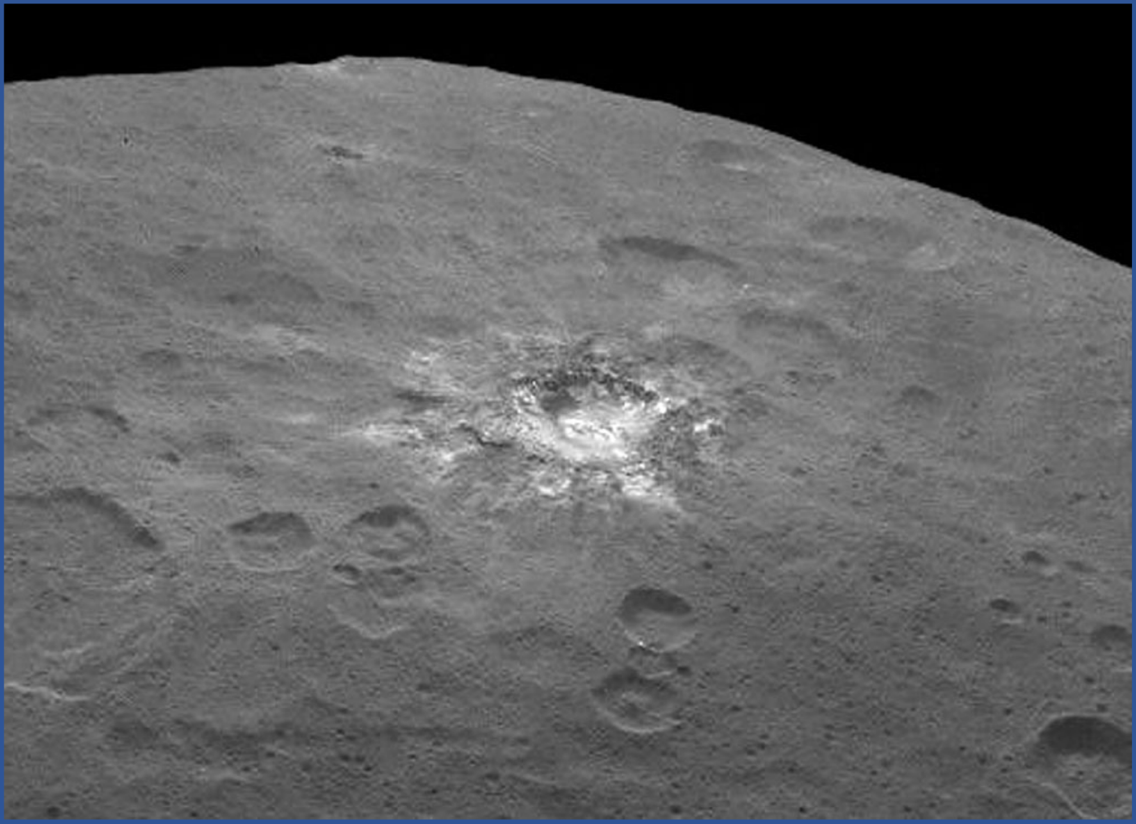
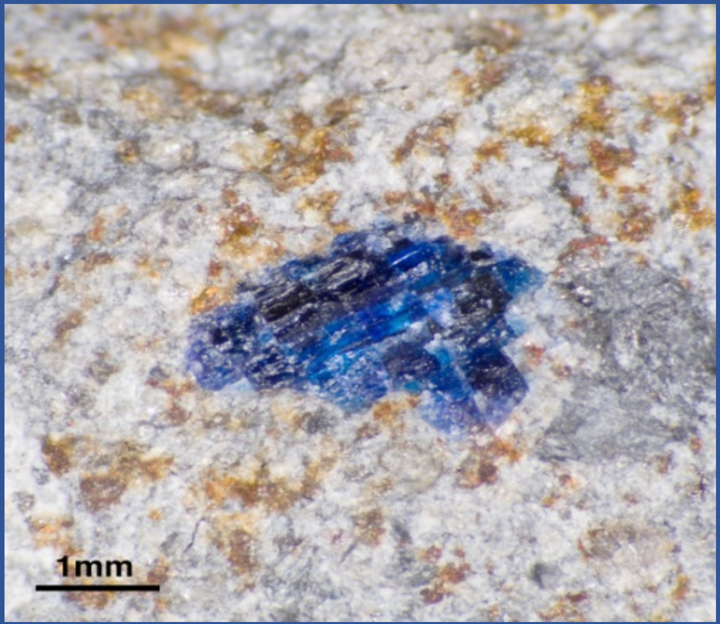
CARBONACEOUS LITHOLOGIES FROM OUTER SOLAR SYSTEM BODIES IN METEORITE REGOLITH BRECCIAS

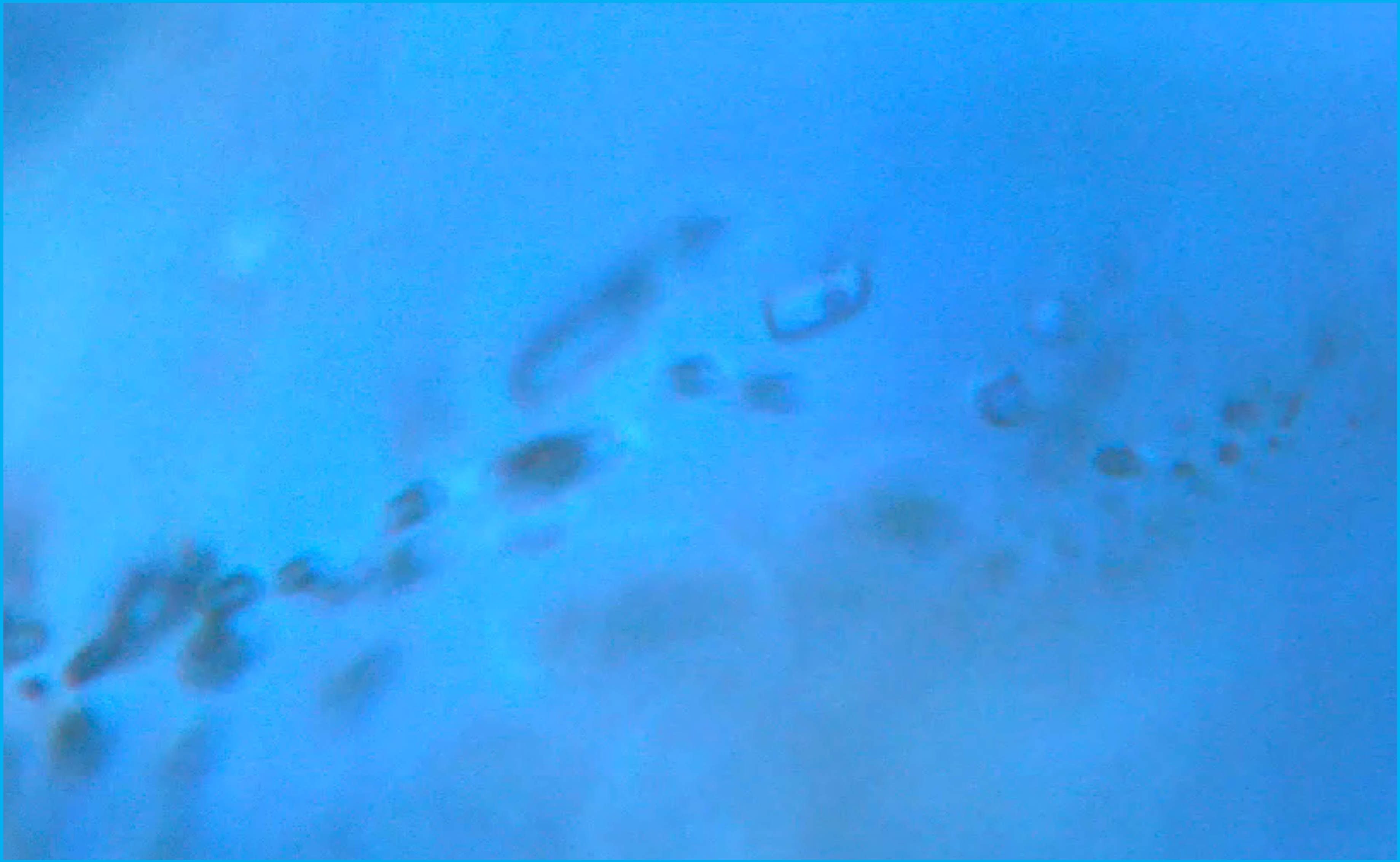
Mike Zolensky
Queenie H.-S. Chan
Yoko Kebukawa
Andrew Steele
Bob Bodnar
Cyrena Goodrich
Qing-Zhu Yin
Matt Sanborn
Yoshi Yurimoto
Motoo Ito
Daisuke Nakashima
Shoichi Itoh
Karen Ziegler
Bill Bottke
Jess Johnson
Richard Greenwood
Peter Jenniskens
Marc Fries
Anna Fiorelli
Brent Turrin
Bob Clayton



Halite in Monahans (H5) and Zag

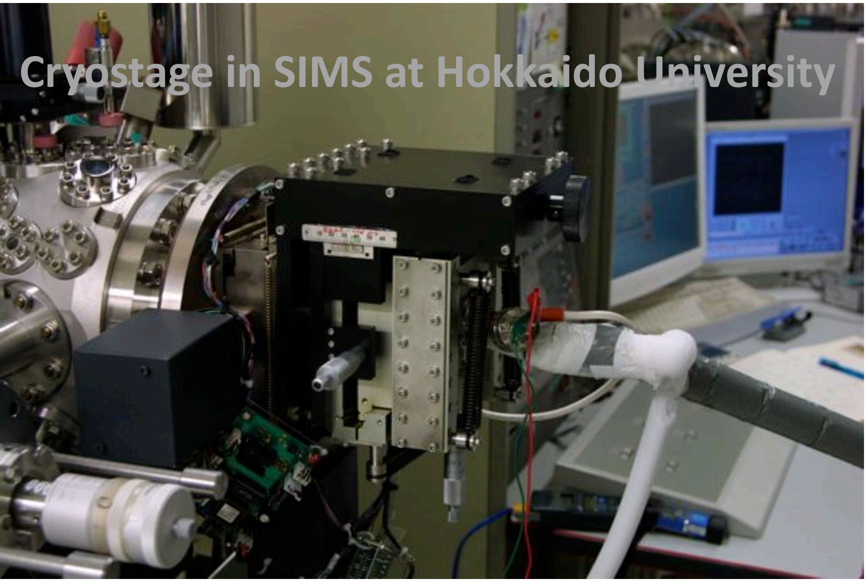
Dated by K-Ar, Rb-Sr and I-Xe systematics to be ~4.5 billion years old (Zolensky et al. 1999; Whitby et al. 2000; Bogard et al., 2001)





10 µm

SIMS Measurements by **Shoichi Itoh and** Yoshi Yurimoto



We waited 10 years to find a collaborator to put a freezing stage inside of their SIMS

SIMS Measurements by **Shoichi Itoh and** Yoshi Yurimoto

Lines are expected mixing lines between cometary (or interstellar) water and ordinary chondrite

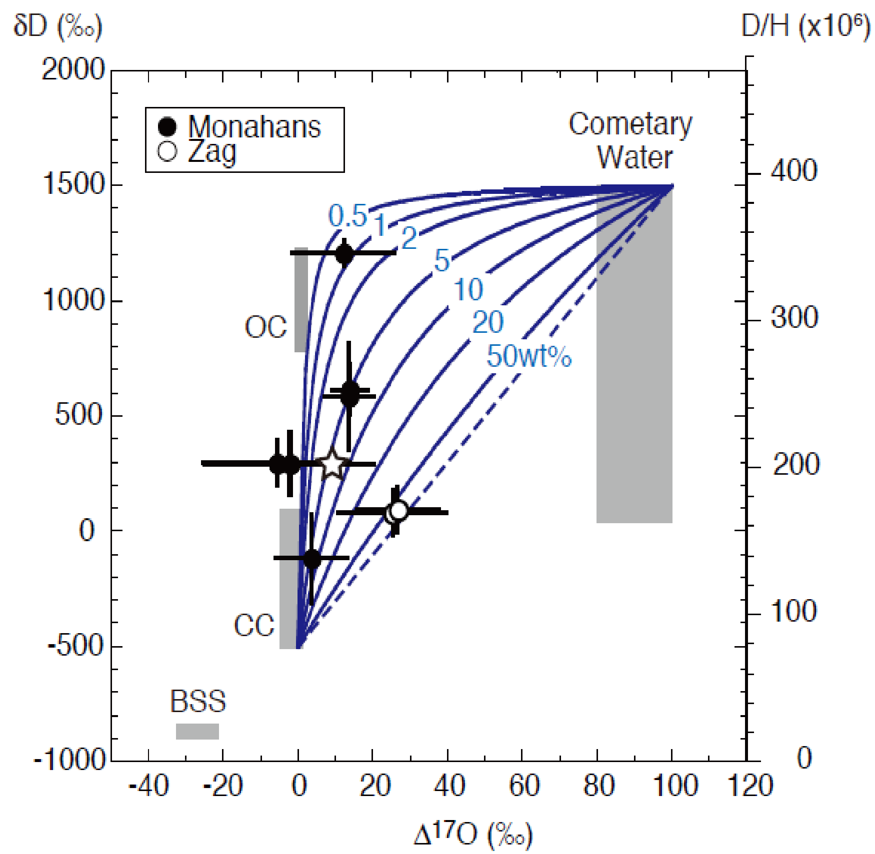
CC: phyllosilicates of carbonaceous chondrites

OC: phyllosilicates of ordinary chondrites

Comet: comet coma water

Interstellar: Interstellar water components in ordinary chondrites

BSS: bulk solar system

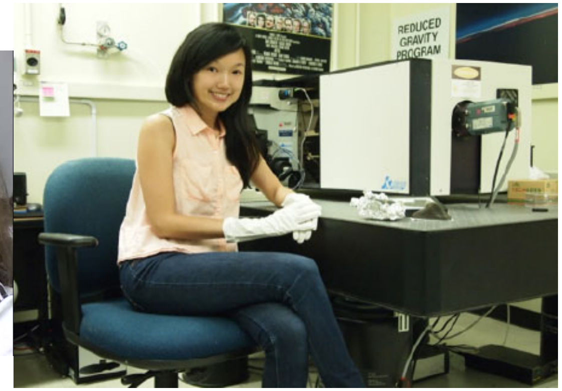


Yurimoto et al., 2014

Solid Inclusions – first spotted by SIMS and Raman

Marc Fries

Steelie

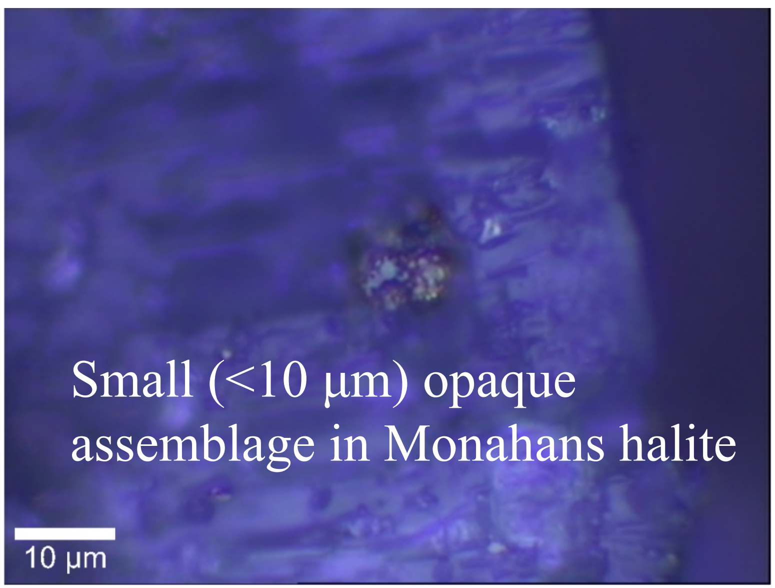


Queenie Chan

Solid inclusions are abundant in the Monahans and Zag halite.

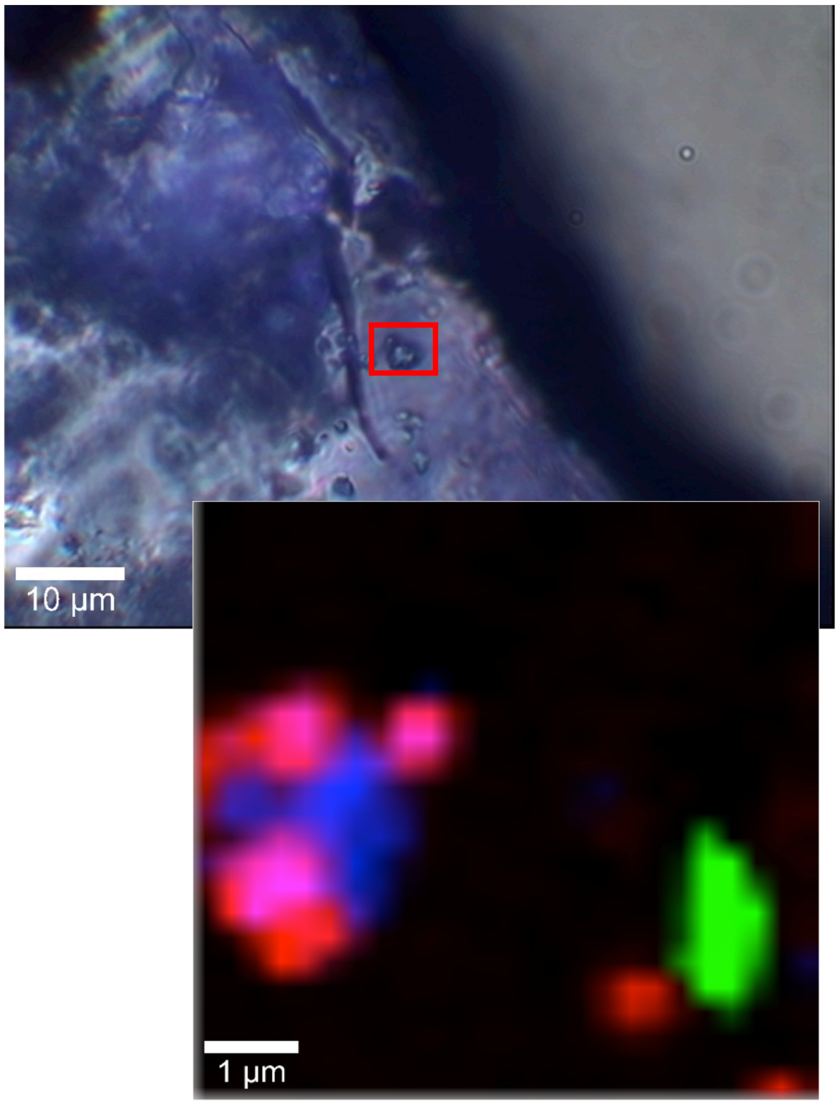
These were entrained within the brines during eruption, and should include unaltered protolith rocks from the rocky mantle and surface of the halite parent object

The solid inclusions include **abundant and widely variable organics** *which cannot have been significantly heated after formation of the halite* (which would have resulted in the loss of fluids from the halite)



Small (<10 µm) opaque assemblage in Monahans halite

Inclusion Mineralogy by Confocal Raman Microspectroscopy



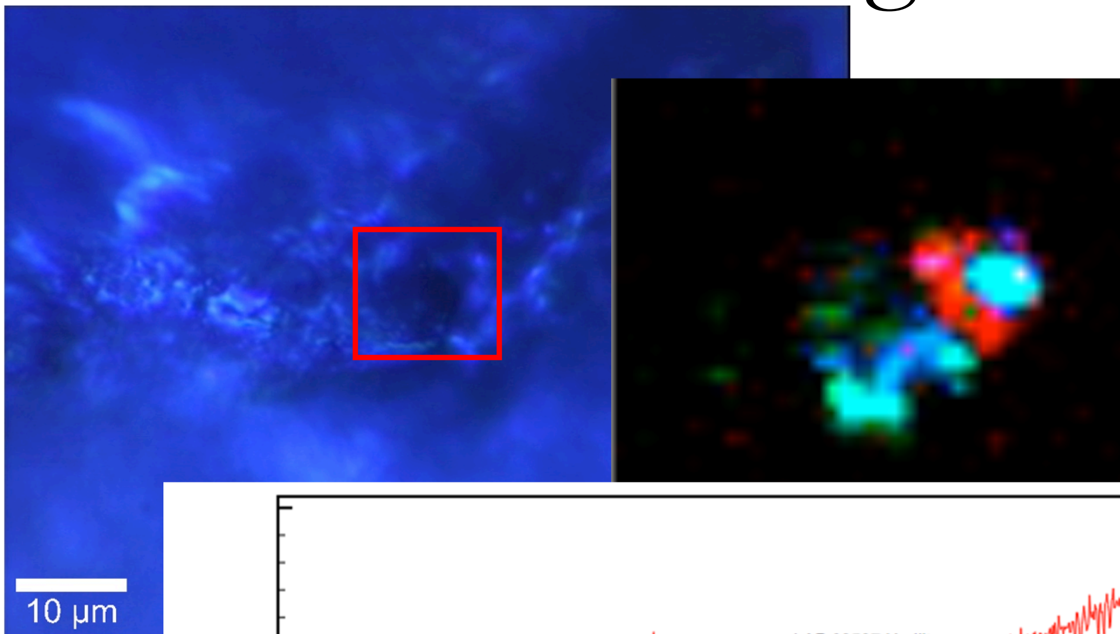
Typical inclusion on the left from Monahans halite

Overall mineralogy **Not consistent with H chondrite mineralogy**

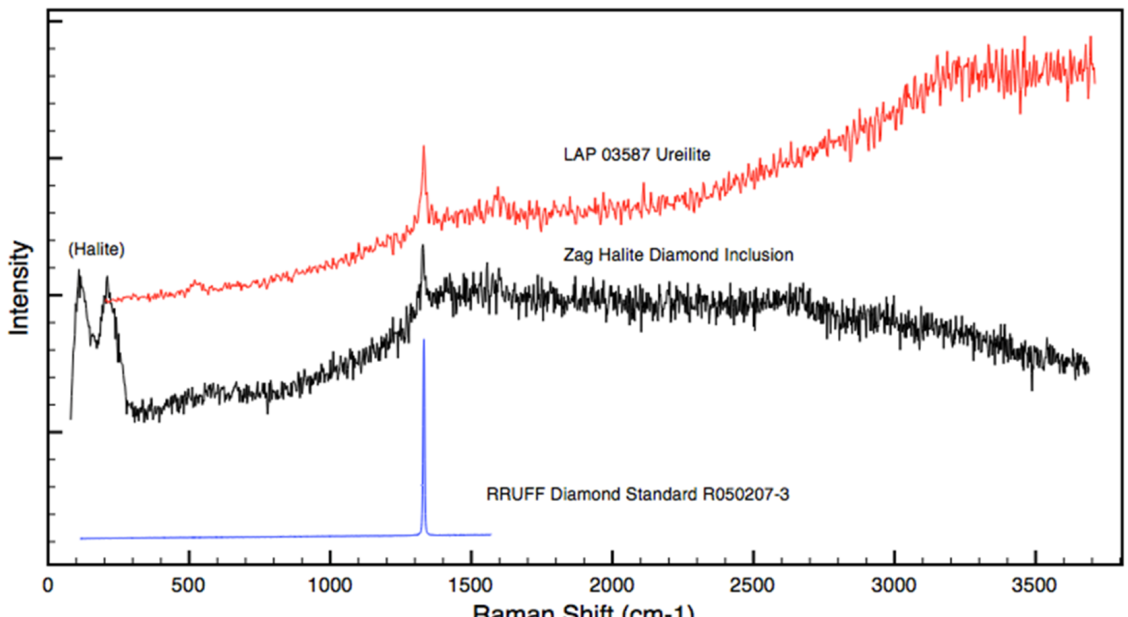
Halites came from elsewhere!

Red: MMC
Green: Pyx
Blue: Olivine

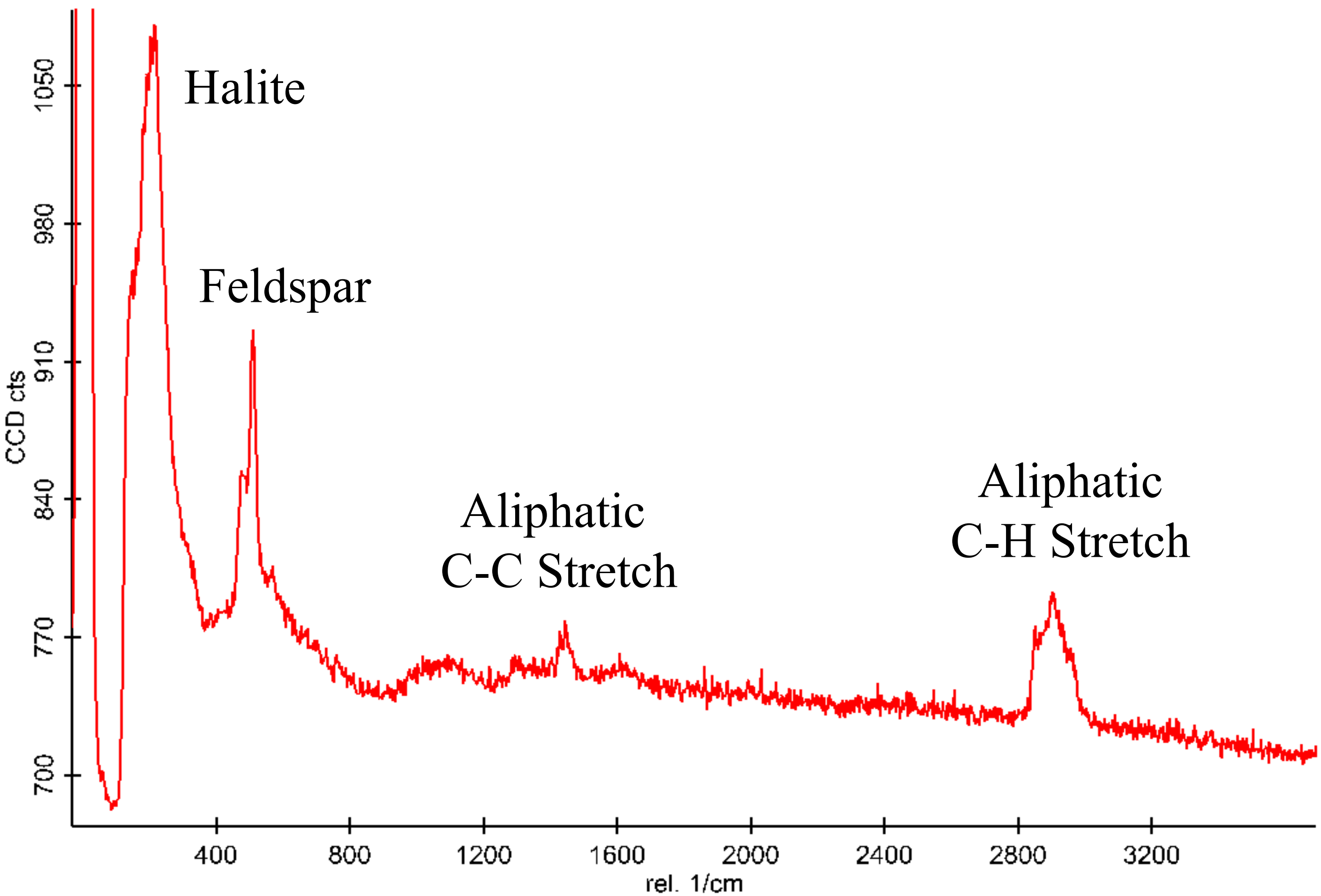
Diamonds in Zag Halite



- Red: Carbonates
- Green: Graphitic MMC
- Blue: Diamond



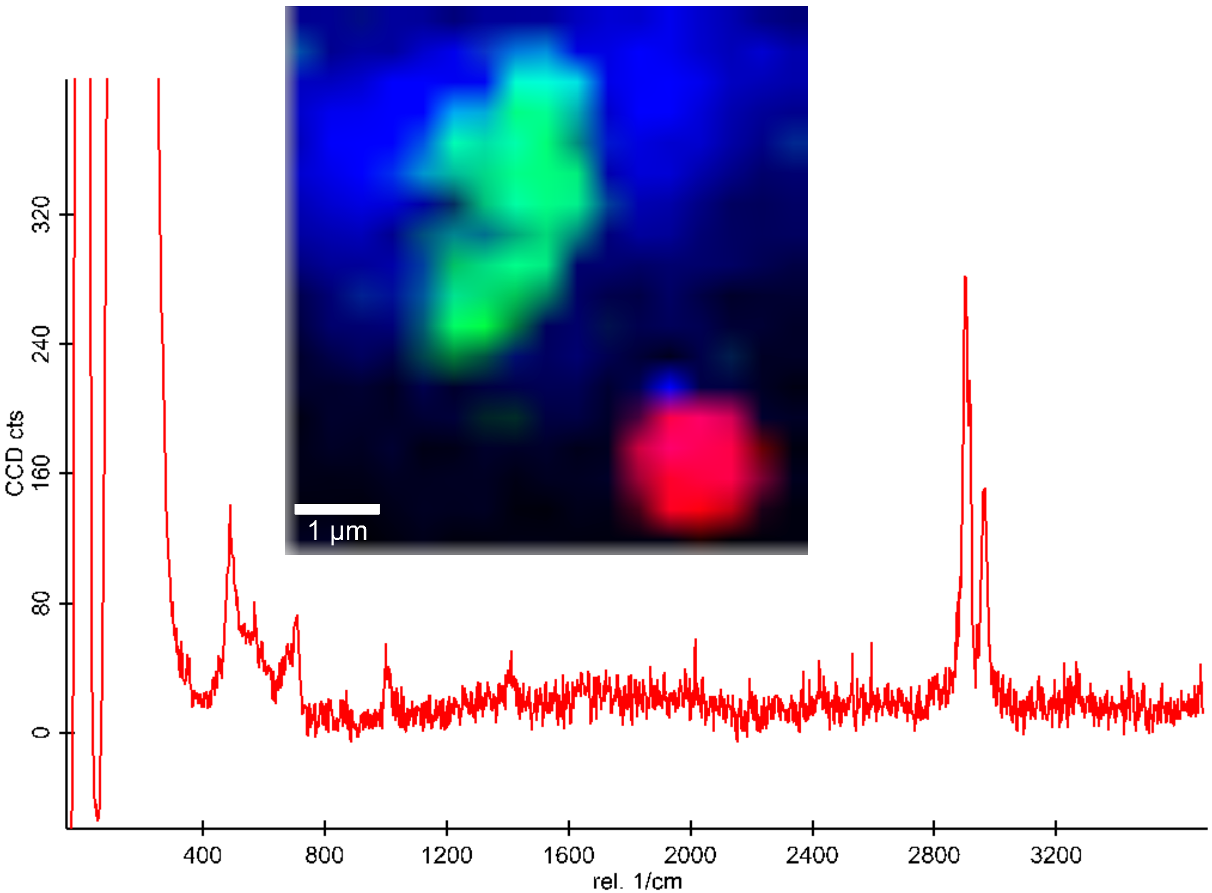
Aliphatic Compounds



One inclusion features aliphatic compounds

Raman spectra are consistent with a mixture of short-chain aliphatic compounds

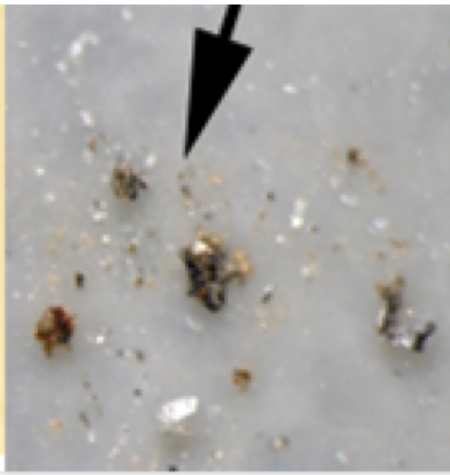
Methyl Chloride

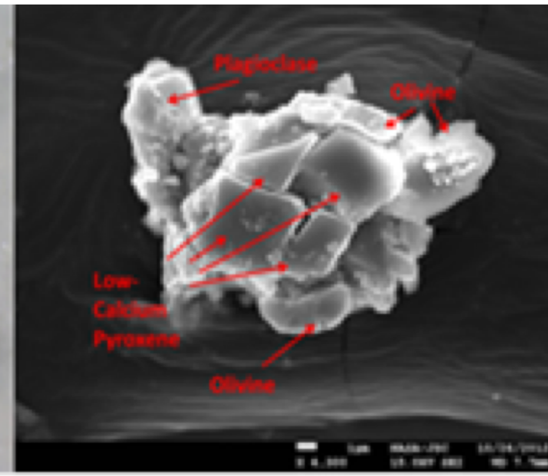


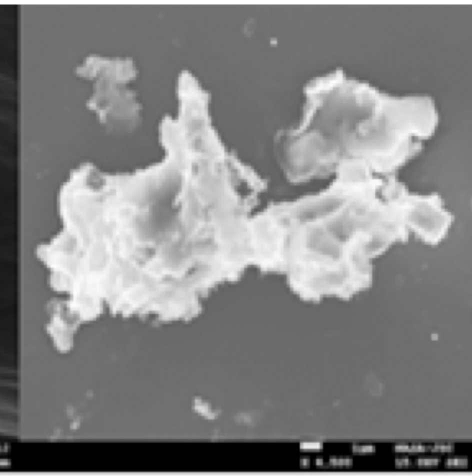
- Red: MMC
- Green: Apatite
- Blue: Methyl Chloride
- Raman peaks are consistent with Cl-substituted methane

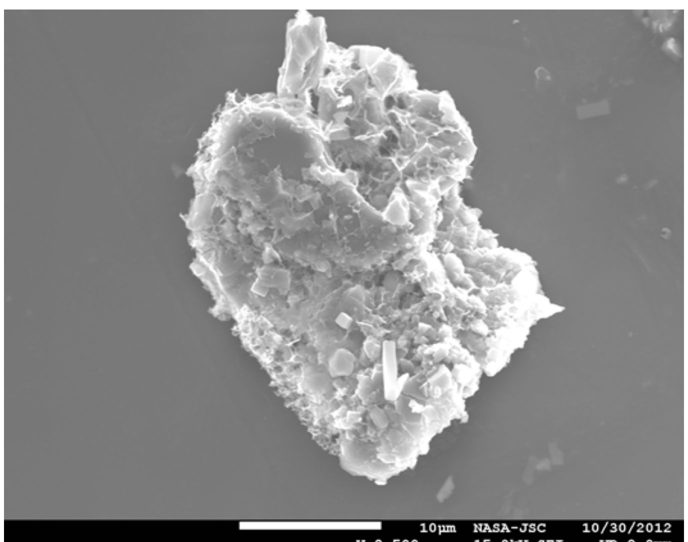
Geysers on Enceladus are observed to include salt (Postberg *et al*, Nature 2009), organics, and *methane* (Waite *et al*, Science 2006)

Solid Residue Grains

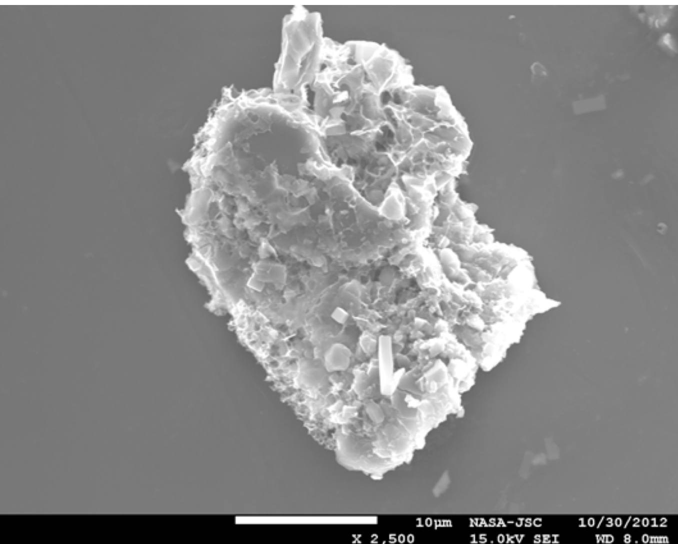






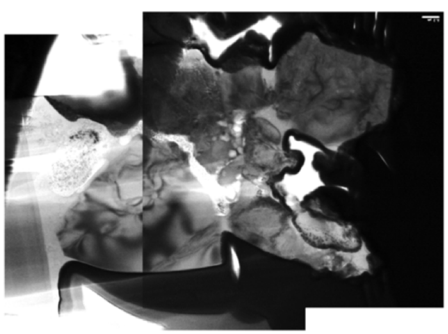


Monahans Residue Grain 4



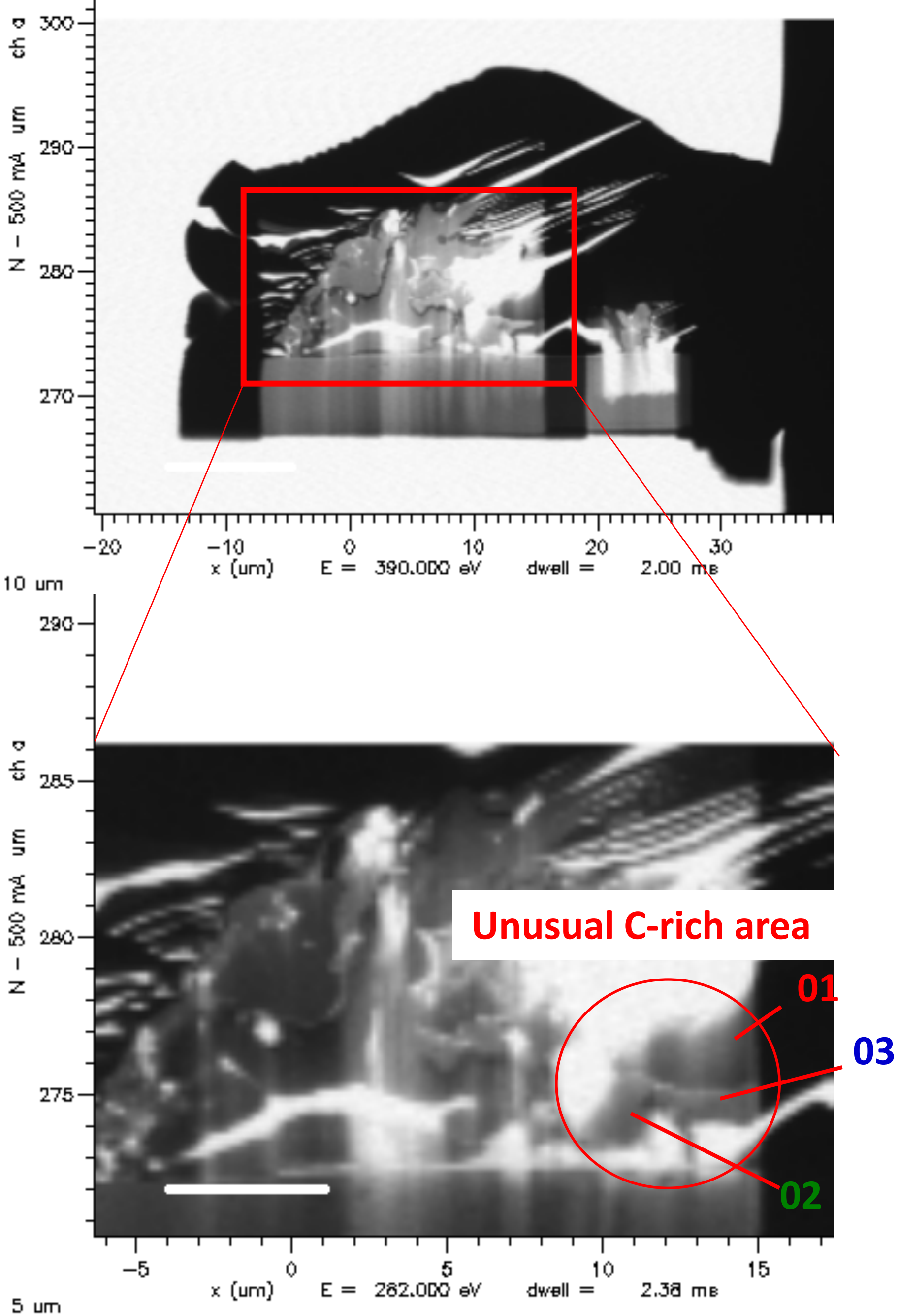
Olivine, High- and low-Ca Pyroxene, Troilite/Pyrrhotite, Glass, and *Carbon-bearing phases*
Being analyzed by FTIR and C –XANES*

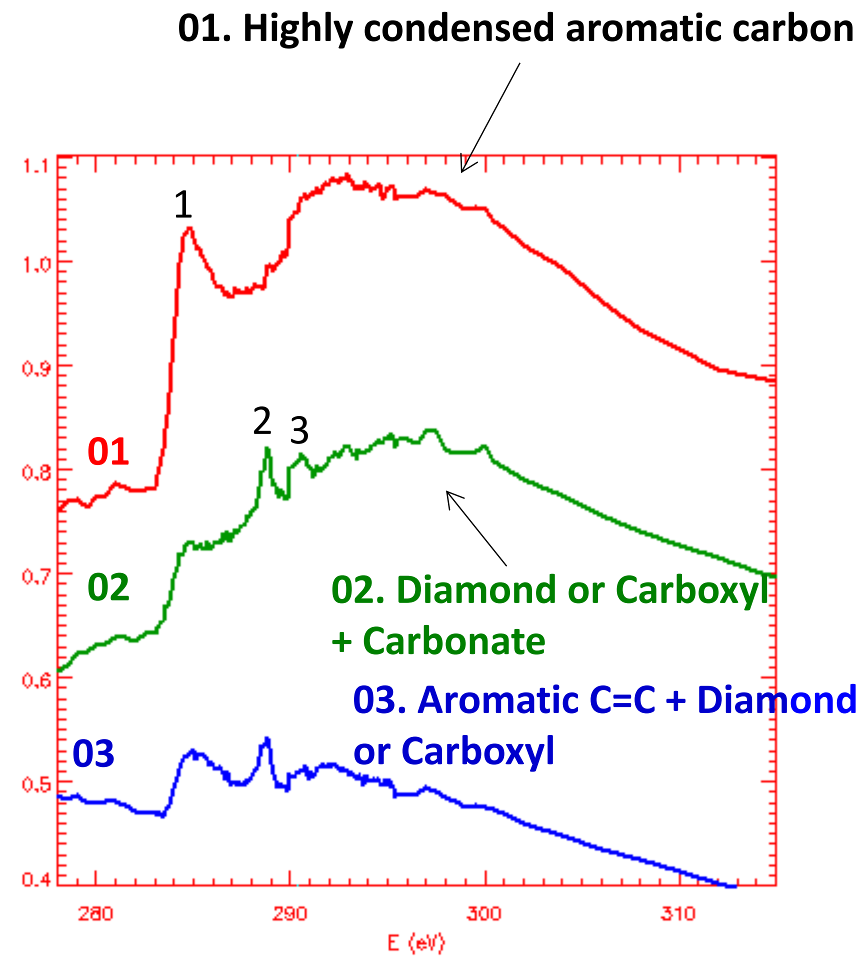
Yoko Kebukawa



*X-ray Absorption Near Edge Structure

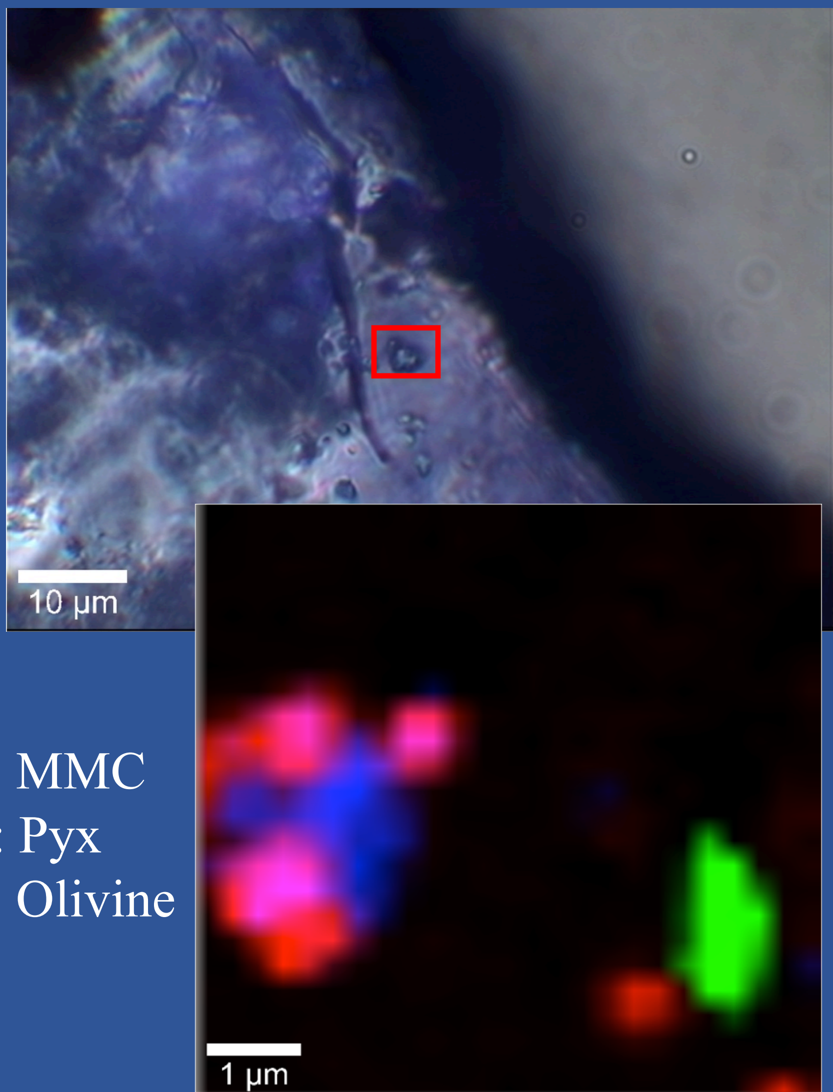
Monahans Residue 4 analyzed by C-XANES





1: 284.7eV C=C
2: 288.8eV Diamond or Carboxyl
3: 290.6eV Carbonate

Inclusion Mineralogy by Confocal Raman Microspectroscopy



R: MMC
G: Pyx
B: Olivine

- Typical inclusion on the left from Monahans halite
- Overall mineralogy consists of:
  - Olivine (wide range)
  - Low- and High-Ca Pyroxene
  - Feldspars
  - Phosphate minerals
  - Saponite
  - Macromolecular carbon
  - Light, condensed organics
  - Methyl chloride
  - Diamond
  - Carbonates
  - Metal
  - Lepidocrocite (on metal?)
  - Magnetite
  - Sulfides
- **Not consistent with H chondrite mineralogy**
- **Halites came from elsewhere!**

Measurements of Amino Acids in Zag Bulk and Zag Halite

Samples

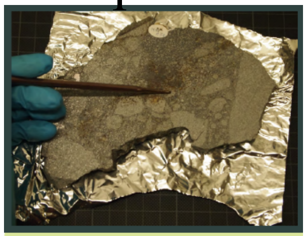


Figure 2 Bulk meteorite Zag (NHM)

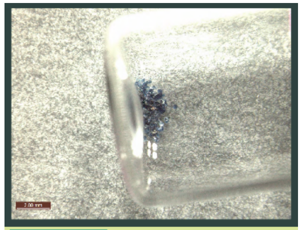


Figure 3 Zag halite (JSC) in a glass ampoule

- Meteorite bulk:
  Zag (JSC): 87 mg & Zag (NHM): 67 mg
- Halite crystals:
  Zag halite (JSC): 3 mg Zag halite (NHM): 2 mg

Analytical technique

Figure 4 The UPLC is capable of performing both fluorescence and mass spectrometry measurments from a single sample injection

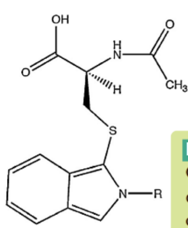


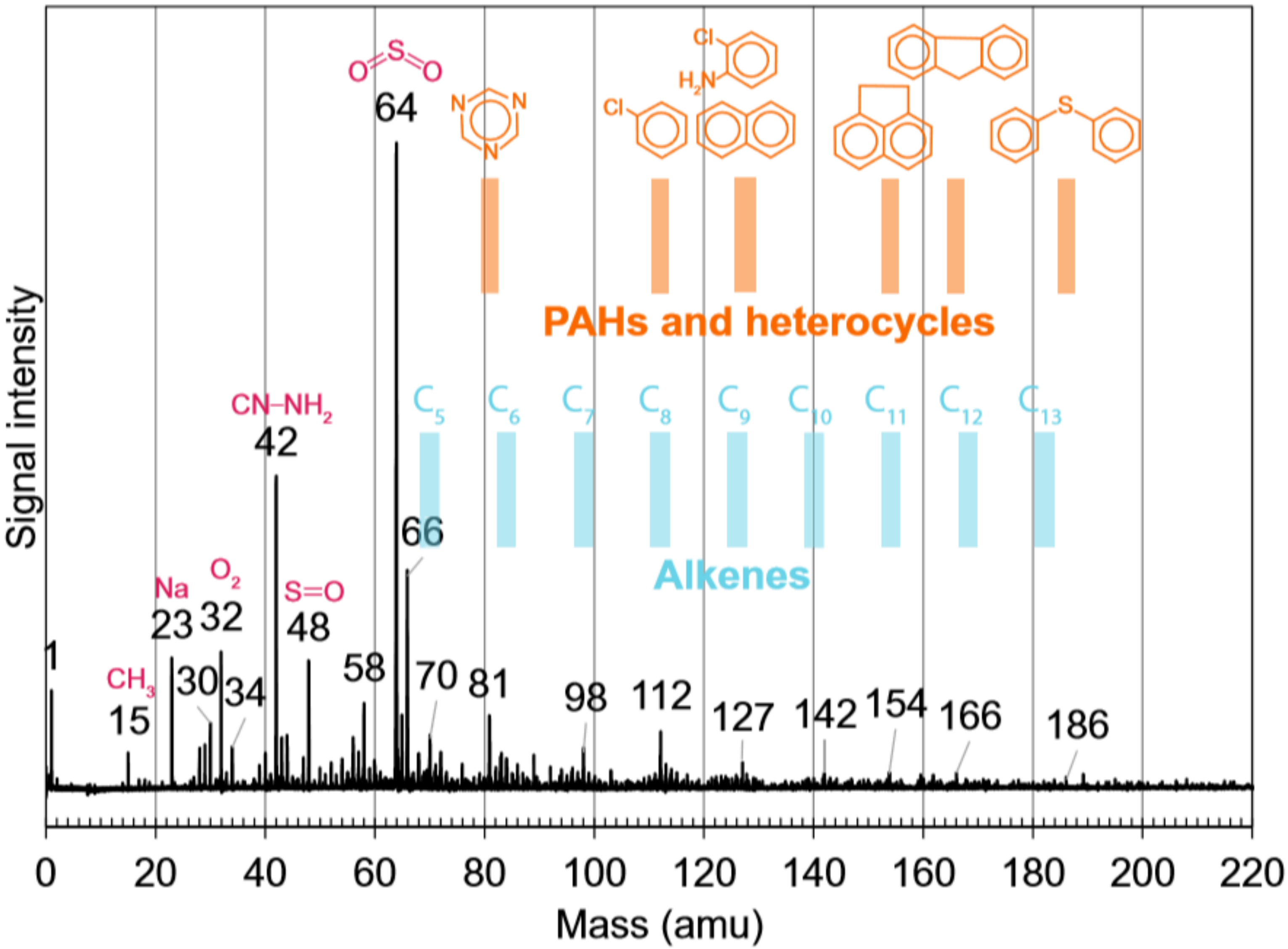
Figure 5 OPA/NAC amino acid derivative

UPLC: Ultra performance liquid chromatography

Queenie Chan

Aaron Burton

μ-L2MS spectra of Zag Halite



Chan et al., *Science Advances*, 2018

Organic Species in Zag Halite

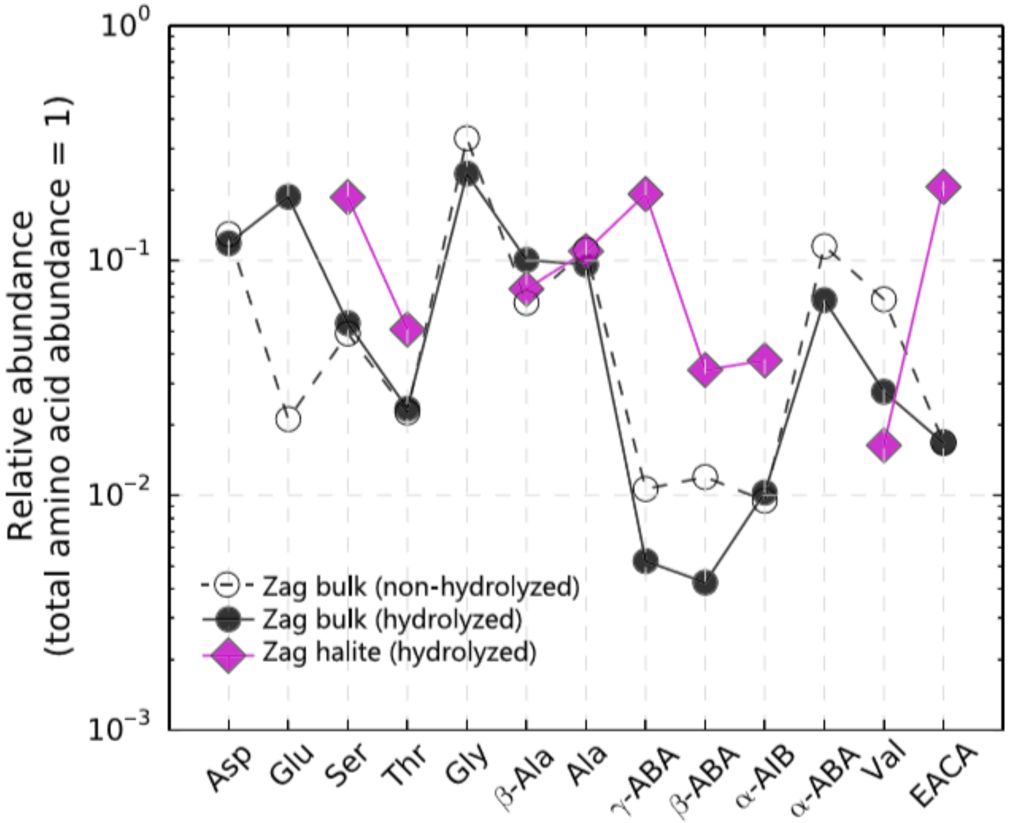
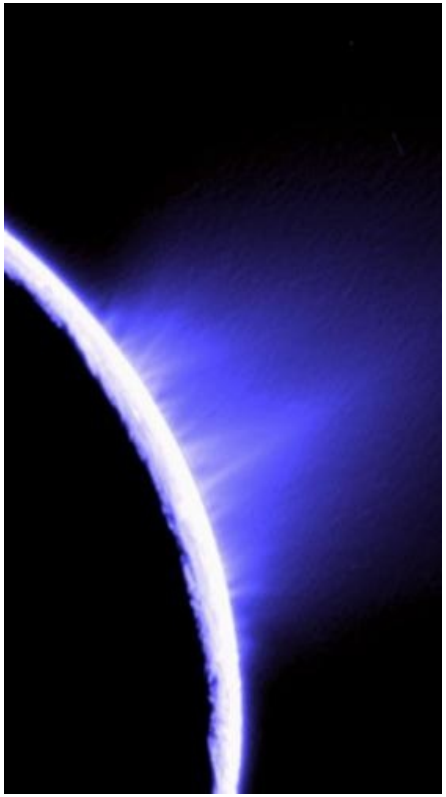


Fig. 6. Relative amino acid abundances (total amino acid abundance = 1) of the 6 M HCl acid-hydrolyzed amino acid extract of the Zag matrix (●), the non-hydrolyzed amino acid extract of the Zag matrix (○), and the acid-hydrolyzed amino acid extract of the Zag halite (◆). Although the Zag matrix is γ-ABA–, β-ABA–, α-aminoisobutyric acid (α-AIB), and EACA-deficient, the halite is shown to exhibit an opposite trend and is enriched in these amino acids. The marked difference in the amino acid contents between the halite and matrix indicates their separate synthetic origins. The abbreviations of the amino acids are defined in table S1.

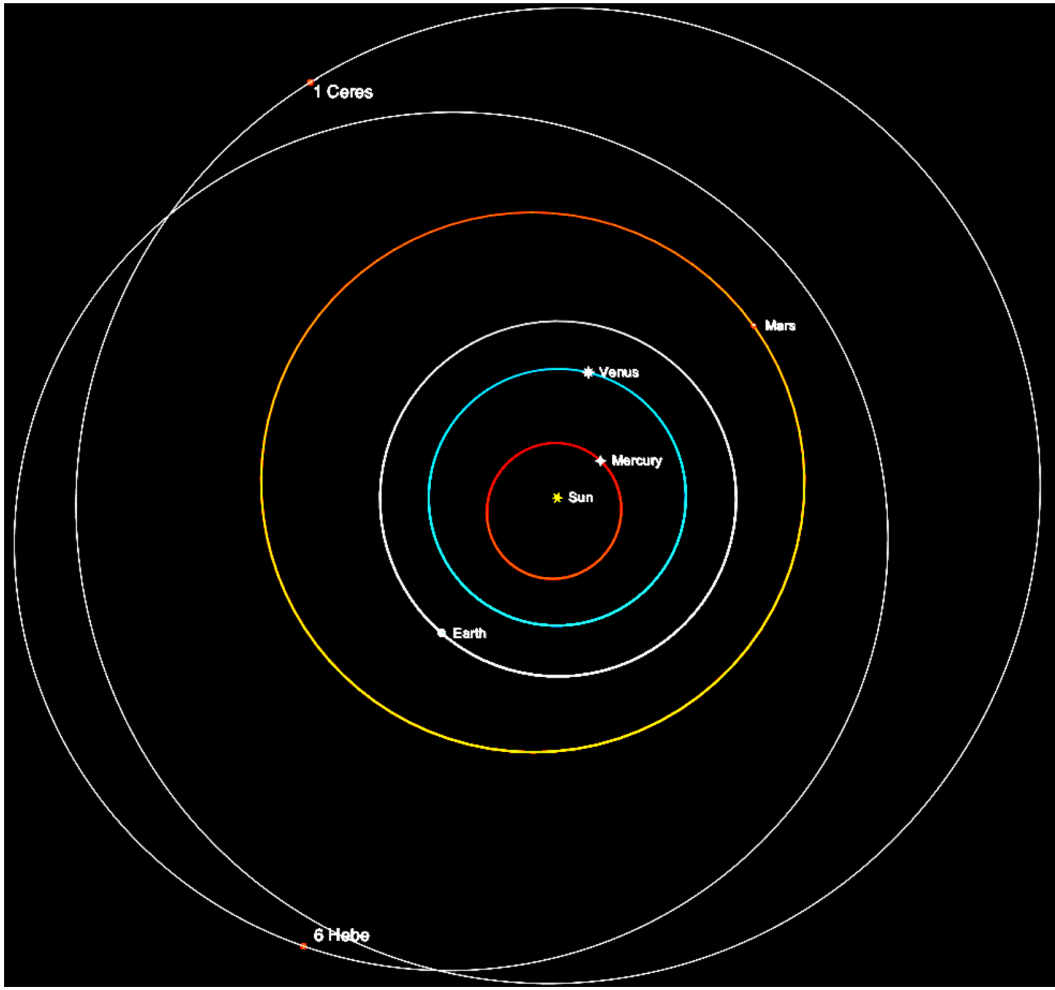
Abbreviations
Asp: aspartic acid
Glu: glutamic acid
Ser: serine
Thr: threonine
Gly: glycine
Ala: alanine
ABA: aminobutyric acid
AIB: aminoisobutyric acid
Iva: isovaline
Val: valine
EACA: ε-amino-n-caproic acid
Ile: isoleucine
Leu: leucine

Chan et al., *Science Advances*, 2018

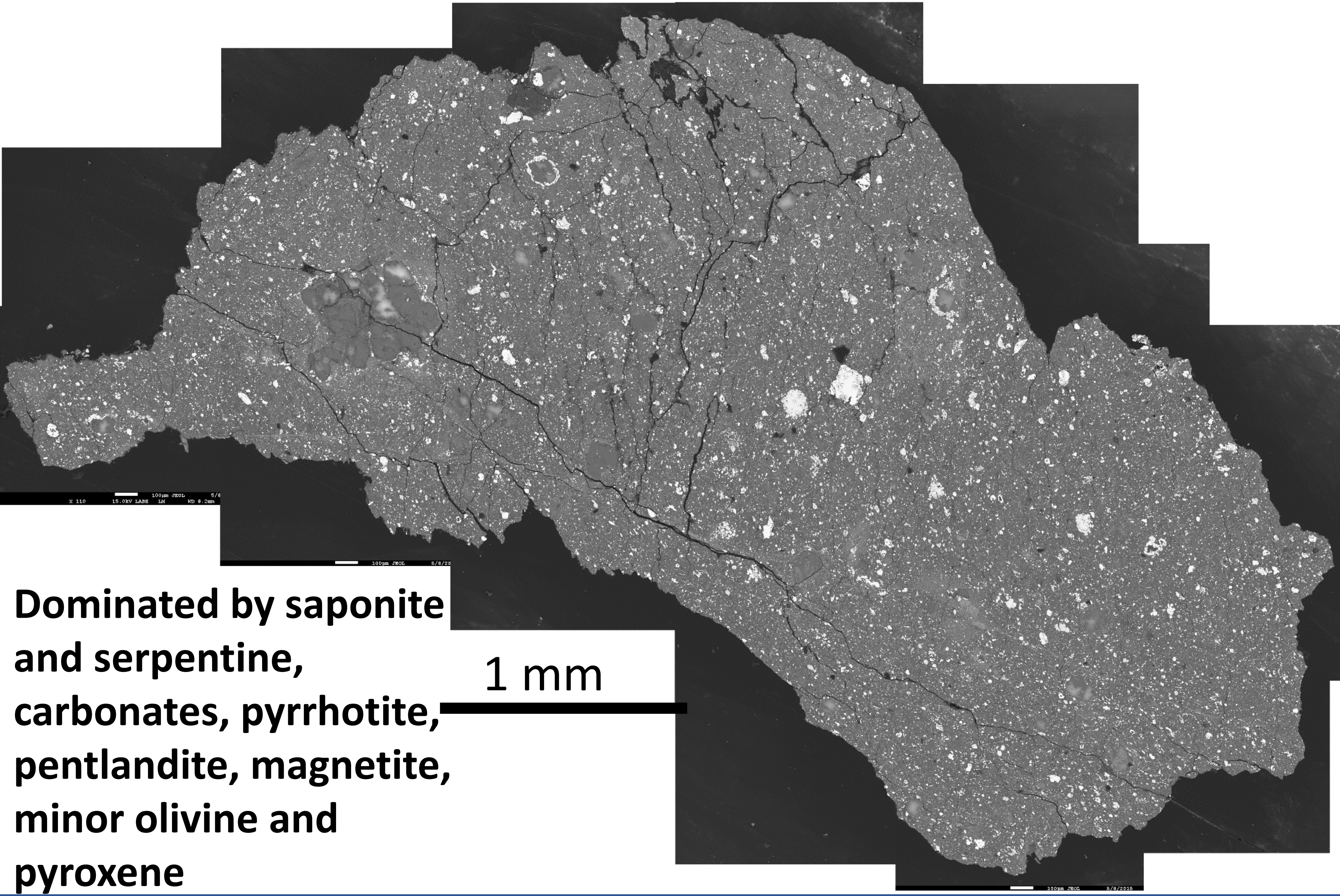
These materials originated on/in a hydrovolcanically active body : Ceres?



Or maybe a TNO – P or D asteroid

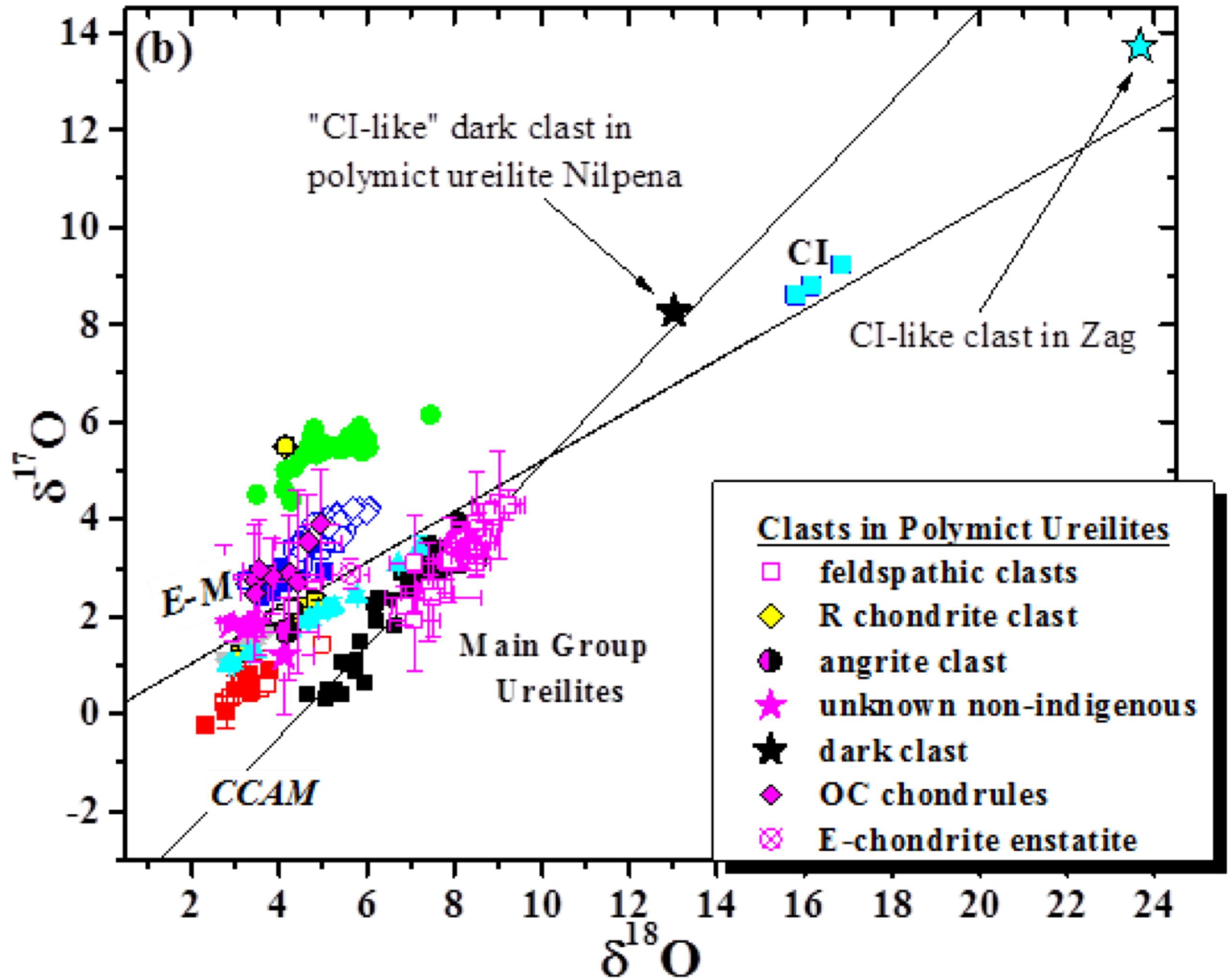


Zag Clast (4 x 10 mm)



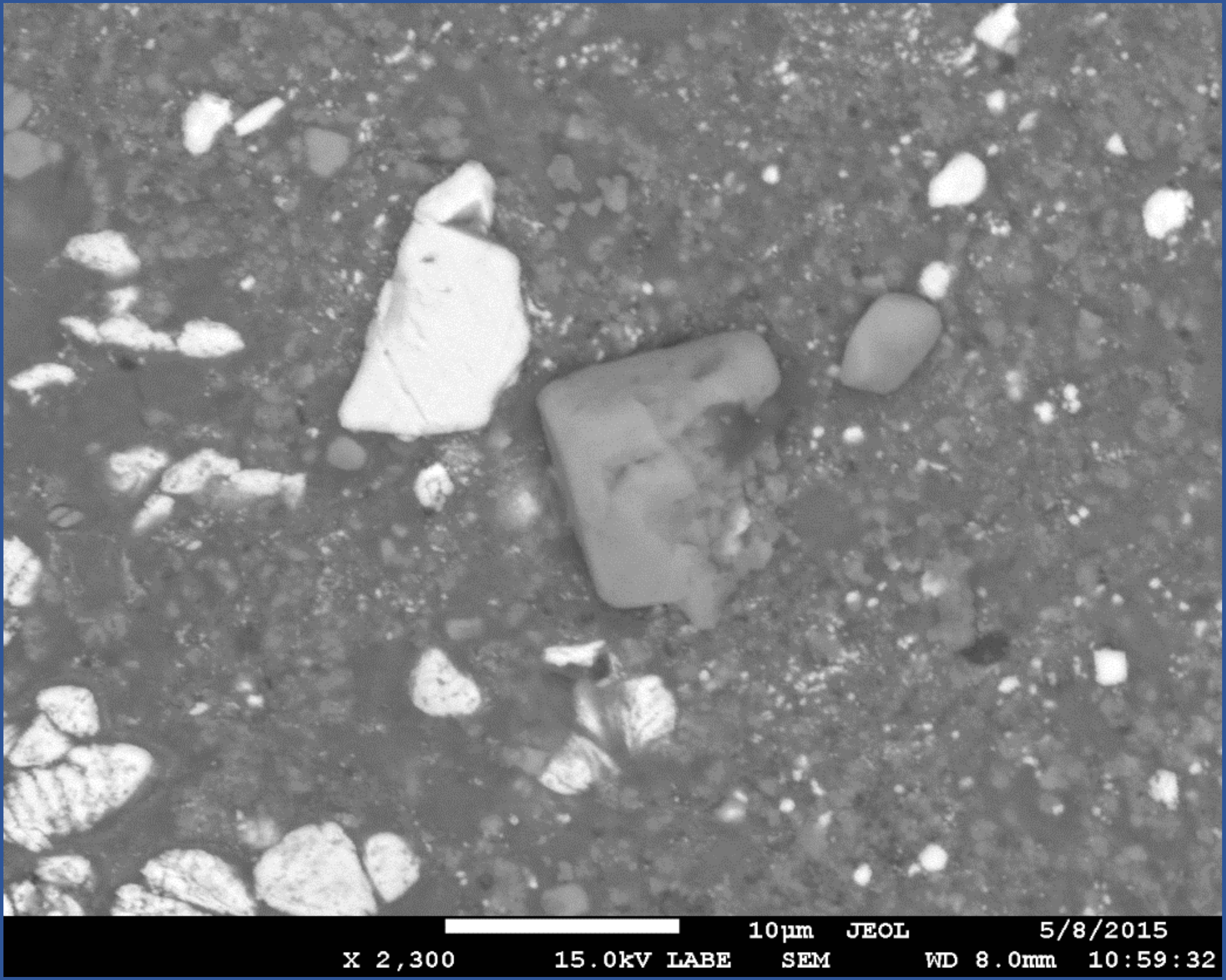
Dominated by saponite and serpentine, carbonates, pyrrhotite, pentlandite, magnetite, minor olivine and pyroxene

Very large $\Delta^{17}O$: +1.41

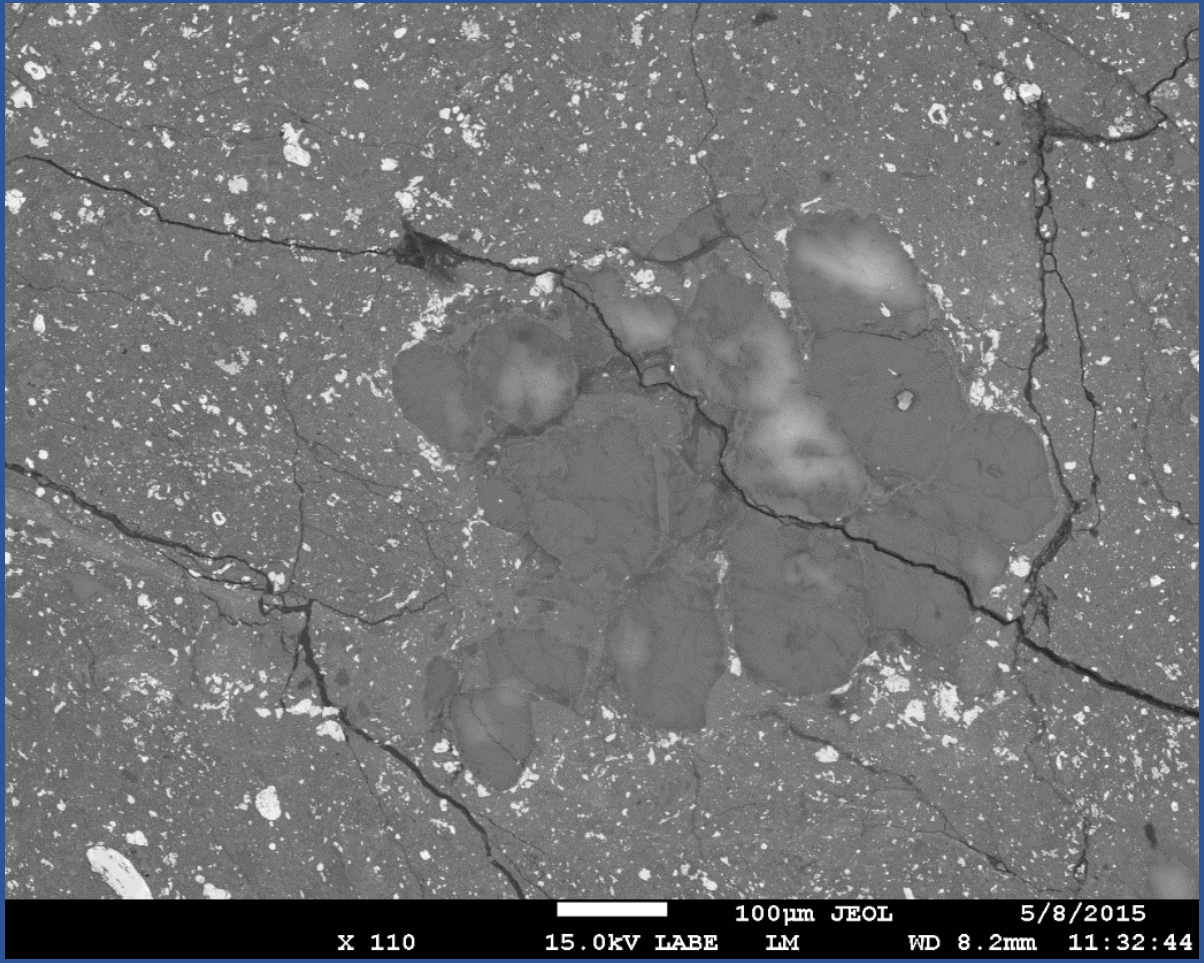


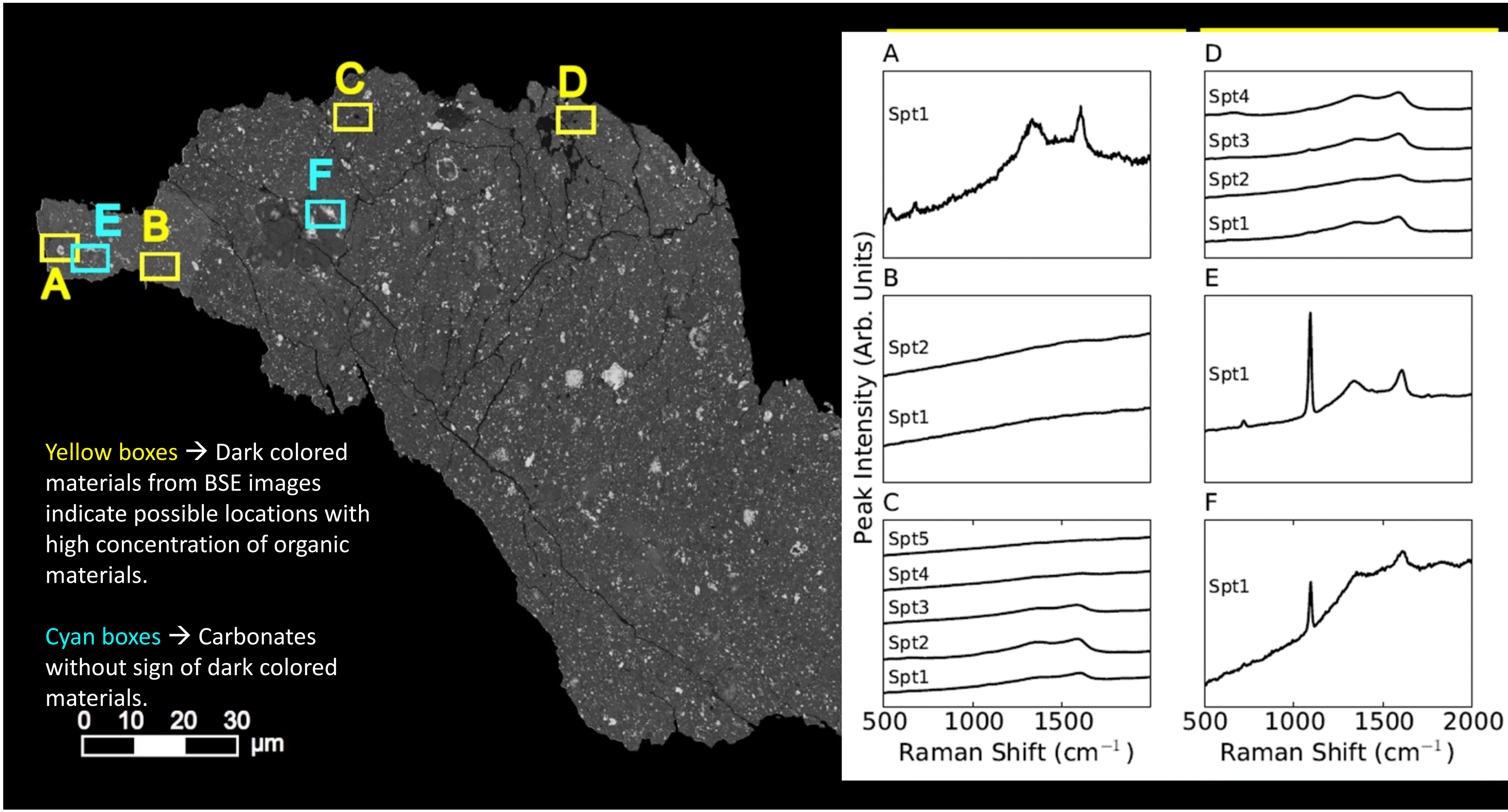
Bob Clayton and Tosh Mayeda, Richard Greenwood

Halite



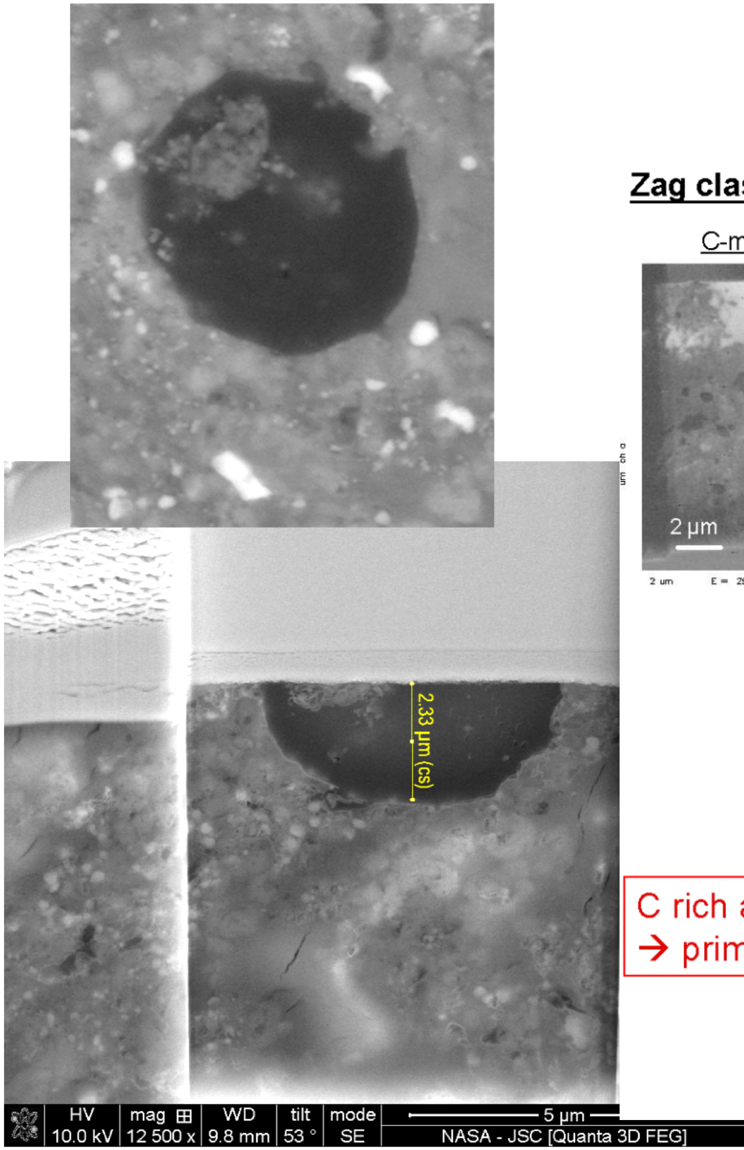
Carbonates

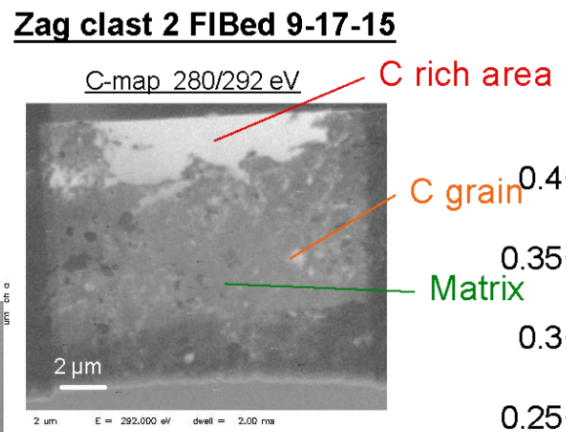


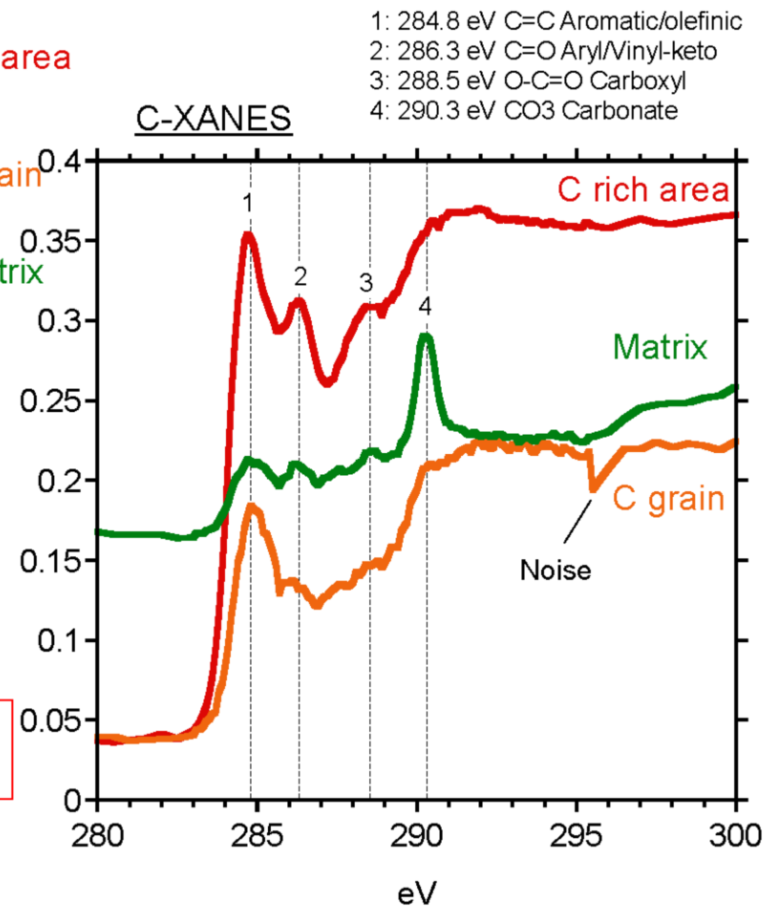


A
E
B
C
D
F
Yellow boxes → Dark colored materials from BSE images indicate possible locations with high concentration of organic materials.
Cyan boxes → Carbonates without sign of dark colored materials.
0 10 20 30
μm
Peak Intensity (Arb. Units)
Spt1
Spt2
Spt3
Spt4
Spt5
500 1000 1500 2000
Raman Shift (cm^{-1})

Organic globule

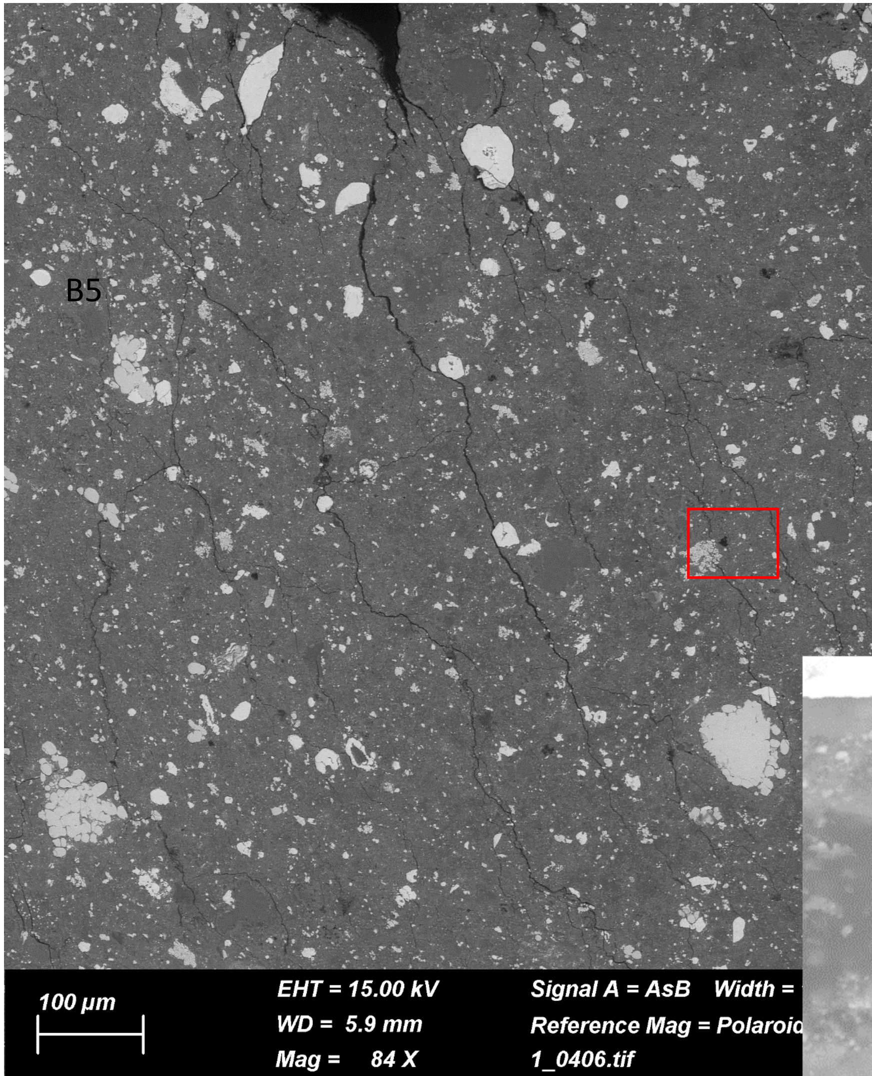
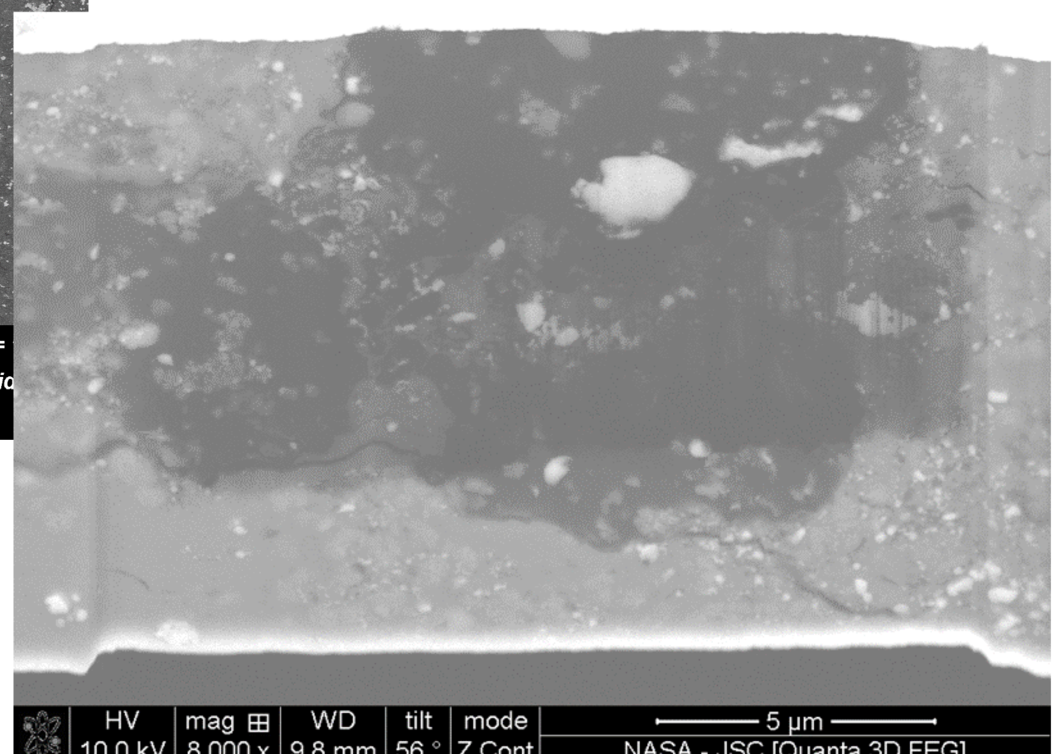




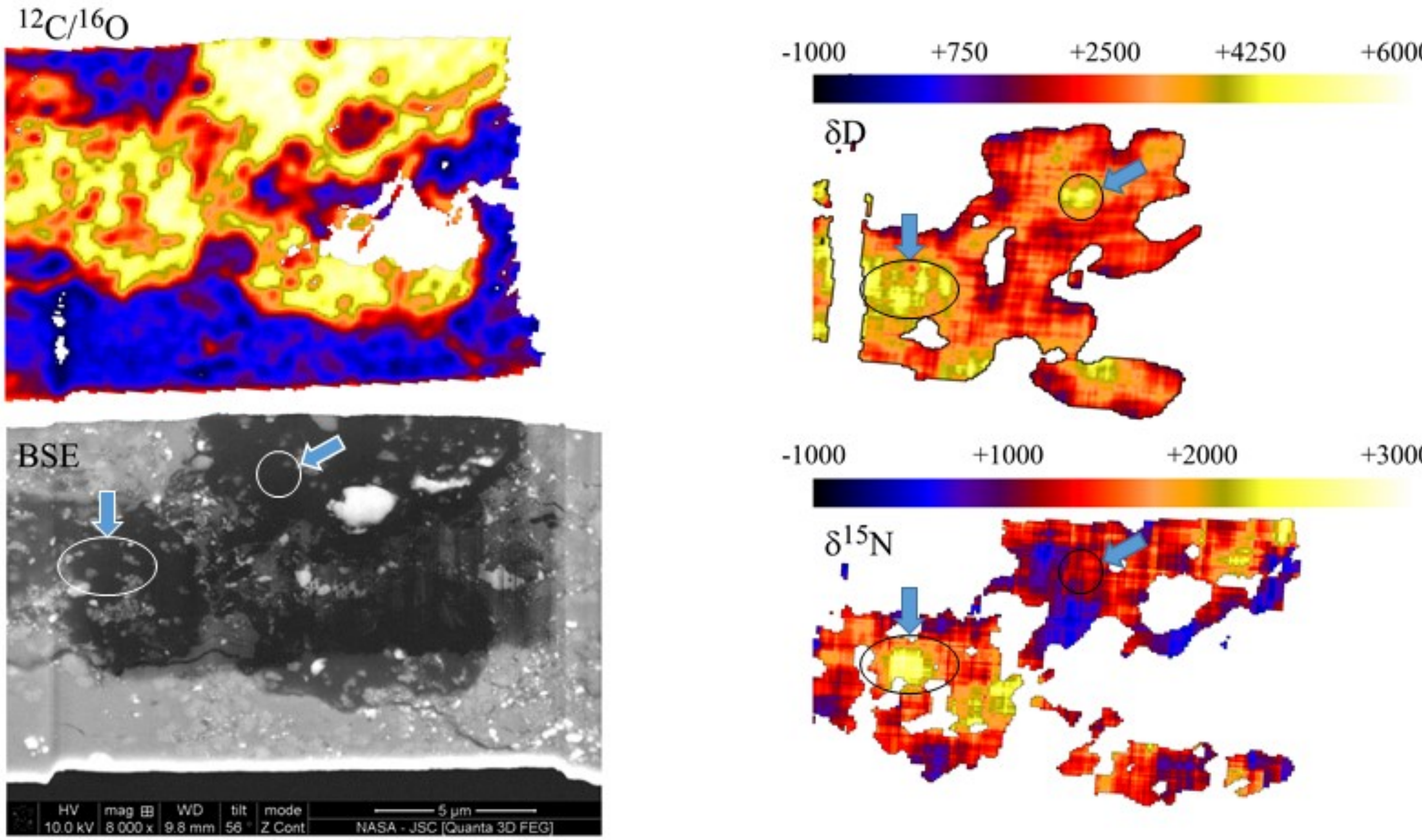


C rich area: Aromatic + C=O
→ primitive IOM like?

Yoko Kebukawa

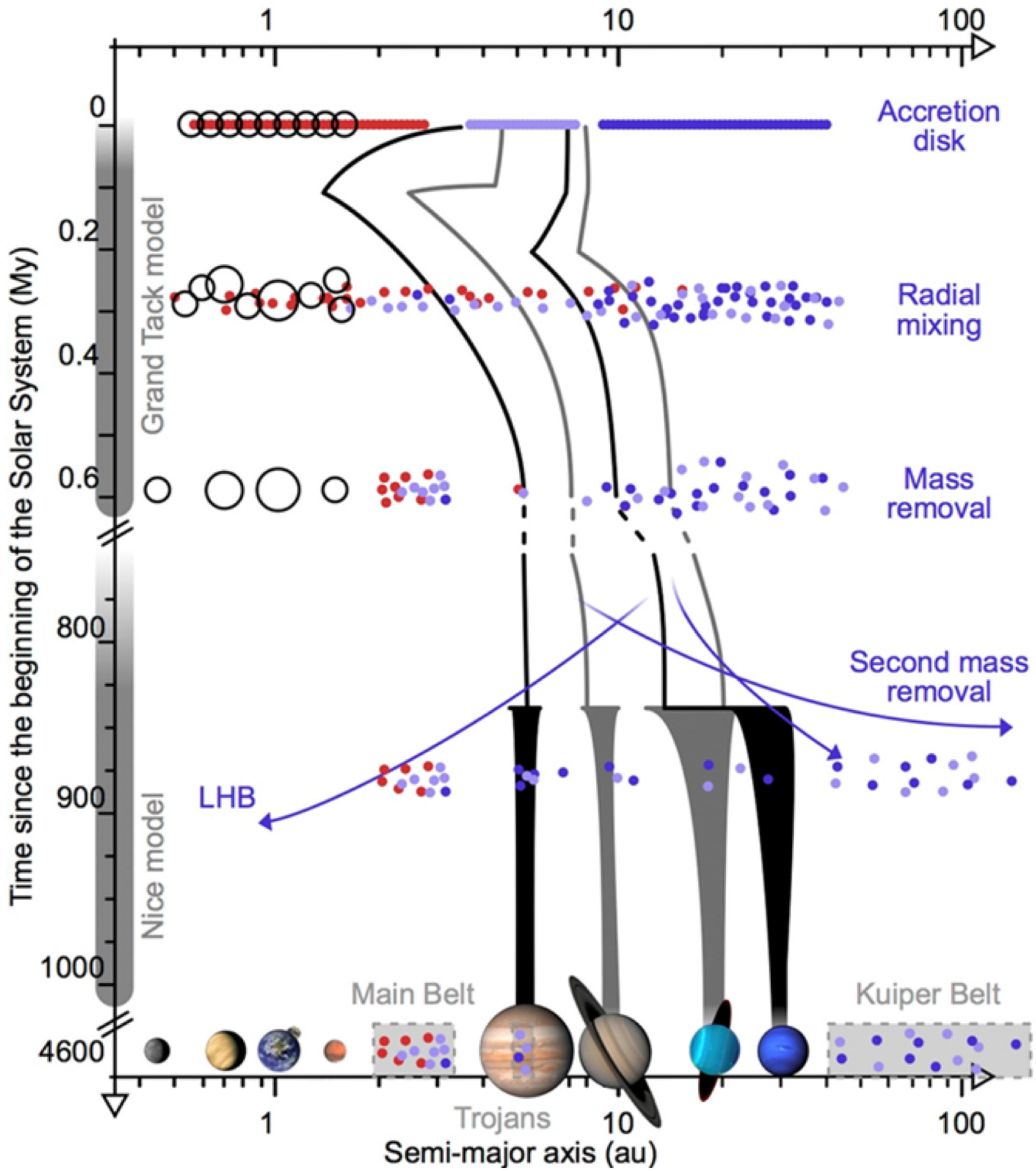

B5
100 µm
EHT = 15.00 kV
WD = 5.9 mm
Mag = 84 X
Signal A = AsB
Width =
Reference Mag = Polaroid
1_0406.tif

HV
10.0 kV
mag
8 000 x
WD
9.8 mm
tilt
56 °
mode
Z Cont
5 µm
NASA - JSC [Quanta 3D FEG]

Zag: NanoSIMS images (12C/16O, D and 15N)



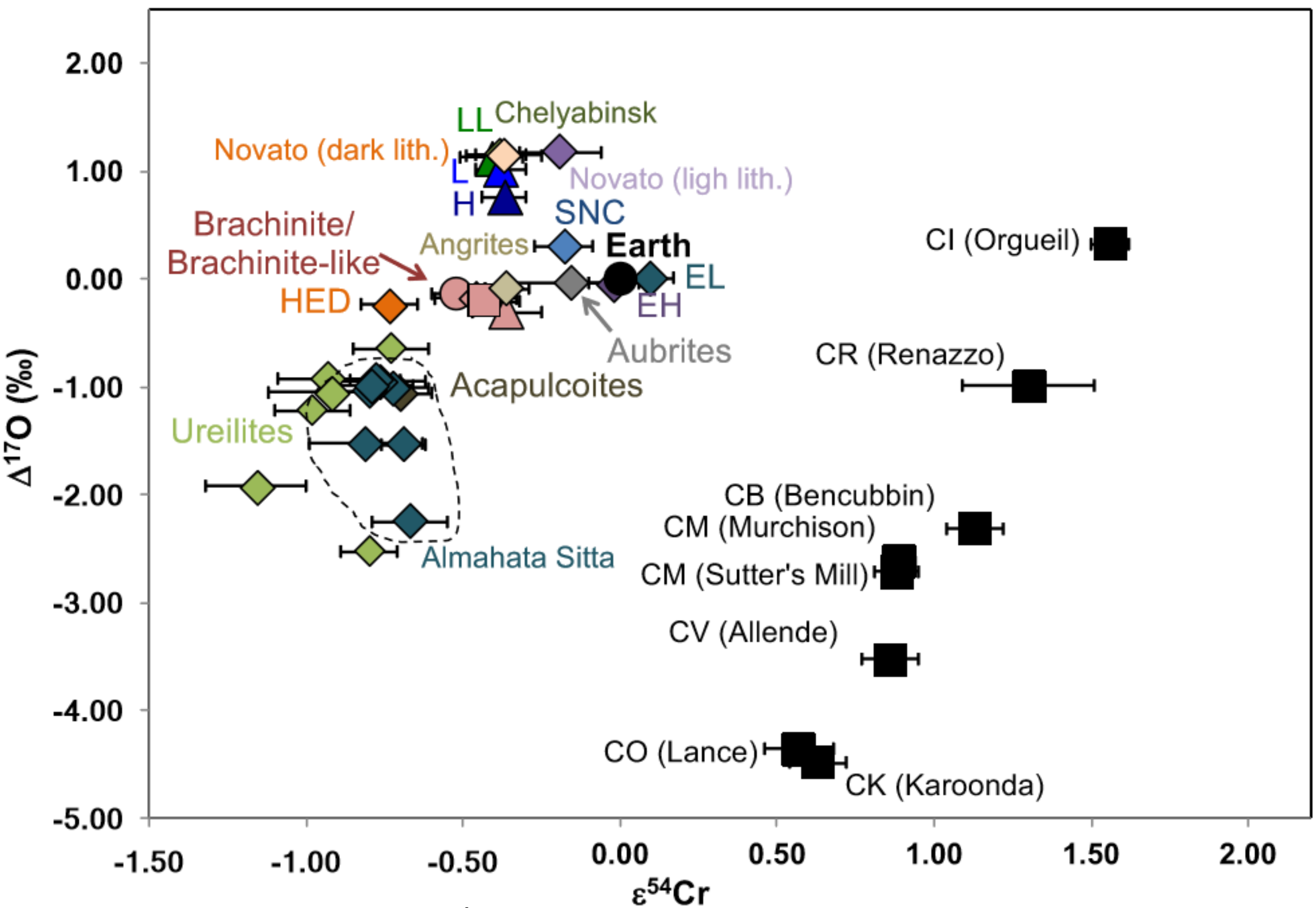
Correlated High Concentrations of Deuterium, ^{15}N and very heavy oxygen probably indicates very cold formation temperature

M. Ito, Y. Kebukawa



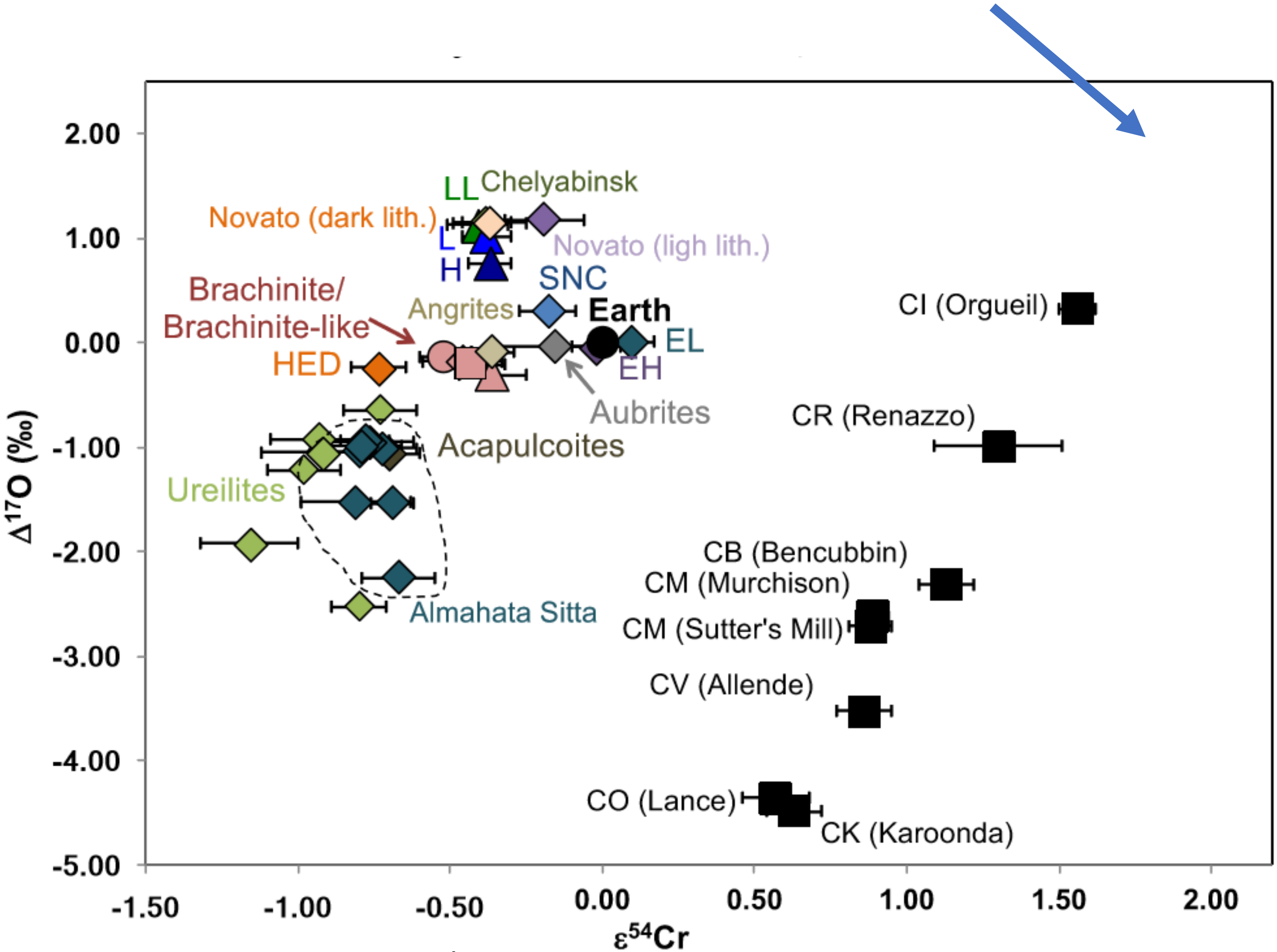
From DeMeo and Carry, 2014

There are two distinct populations of meteorites, based on neutron-rich isotopes of Ti, Cr, Ni, Mo, when plotted with $\Delta^{17}O$

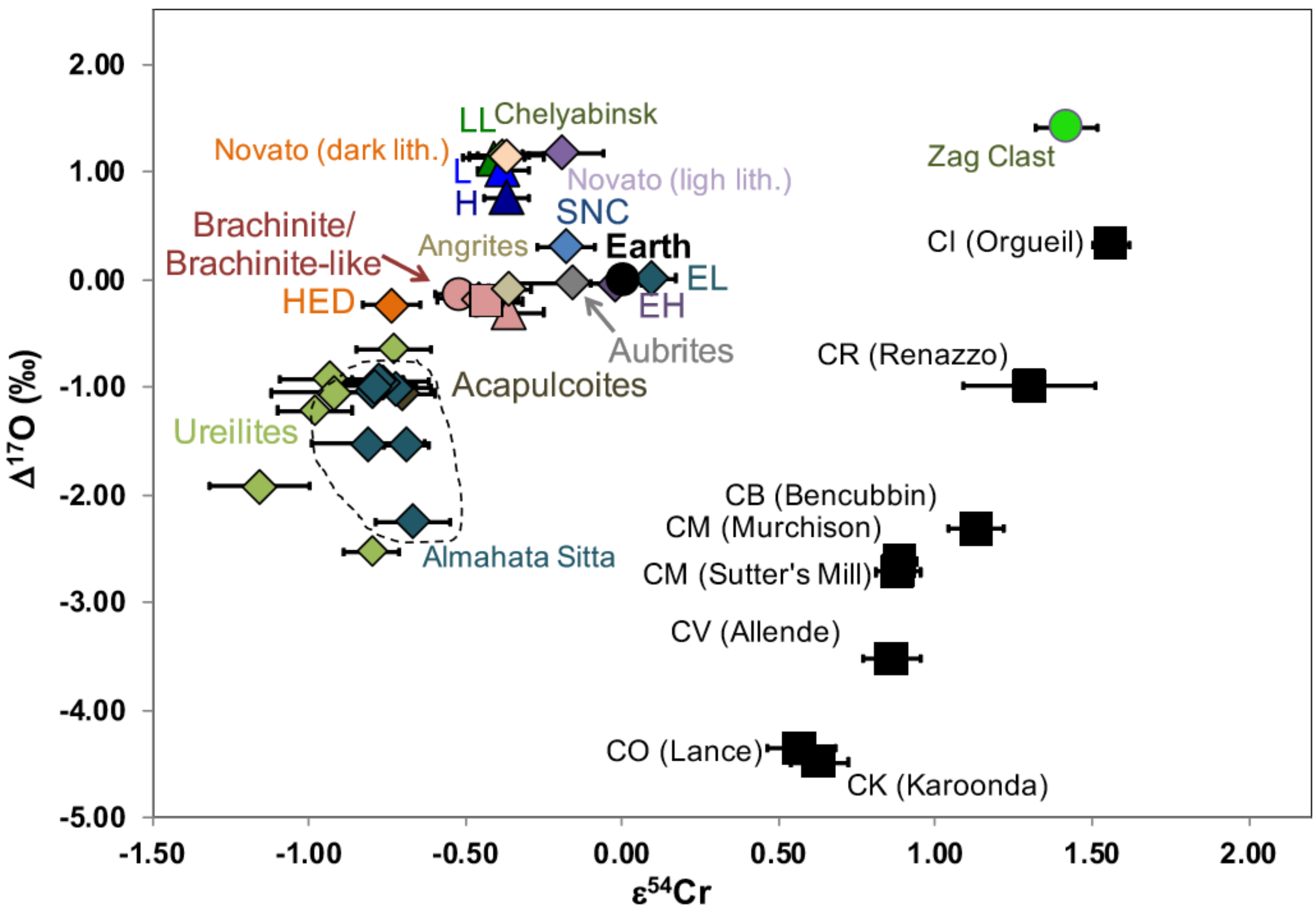


From Yin et al.

Can we find materials that formed farther outward from Jupiter?



From Yin et al.



Qin-Zhu Yin and Matt Sanborn

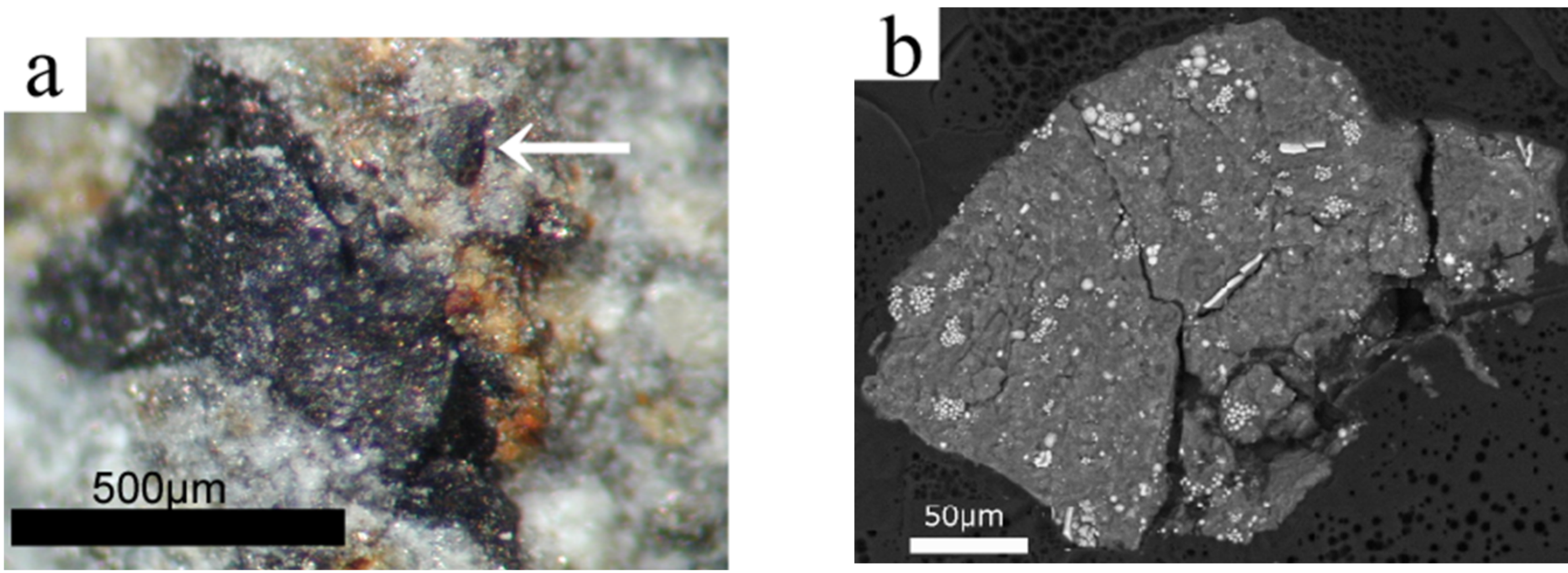
Hydrous clasts

Tsukuba (H5)

Ebeam work published many years ago

No isotopes

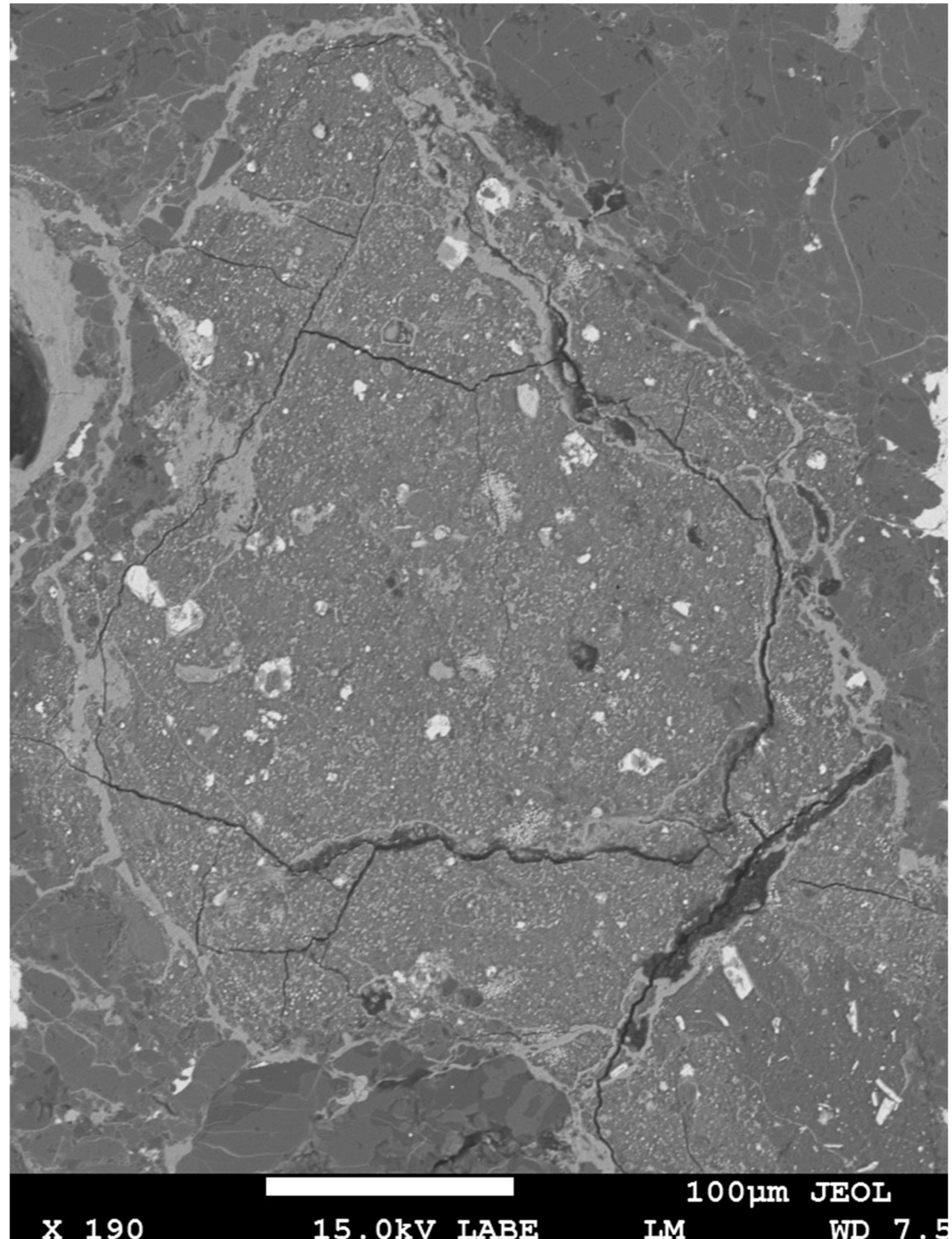
I have some tiny bits from Daisuke Nakashima



Hydrous clasts

NWA 8369 H5

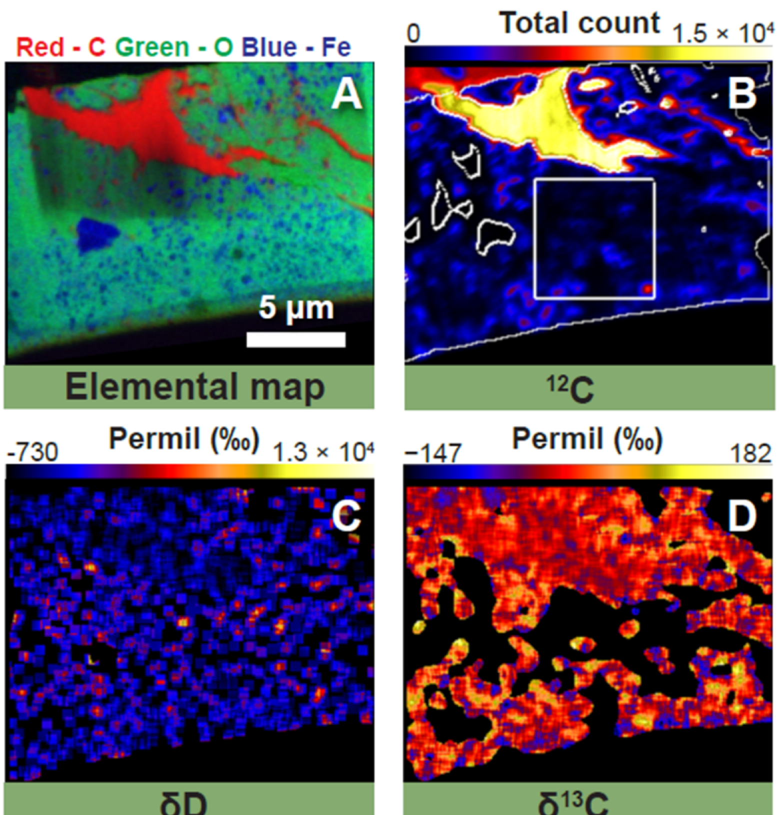
Microprobe work only so far

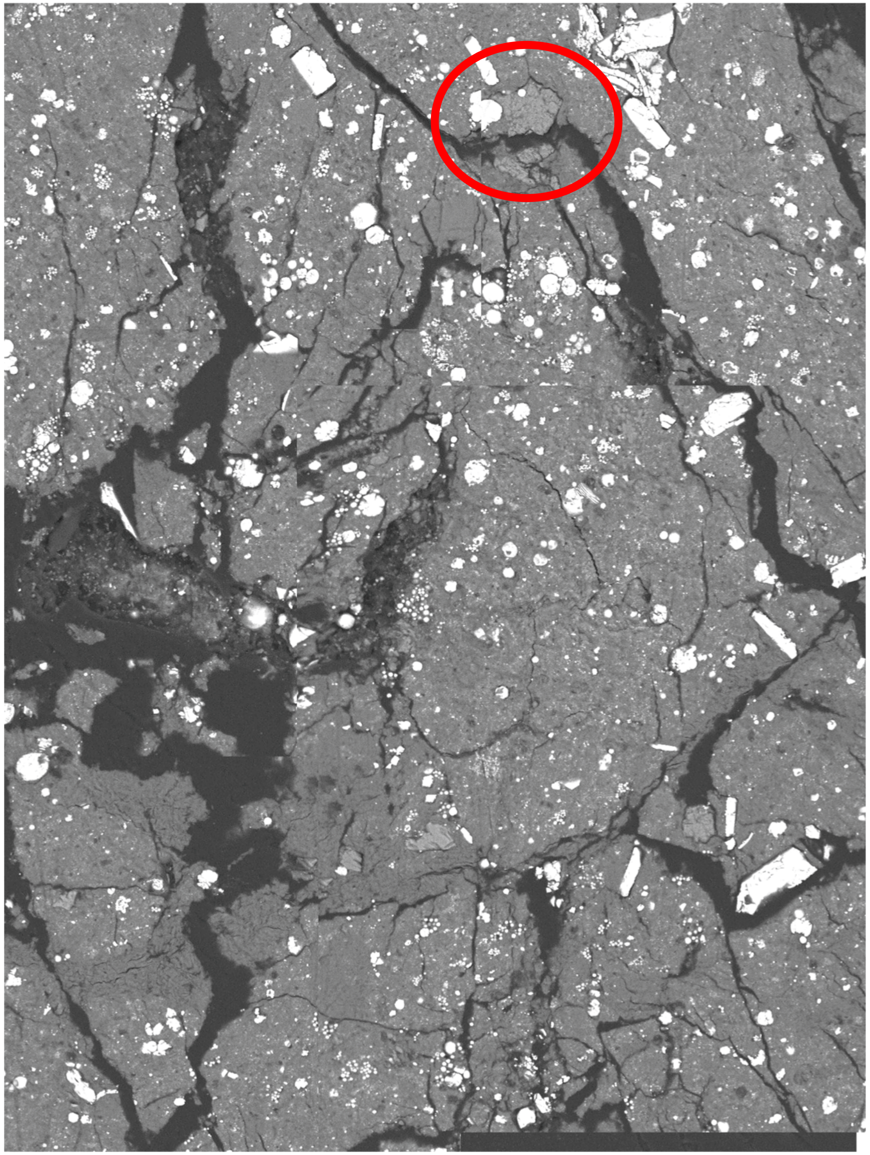


Hydrous clasts

Carancas (H4/5) – small clast in a sample from Jason Utas

Queenie Chan and Yoko Kebukawa did some analyses of organics from a FIB slice

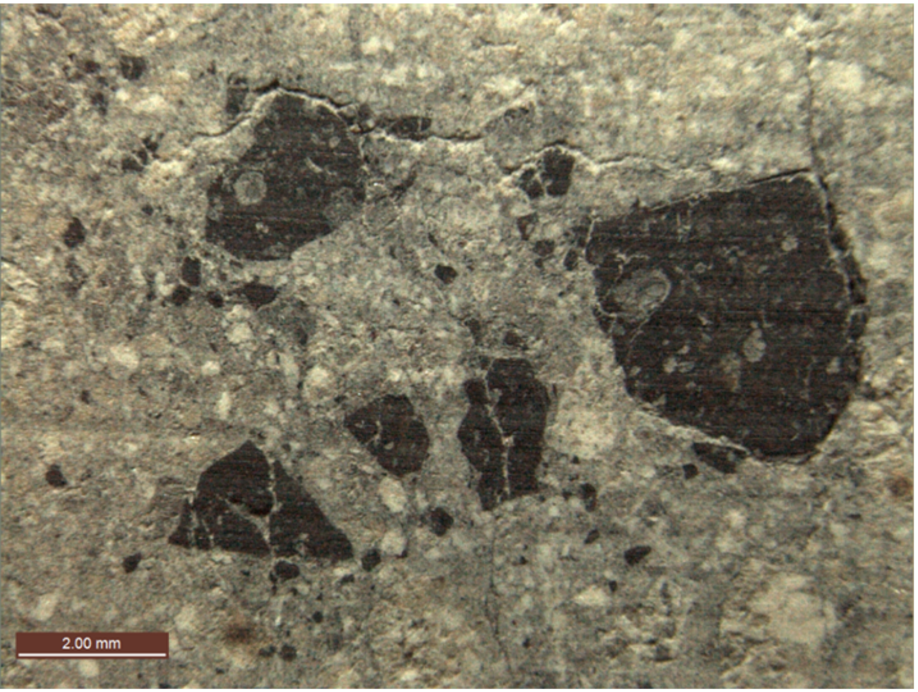




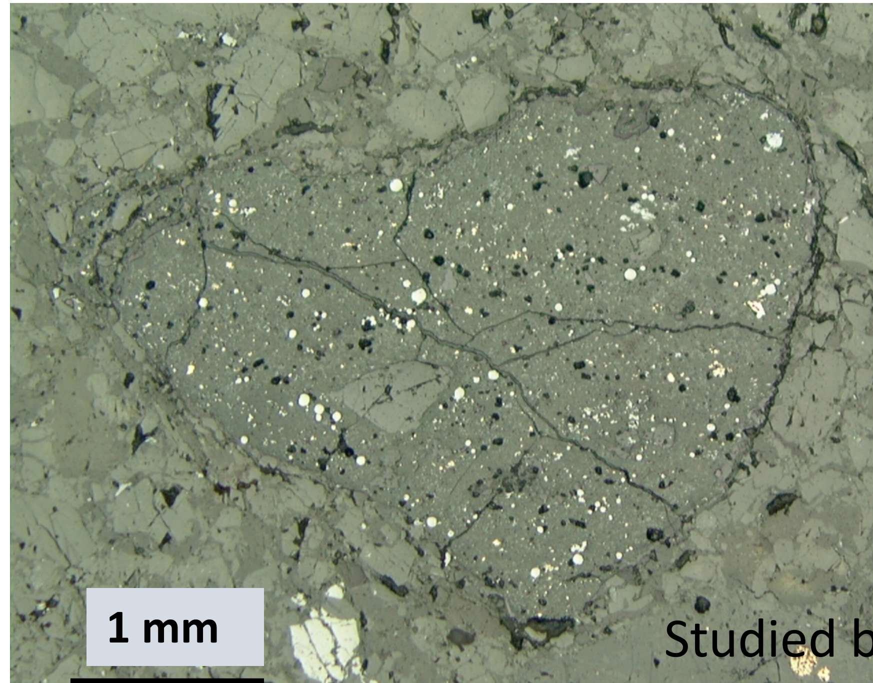
Carancas crater

September 15, 2007, near Lake Titicaca in Peru

CR/CI/MM like clasts in HEDS



NWA 6695
(Howardite)



Y-791834
(Eucrite)

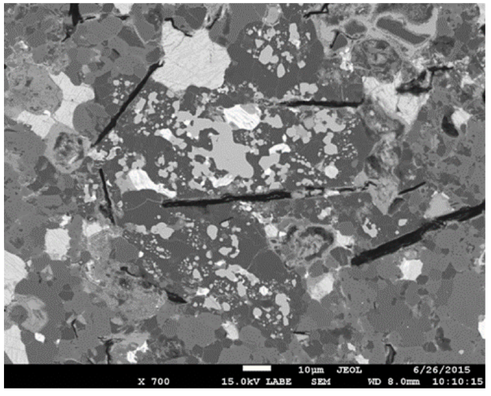
Studied by Zolensky, Gounelle, Briani, Buchanan, etc

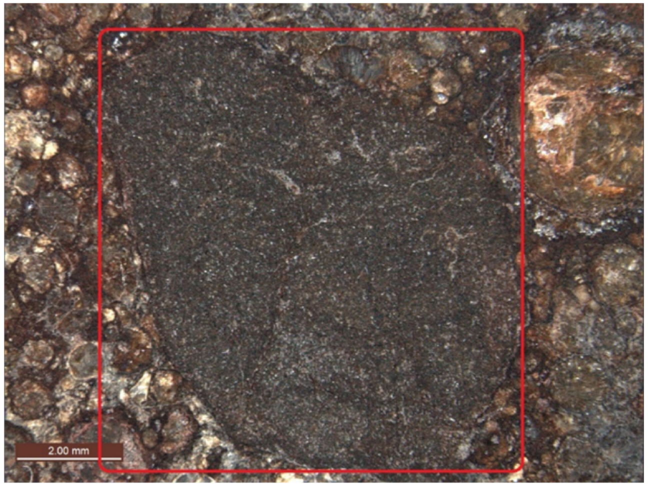
Our idea is that these hydrous clasts are identical to P and D class asteroid material

We plan to date the carbonates to try to determine when they altered

There are associated carbon-rich anhydrous clasts that we propose to be the products of impacts of the outer ss materials into the inner ss asteroids

We plan to date these by Ar-Ar





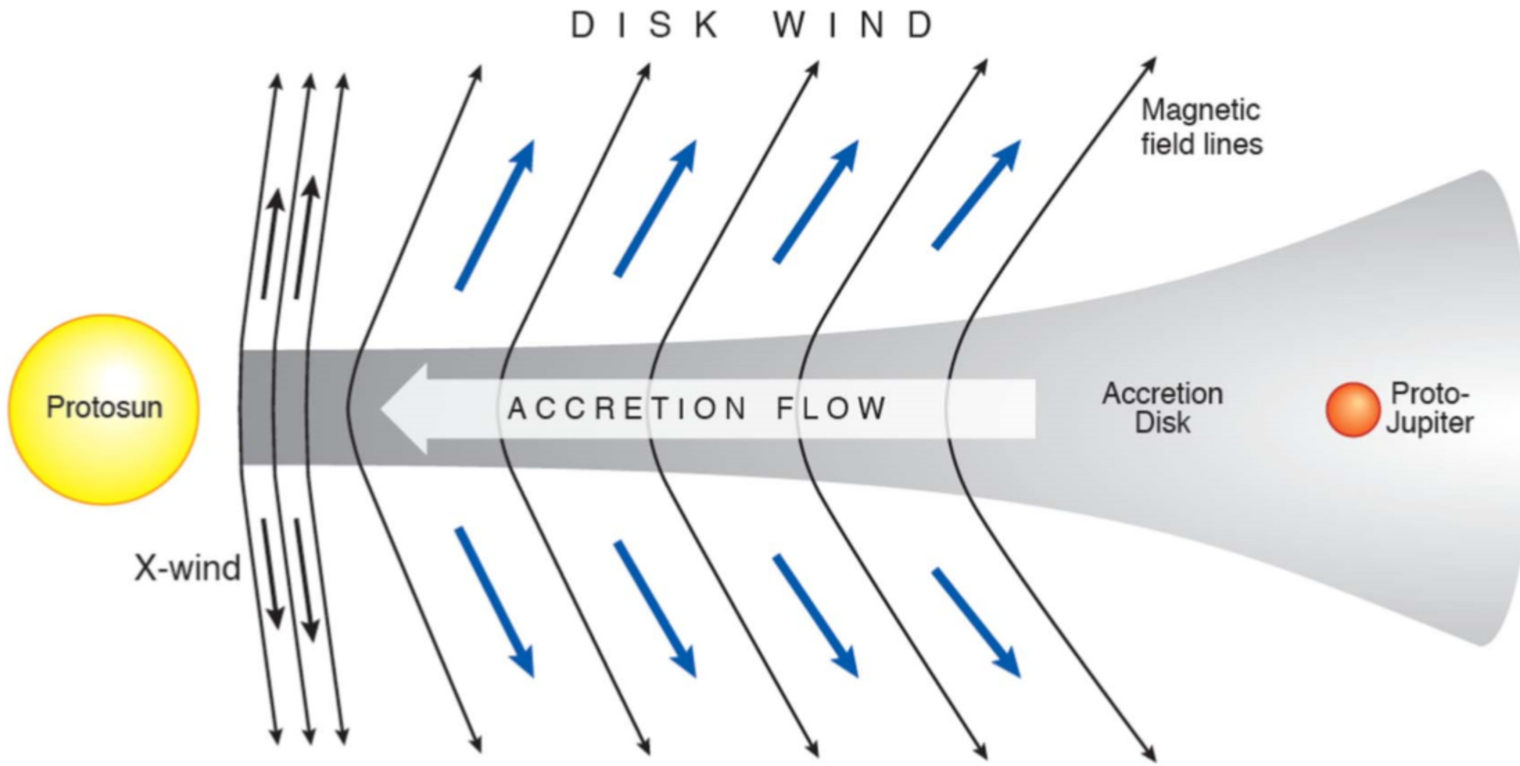


Figure 4. Cartoon showing the protosolar disk, which surrounds the young Sun, and two mechanisms that have been proposed to accelerate ionized gas along magnetic field lines and launch refractory inclusions and chondrules to the outer part of the disk: the X-wind from close to the protostar (Shu et al. 1996) and disk winds (Salmeron & Ireland 2012). The X-wind model has many problems (Krot et al. 2009; Desch et al. 2010). However, ALMA observations suggest that disk winds, which are responsible for removing

From Scott et al., Ap J, 2017

From Gerber et al., 2016