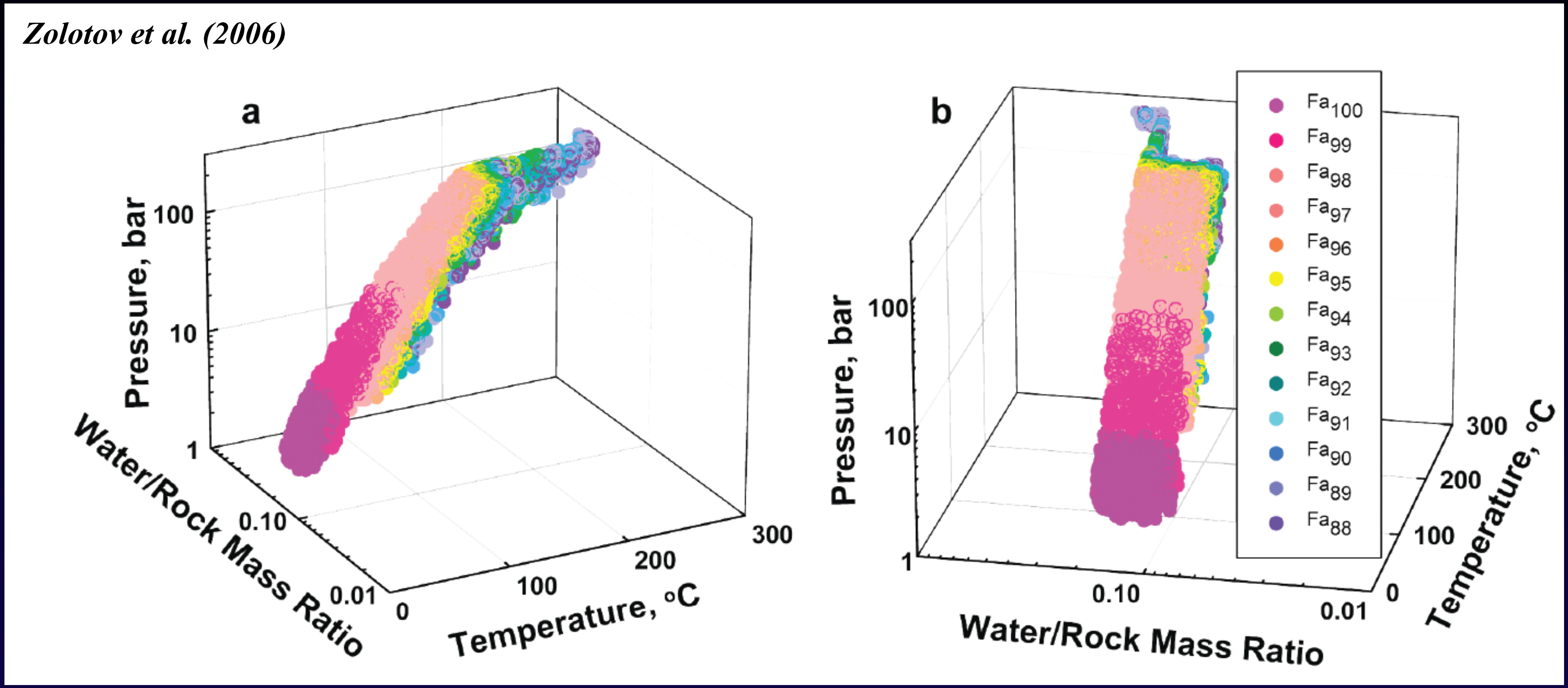
C. M. O'D. Alexander,[1]* R. Bowden,[2] M. L. Fogel,[2] K. T. Howard,[3,4] C. D. K. Herd,[5] L. R. Nittler[1]

Science, 337, 721 (2012)



Determining the source(s) of hydrogen, carbon, and nitrogen accreted by Earth is important for understanding the origins of water and life and for constraining dynamical processes that operated during planet formation. Chondritic meteorites are asteroidal fragments that retain records of the first few million years of solar system history. The deuterium/hydrogen (D/H) values of water in carbonaceous chondrites are distinct from those in comets and Saturn's moon Enceladus, implying that they formed in a different region of the solar system, contrary to predictions of recent dynamical models. The D/H values of water in carbonaceous chondrites also argue against an influx of water ice from the outer solar system, which has been invoked to explain the nonsolar oxygen isotopic composition of the inner solar system. The bulk hydrogen and nitrogen isotopic compositions of CI chondrites suggest that they were the principal source of Earth's volatiles.

Origin of fayalite-bearing assemblages



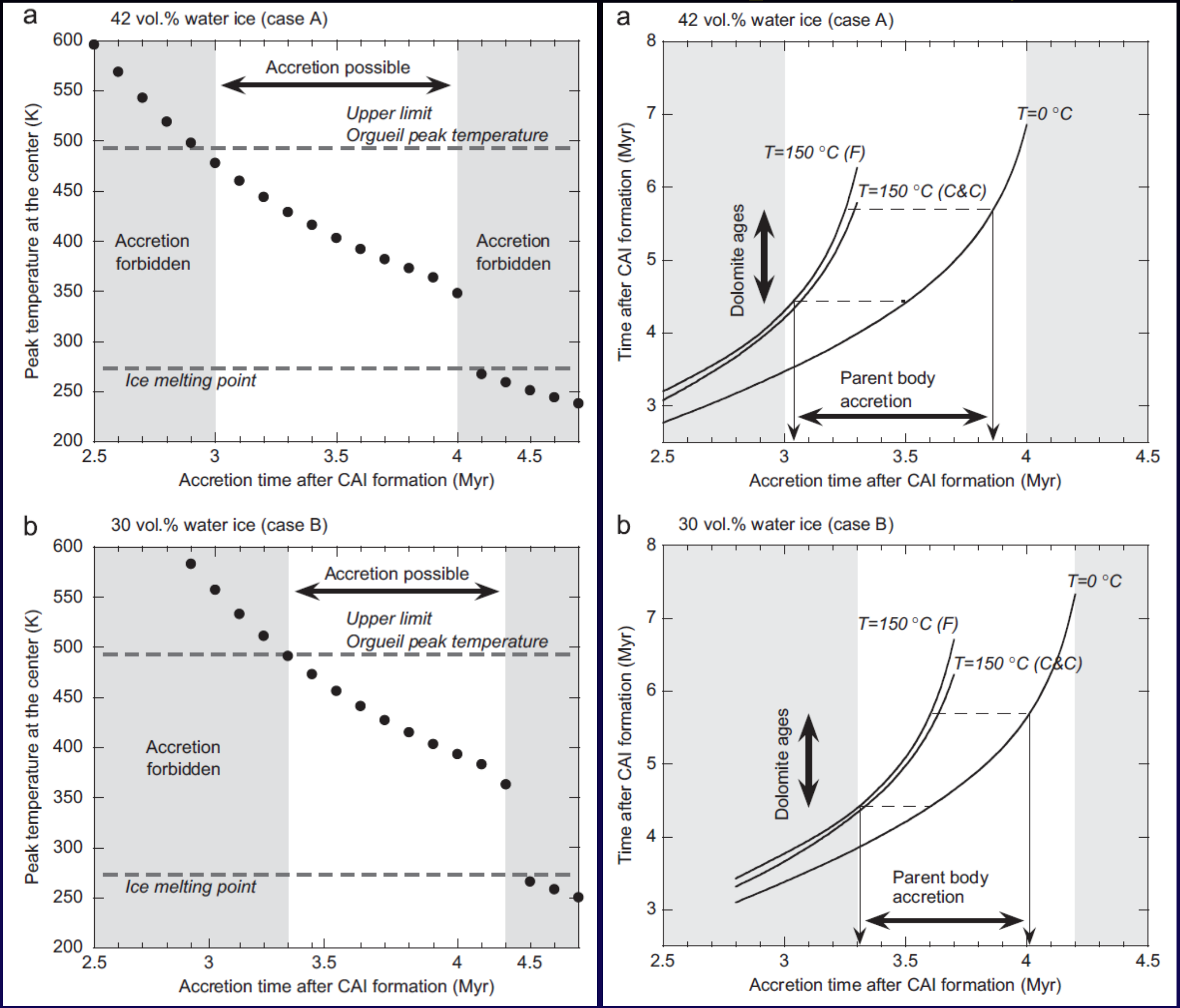
Zolotov et al. (2006)

- fayalite & magnetite formed *in situ,* during fluid-rock interaction at water/rock ratio ~0.1–0.2 & temperatures ~100–300°C
- differences in $\Delta^{17}O$ of fayalite+magnetite in UOCs & CCs

UOC:	+4.5±1.1‰
CV & CO:	–0.4±0.9‰
CO-like:	–1.6±0.9‰

may reflect spatial or temporal variations in O-isotope compositions of water ices that accreted into their parent asteroids

Accretion time of the CI parent body



Fujiya et al. (2013)

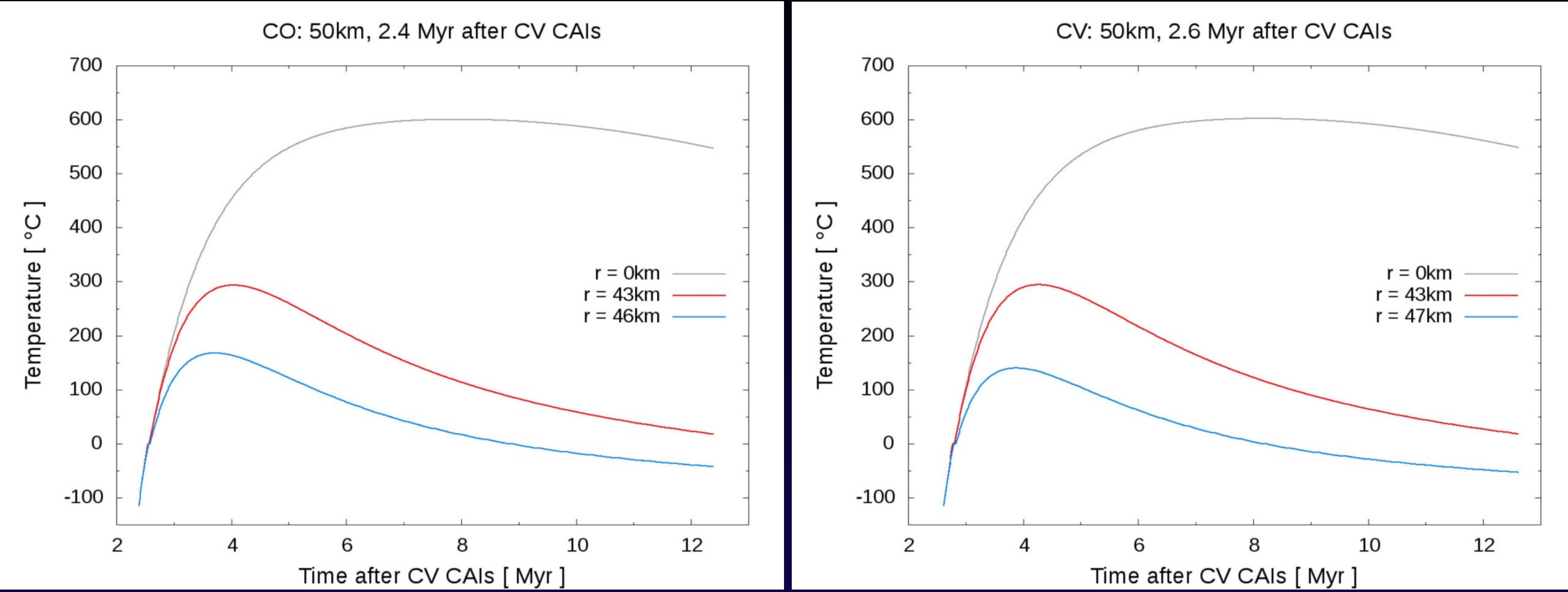
- CIs accreted 3–4 Myr after CV CAIs: based on peak temperature experienced by CIs & ^{53}Mn-^{53}Cr ages & formation temperature of carbonates

Accretion ages of CV & CO asteroids

- COs & CVs define metamorphic sequences of petrologic types 3.0–3.7 & 3.1–3.6 with peak metamorphic temperature of ~600°C *(Huss et al. 2006; Bonal et al. 2006, 2007)*
- ^{26}Al major heating source of asteroids
- $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ in the disk after epoch of CAI formation could have been uniform at ~5×10^{-5} *(e.g., Schrader et al. 2013)*

→ peak metamorphic temperatures can be used to constrain accretion ages of CV & CO parent asteroids

Accretion ages of CV & CO asteroids & formation of fayalite


CO: 50km, 2.4 Myr after CV CAIs

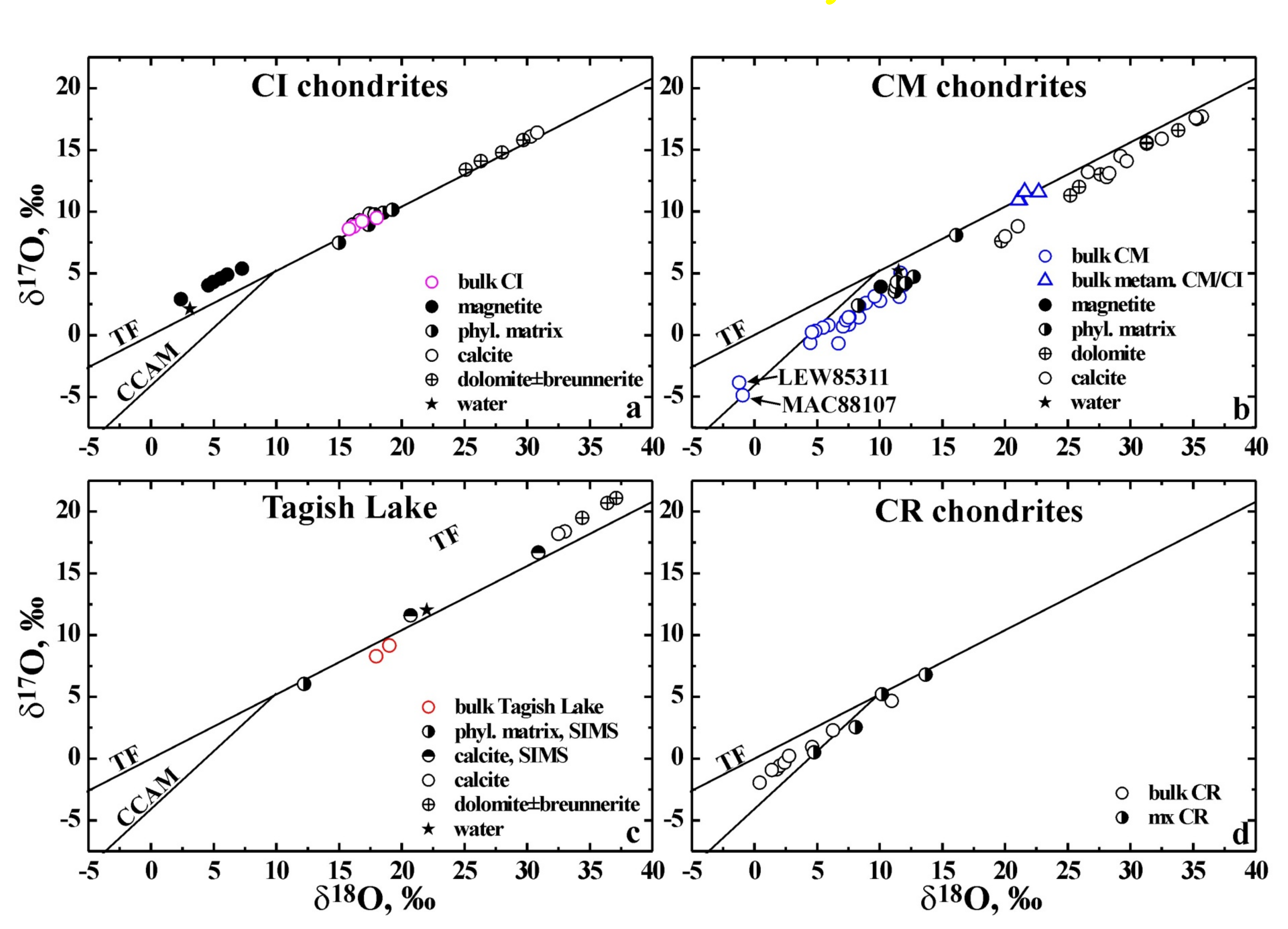
CV: 50km, 2.6 Myr after CV CAIs

- numerical modeling of thermal history of CV & CO like asteroids with radius of 50 km, water/rock ratio 0.2, & peak metamorphic temperature ~600°C
- CV & CO asteroids must have accreted within ≤ 2.6 Myr after CV CAIs, consistent with ^{26}Al-^{26}Mg ages of CO chondrules (2.8±0.8 Myr after CAIs, *Kita & Ushikubo 2012*)
- CV & CO fayalite could have precipitated < 5 Myr after CAIs in the outer portions of these asteroids

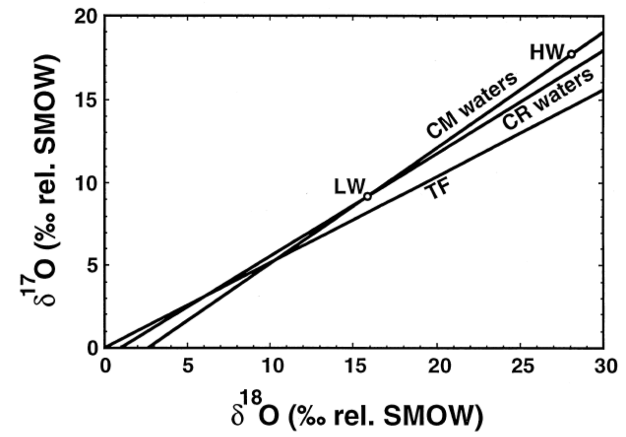
→ CO & CV asteroids accreted with water ices shortly after chondrule formation

- CI & CM parent bodies accreted 3–4 Myr after CAIs *(Fujiya et al. 2012, 2013)*

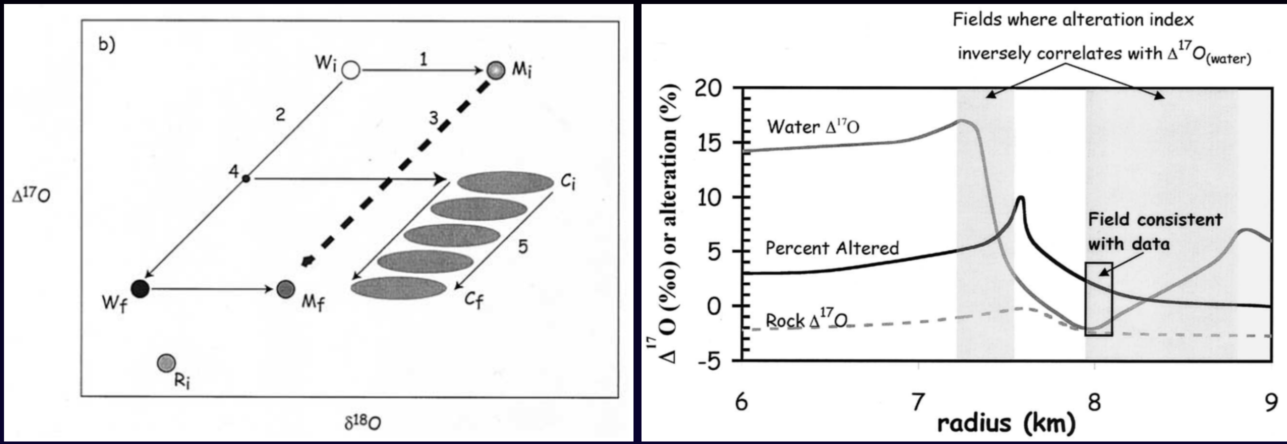
Chondritic water as a potential record of influx of ice from the outer into the inner Solar System



Oxygen-isotope composition of water ices in CCs



Clayton & Mayeda (1999)



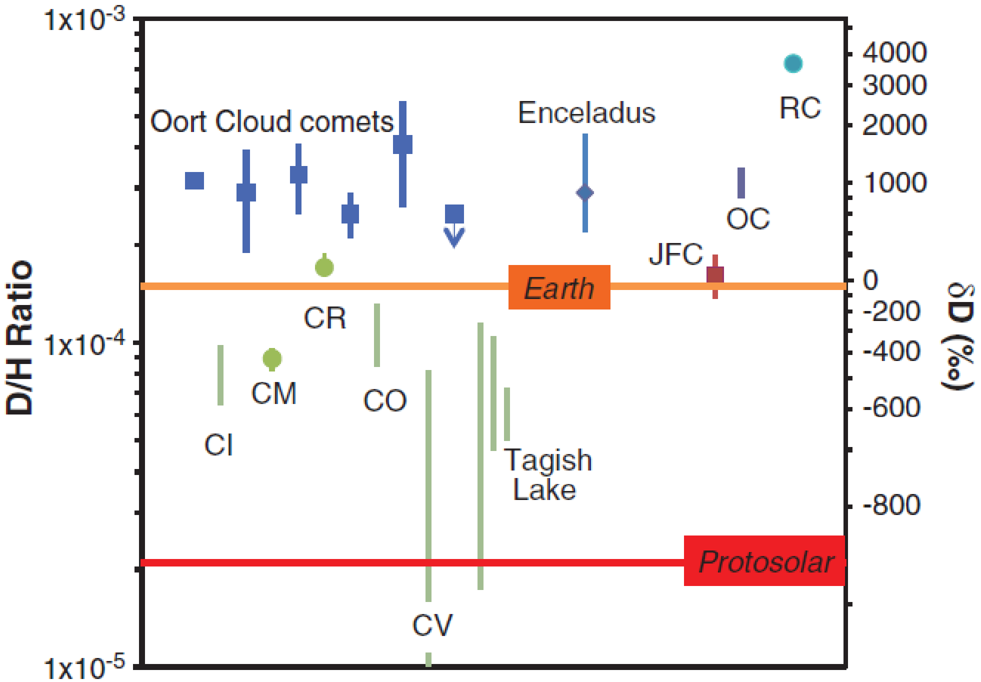
Benedix et al. (2003)

Previous estimates of the initial Δ^{17}O values of water ices in carbonaceous chondrites

- CMs & CRs: +0.9‰ ÷ +3‰ *(Clayton & Mayeda 1999)*
- CIs: +1.7‰ *(Leshin et al. 1997)*
- CMs: > –0.7‰ *(Benedix et al. 2003)*
- up to +20‰ *(Young et al. 1999; Young 2001)*

Sources of water on asteroids: Insights from H, N & O isotopes

Fig. 2. Comparison of the estimated hydrogen isotopic compositions of water in various chondrite groups with those measured in Oort cloud and Jupiter family comets (JFC), and Saturn's icy moon Enceladus. See (3) for details and sources.



- variable amounts of the outer solar system water re-equilibrated at high temperature during chondrule formation with nebular H_2 acquiring ~solar H-isotopic compositions
  - expected inverse correlation between chondrule abundances in chondrites & their initial water D/H values

    chd abundances: OC ≈ RC > CV ≈ CO ≈ CR > CM > Tagish Lake > CI

    initial water D/H: RC > OC > CR > CV ≈ CO ≈ CM ≈ Tagish Lake ≈ CI

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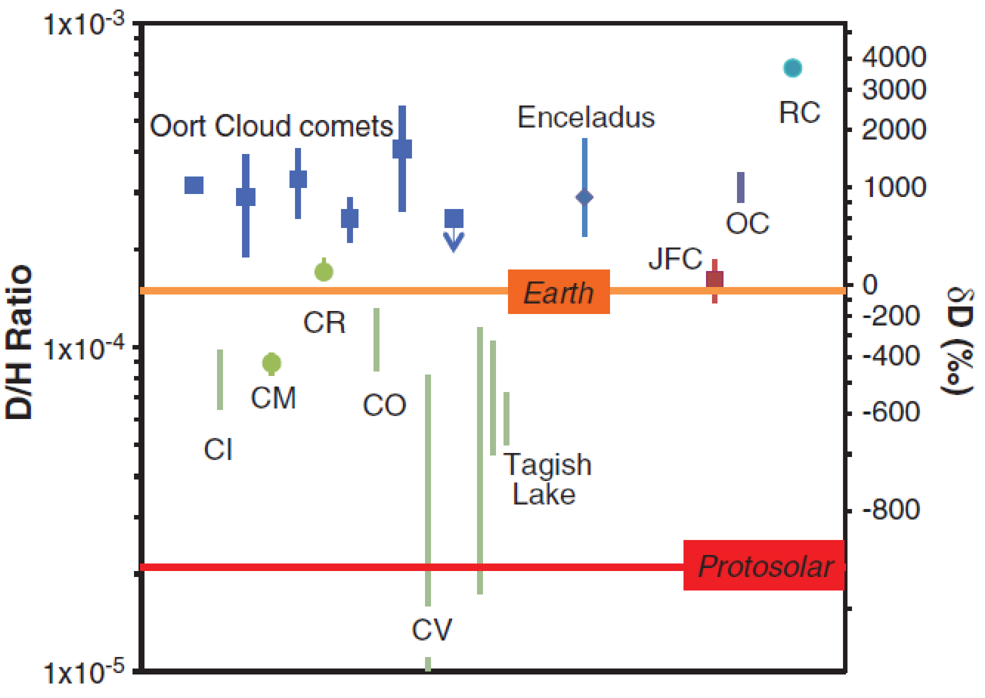

- isotopically solar-like water re-equilibrated with nebular H_2 sunward of the snow line & subsequently migrated out to the chondrite-formation region beyond the snow line, e.g., via the cold finger effect
  - water in OCs & RCs would then be essentially pure outer solar system ice
  - water in OCs & RCs should be more ^{16}O-depleted than in CCs (need to check)

"Thus, at present there is inconsistency between the ice influx model & our results, unless, perhaps, the major ice influx occurred long before chondrite formation & the ice that chondrites accreted formed locally (with smaller isotopic anomalies) because transport in the disk had become less efficient"

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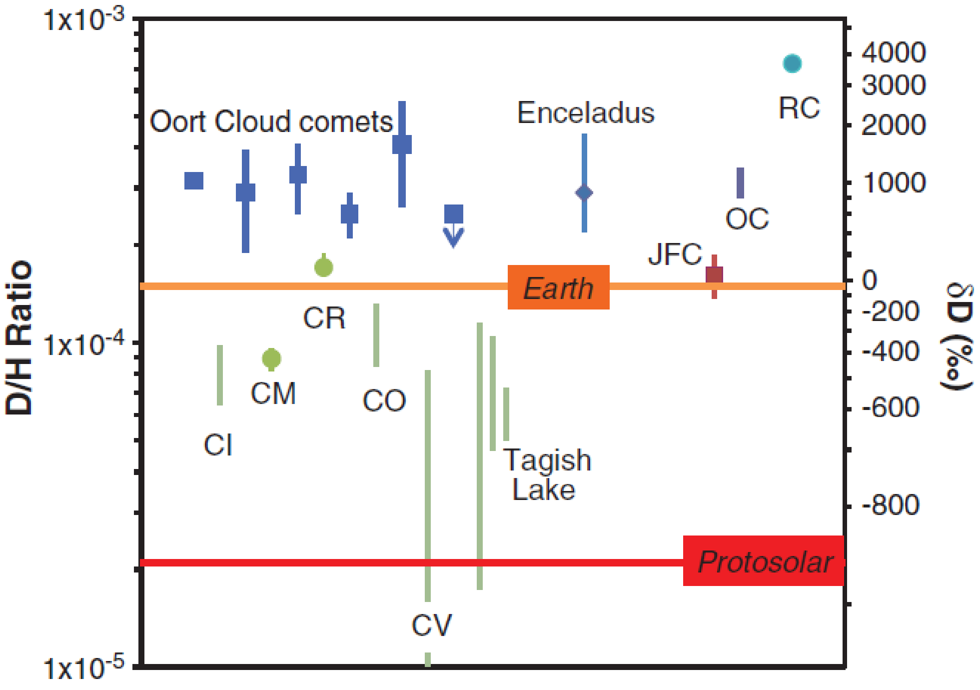

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