Silicates in the protoplanetary disk

Hugues Leroux
Unité Matériaux et Transformations
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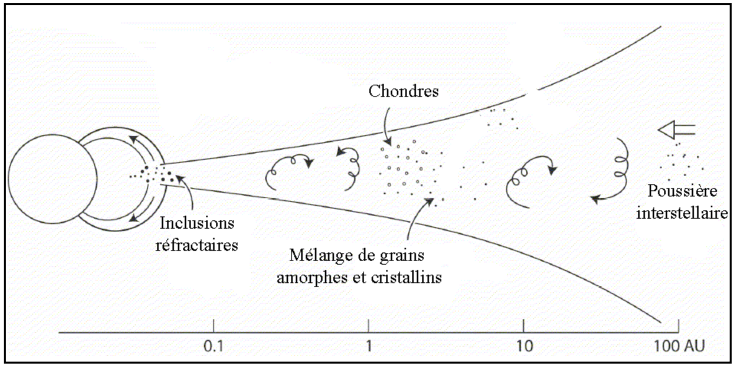
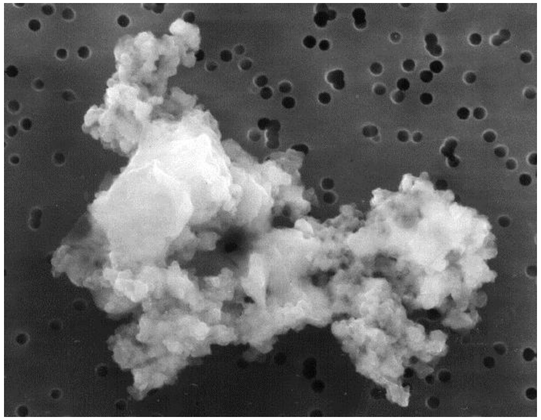
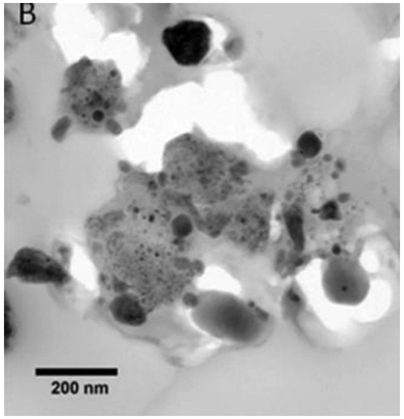






Les Houches, February 2017

Solid matter in the interstellar medium

➢ first solids of the solar system (solid precursors)

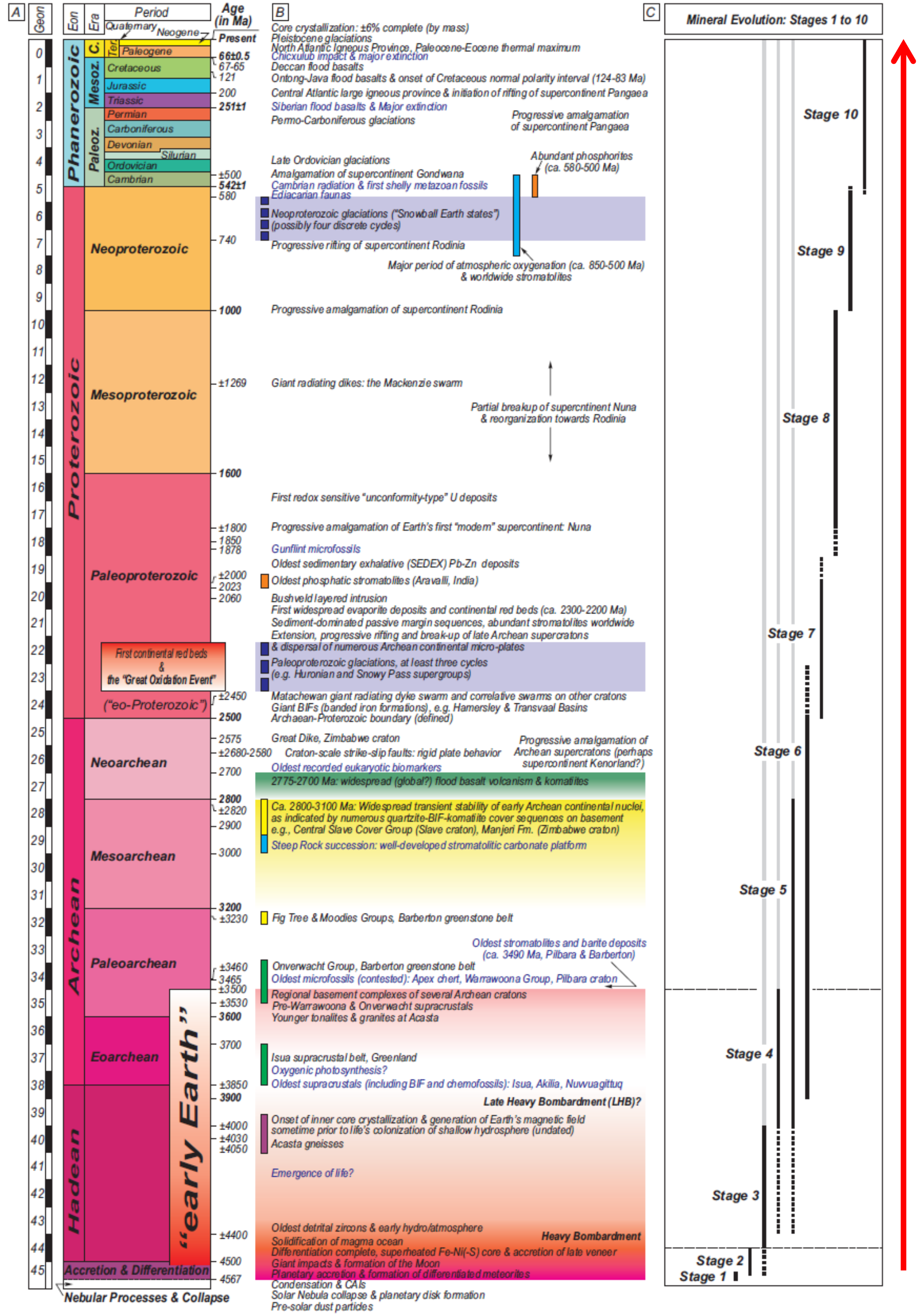
- Ices
- Carbonaceous matter
- Silicates

- The grains are amorphous
- Small sized, typically 100 nm
- Probably porous, implanted by H and He
- Probably in form of aggregates in pre-stellar molecular clouds

Mineral evolution in the protoplanetary disk ?

Mineral evolution on Earth

Hazen et al 2008



Number of mineral phases

+ 4000

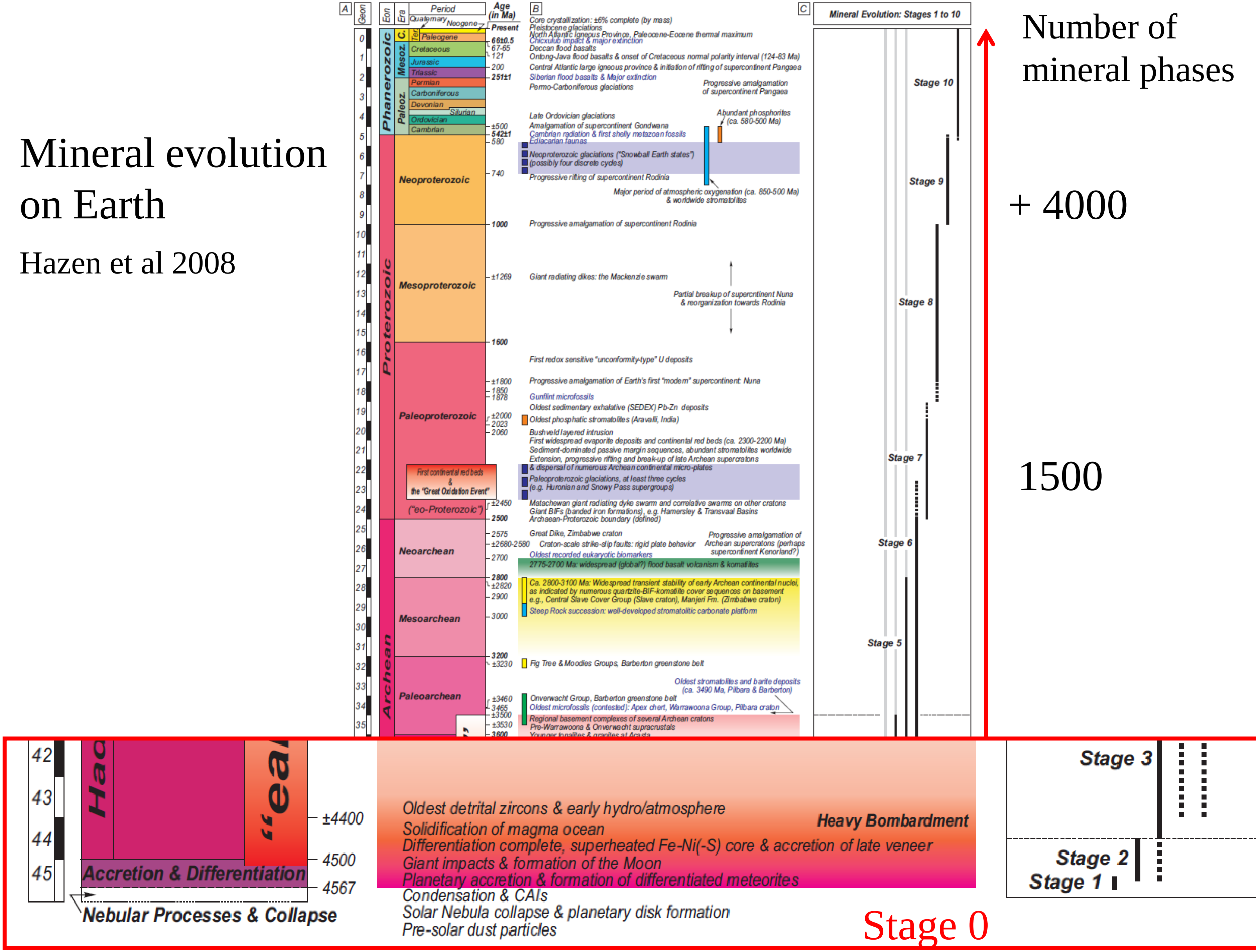
1500

500

50

Mineral evolution on Earth

Hazen et al 2008



American Mineralogist, Volume 93, pages 1693–1720, 2008

REVIEW PAPER

Mineral evolution

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ABSTRACT

The mineralogy of terrestrial planets evolves as a consequence of a range of physical, chemical, and biological processes. In pre-stellar molecular clouds, widely dispersed microscopic dust particles contain approximately a dozen refractory minerals that represent the starting point of planetary mineral evolution. Gravitational clumping into a protoplanetary disk, star formation, and the resultant heating in the stellar nebula produce primary refractory constituents of chondritic meteorites, including chondrules and calcium-aluminum inclusions, with ~60 different mineral phases. Subsequent aqueous and thermal alteration of chondrites, asteroidal accretion and differentiation, and the consequent formation of achondrites results in a mineralogical repertoire limited to ~250 different minerals found in unweathered meteorite samples.

Following planetary accretion and differentiation, the initial mineral evolution of Earth's crust

Astron. Astrophys. 339, 904–916 (1998)

ASTRONOMY AND ASTROPHYSICS

Steps toward interstellar silicate mineralogy

IV. The crystalline revolution

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Abstract. Mid- and far-infrared spectra gained by the Short Wavelength Spectrometer (SWS) of the Infrared Space Observatory (ISO) satellite have provided striking evidence for the presence of crystalline silicates in comets, circumstellar envelopes around young stars and, most of all, evolved stars and planetary nebulae. Since optical properties of astrophysically relevant crystalline silicates are lacking in the literature, in this paper mass absorption coefficients (MACs) of olivines and pyroxenes for a wide range of Mg/Fe ratios are presented, which

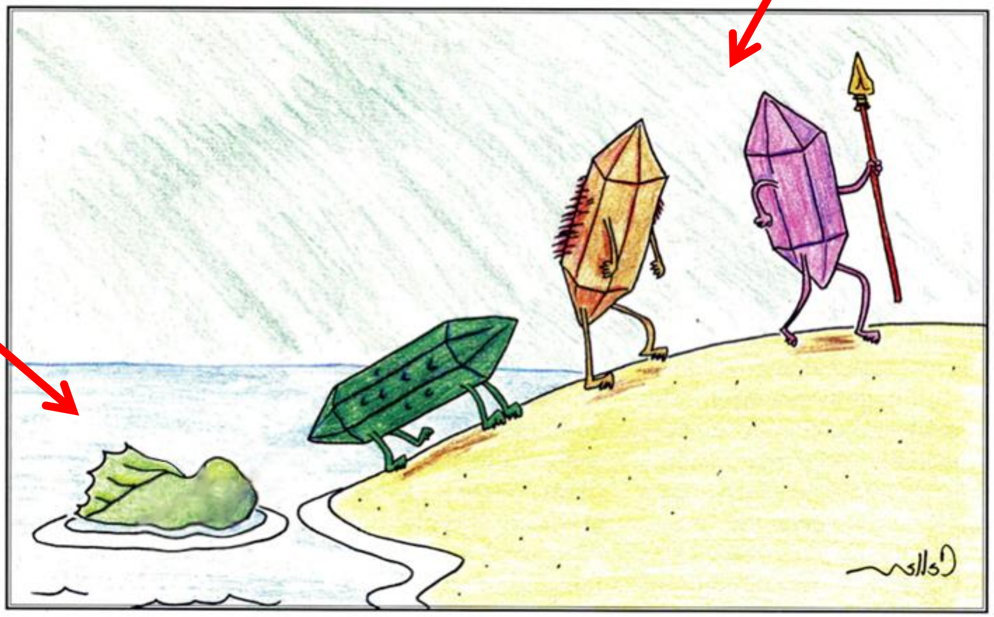
1. Introduction

Before the Infrared Space Observatory (ISO, Kessler et al. 1996) opened the mid- and far-infrared range for high-resolution spectroscopy, it was generally assumed that cosmic dust silicates were of amorphous structure. Exceptions were the cometary dust (Hanner et al. 1994, Hanner 1996), interplanetary dust particles (IDPs, Mackinnon & Rietmeijer 1987, Bradley et al. 1992), dust disks of β Pictoris-type around main-sequence stars (Knacke et al. 1993, Fajardo-Acosta & Knacke 1995), and the

Silicate evolution in the protoplanetary disk

Protostellar
silicate

Interstellar
silicate



- The solid precursors (interstellar matter) are largely amorphous
- The early stage of the evolution concern a low number of phases

Silicates

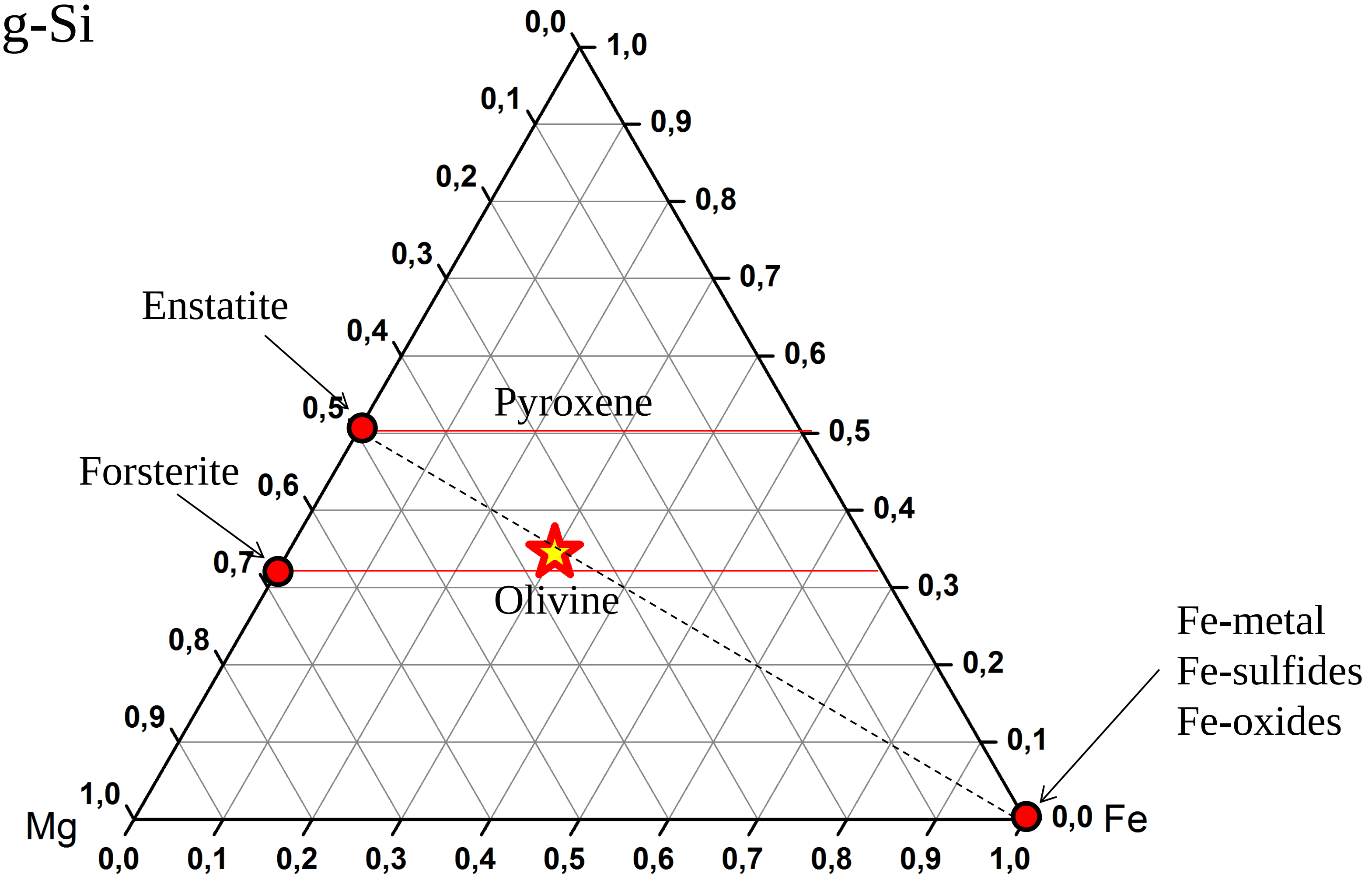
- Amorphous silicates Fe,Mg,Si,O
- Olivine $(Fe,Mg)_2SiO_4$ —— (Mg+Fe)/Si=2
- Pyroxenes $(Fe,Mg)SiO_3$ —— (Mg+Fe)/Si=1

Association with:

- Fe-sulfides
- Fe-Ni metal

… and some other accessory phases

Ternary diagram
Fe-Mg-Si

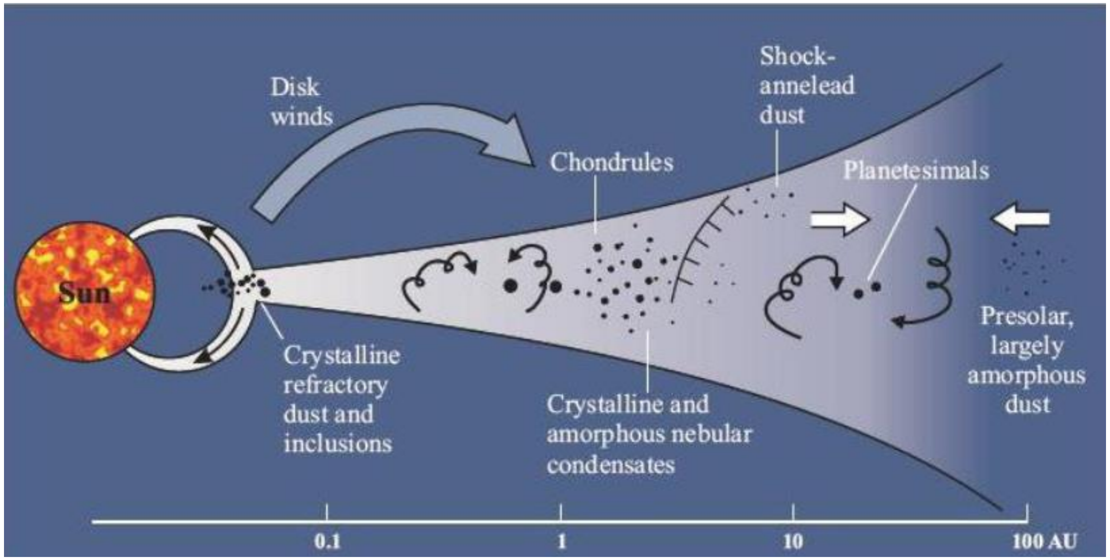


Primitive material

- Matter that has undergone virtually no transformation during its stay on a parent body (secondary processes).
- This solid matter could represent the « building blocks » from which the objects of the Solar System were formed.

➢ Understanding the chemical and mineralogical evolution that marked the transition from interstellar matter to the solar nebula matter

➢ Dynamics and kinetics of the transformation of solids in the protoplanetary disk



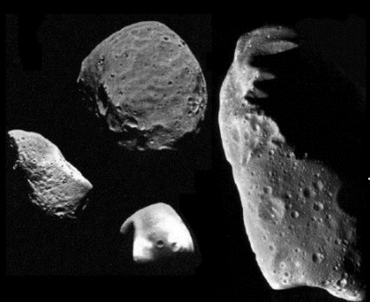
Protoplanetary disk, adapted from Scott 2007

Objects of the solar system

Mercury Venus Earth Mars Jupiter Saturn Uranus Neptune

Asteroid belt

Kuiper belt

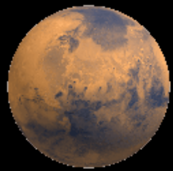


Meteorites

comets

Objects of the solar system

Planets and satellites → Modification of the solid mater by planetary processing



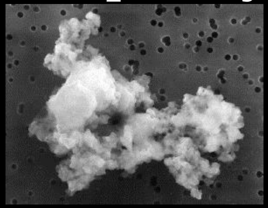
Asteroïds

→ Sampled by meteorites

→ 99.9 % of the meteorites tell us the history of the parent bodies

→ Some of the meteorites are « primitives »

Contemporary dust



→ IPDs, micrometeorites

→ Some of them are « primitives » - cometary origin ?

Comets

→ « freezer » of the solar system

→ Mission Stardust

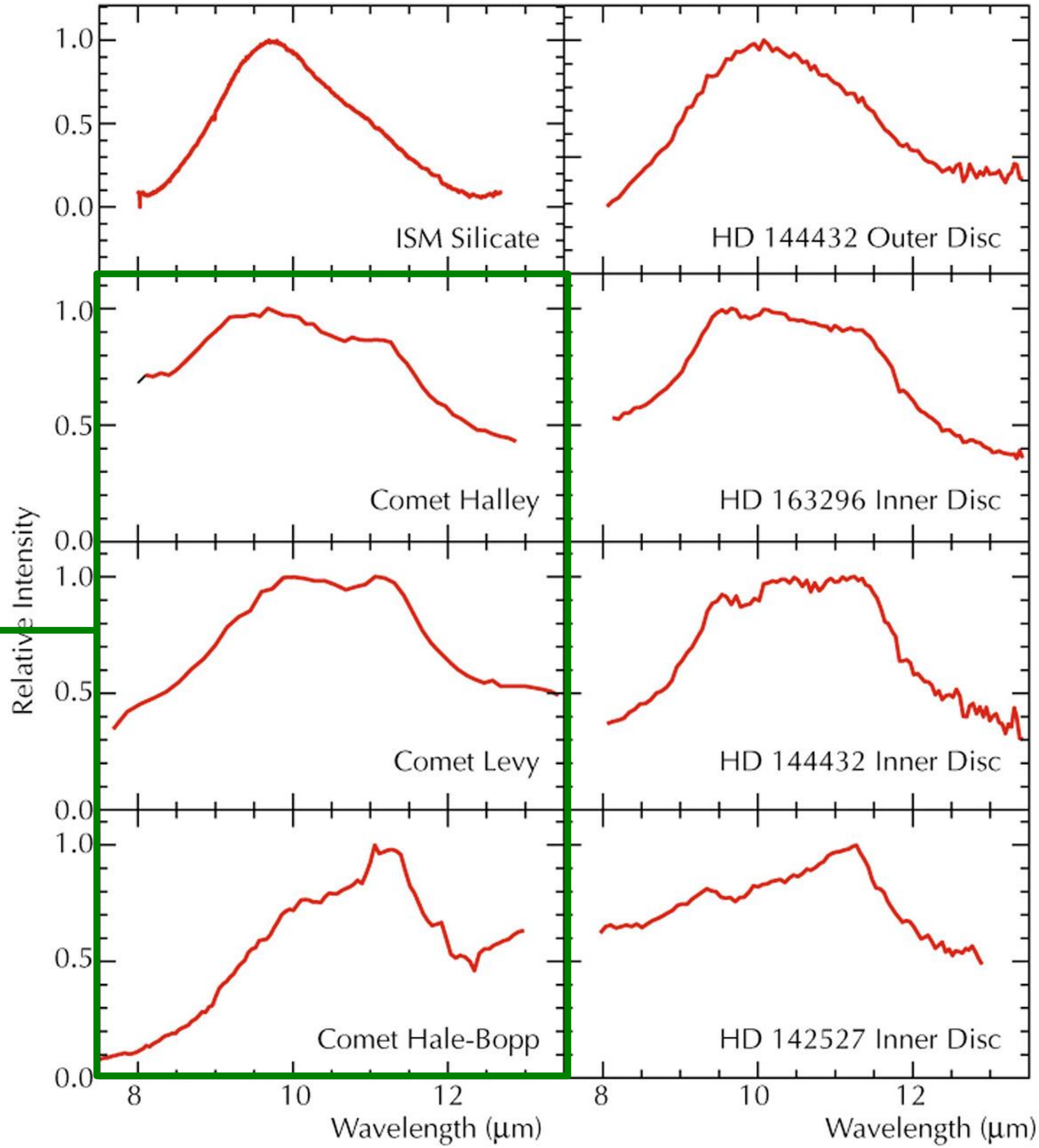
Outlines

- Part 1: Silicates in comets, with a special focus on the results of the Stardust mission
- Part 2: Silicates in IDPs and micrometeorites, including a focus on ultracarbonaceous micrometeorites (UCAMMs).
- Part 3: Silicates in fine-grained matrices of primitive chondrites

Part 1: Silicates in comets

10 µm band (silicates)

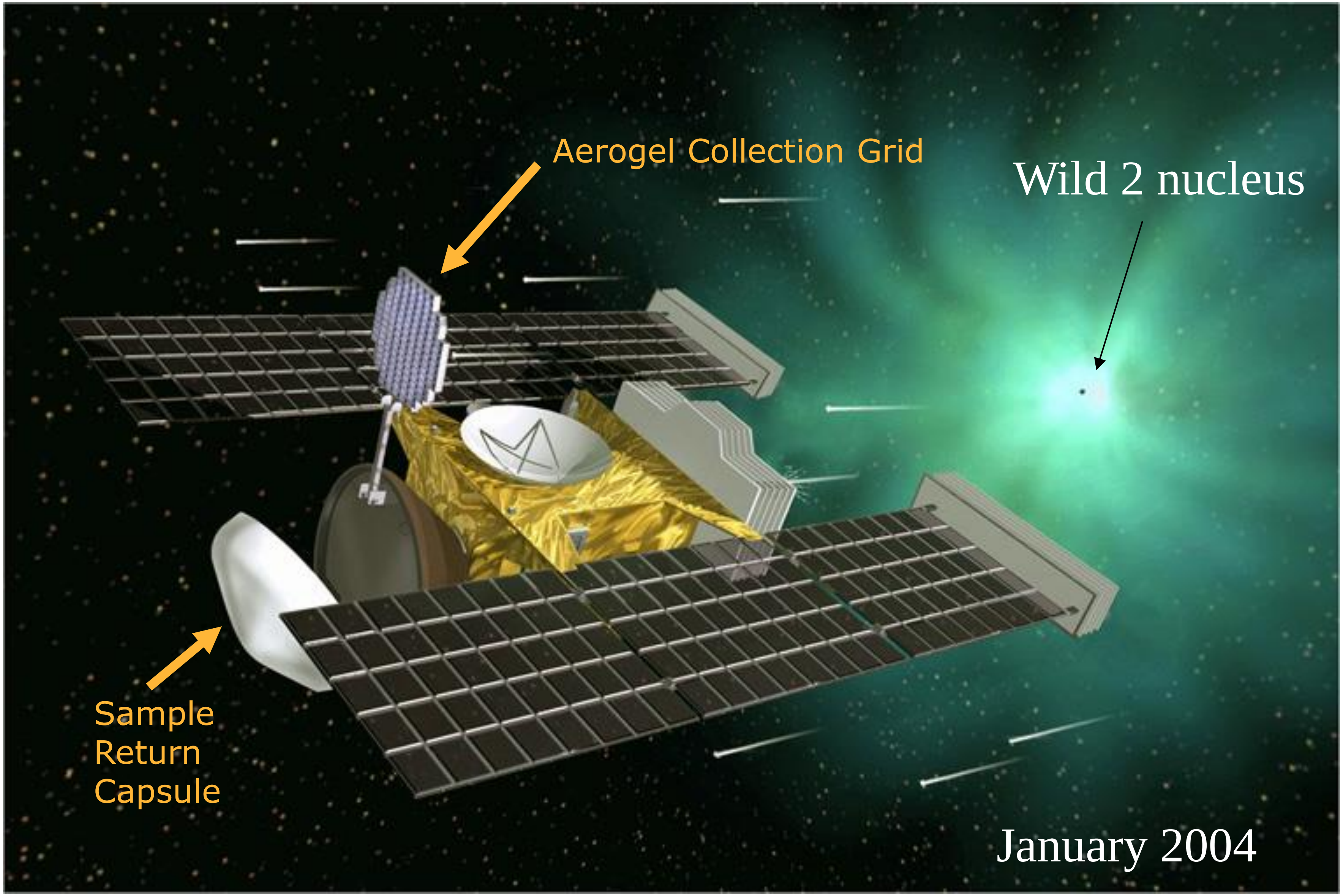
- Interstellar medium
- New stars
- Comets



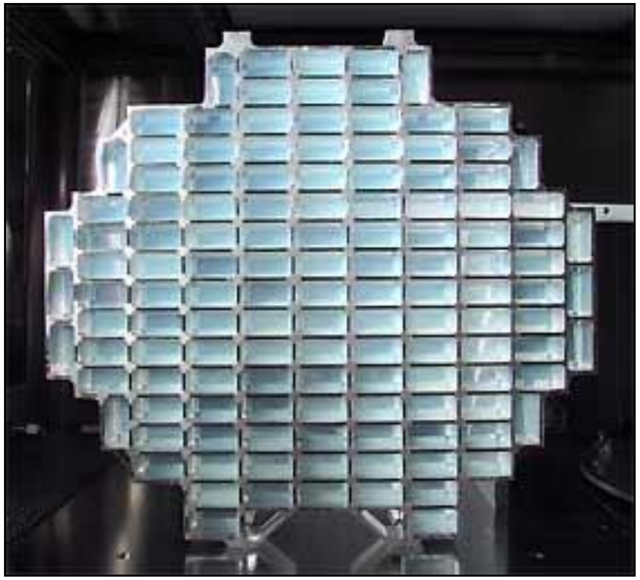
Silicates are (partly) crystalline around stars

Stardust: Flyby Sample Return Mission

The cometary dust was trapped in the coma (6 km/sec)



Dust Collector



Silica aerogel

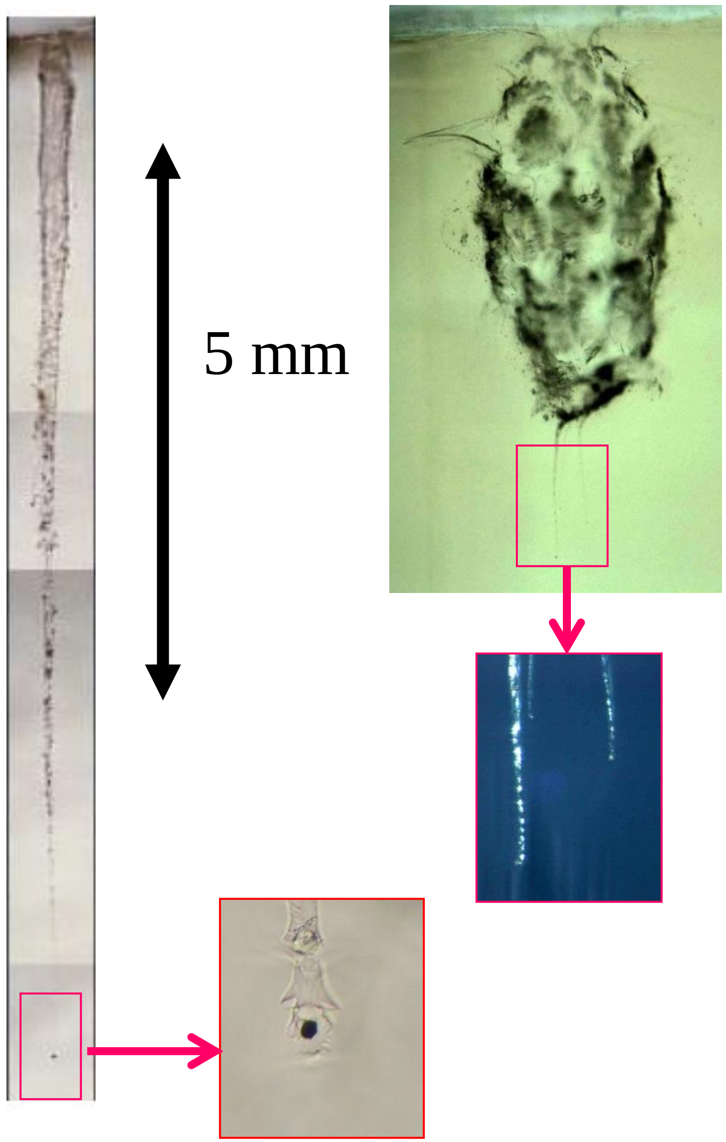
What is silica aerogel?

- Porous, sponge-like structure (99.8 percent empty space)

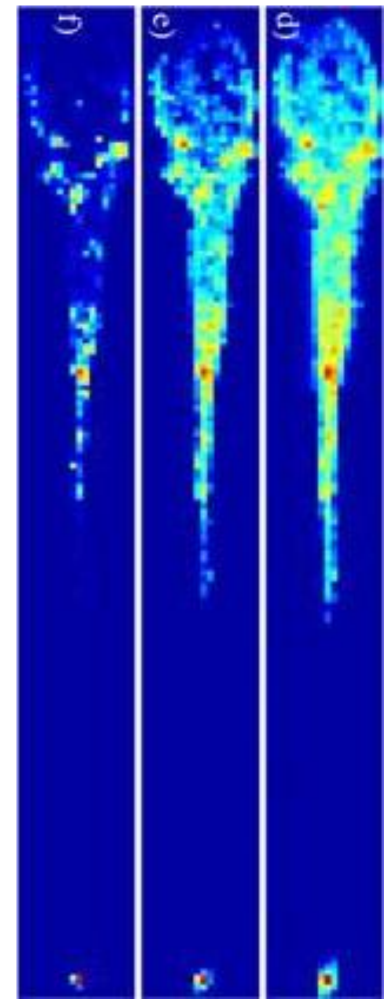
Role of aerogel?

- Decelerate gently as possible the Wild 2 dust (relative velocity = 6 km/sec).

Grain capture under extreme conditions
Tracks in the aerogel

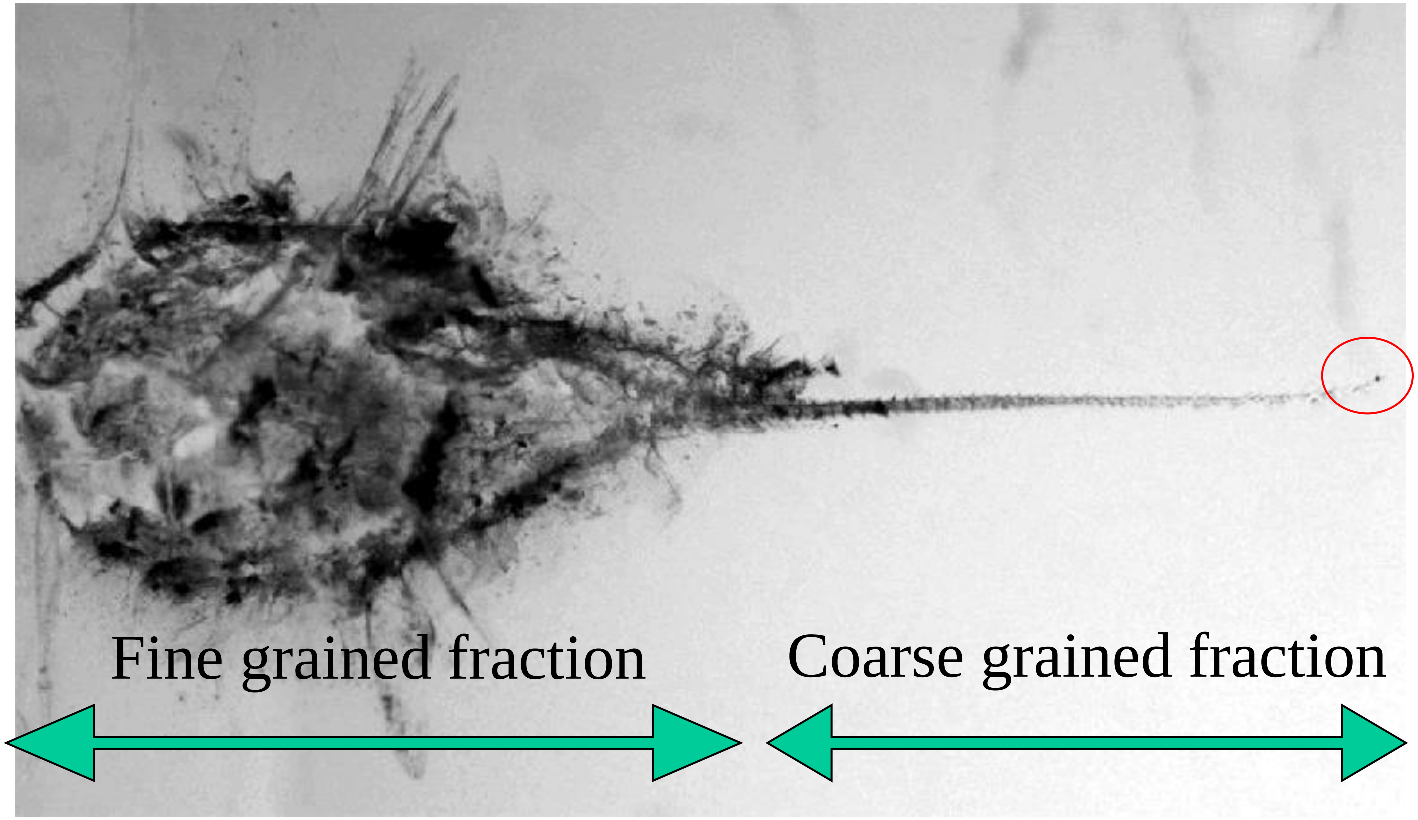


Synchrotron X-ray fluorescence maps for entire impact tracks



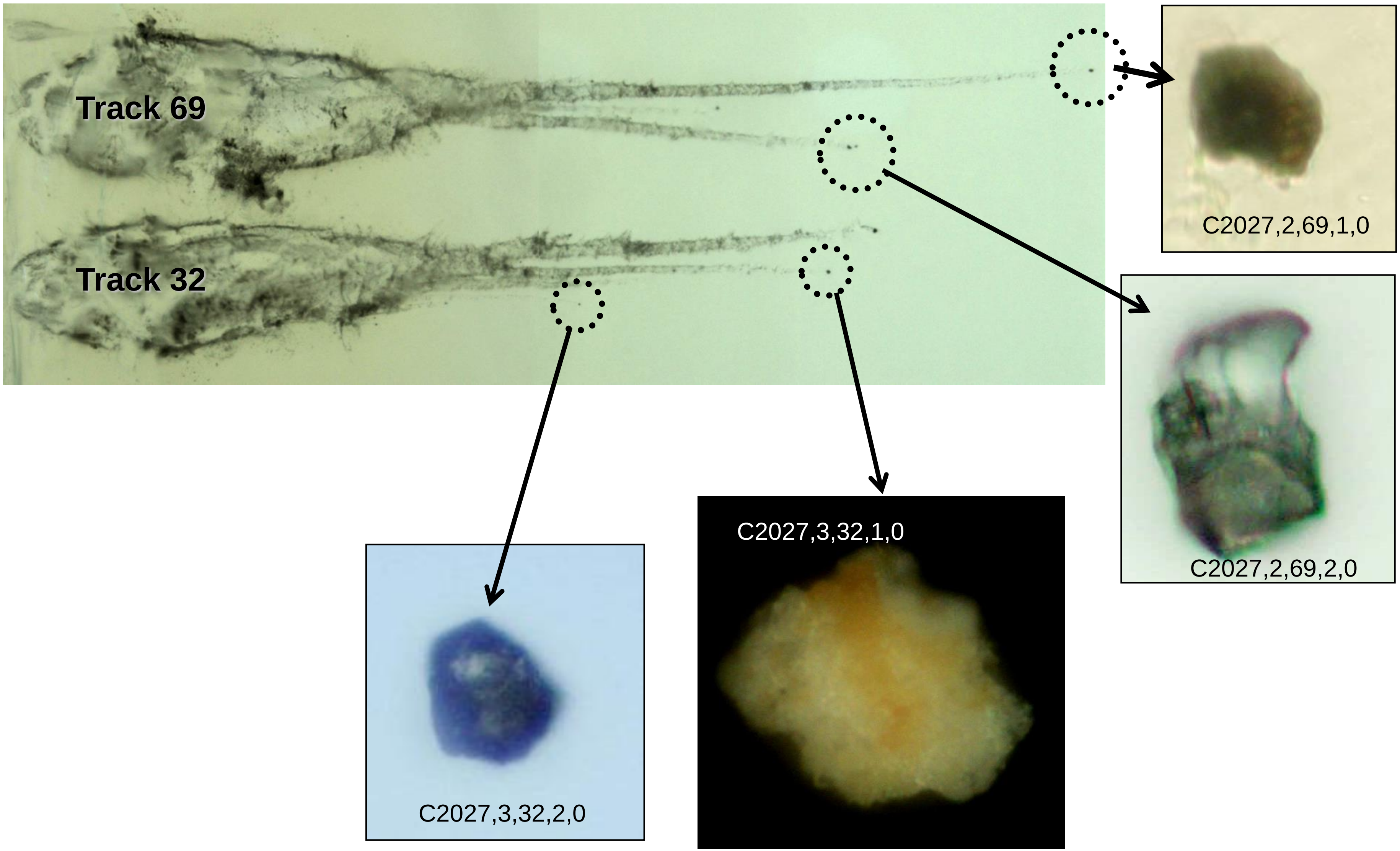
Ishii et al, 2008, MAPS

Grain capture under extreme conditions
Tracks in the aerogel



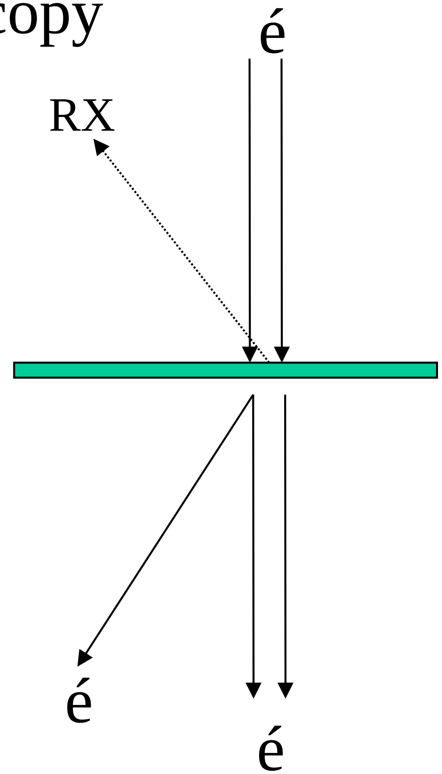
- Peak pressure ~ 0.3 - 1 GPa
- Tensile strength of aggregate (IDP-like) ~ 0.1 MPa
- Physical separation between coarse and fine-grained material
- Peak temperature : up to 2000 K - Possible thermal modification

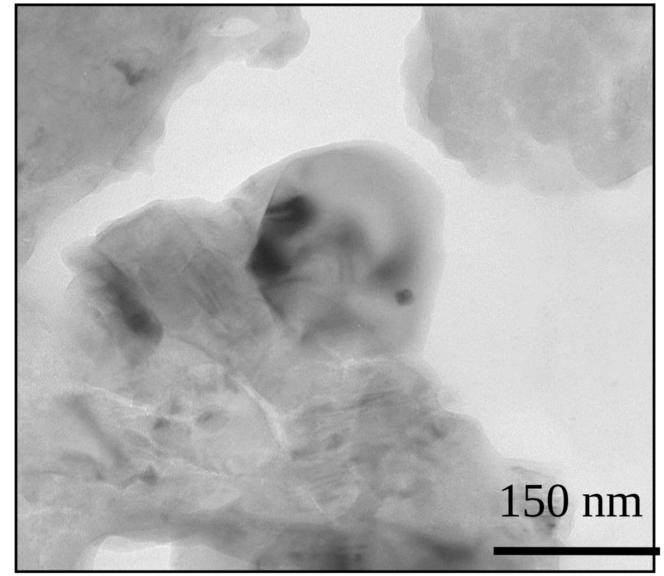
Terminal particles : coarse-grained fraction



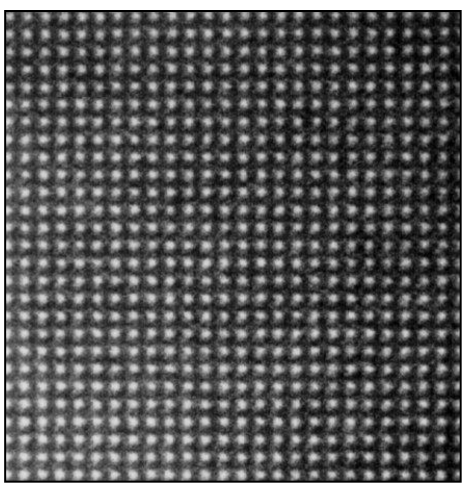
Transmission electron microscopy

University of Lille

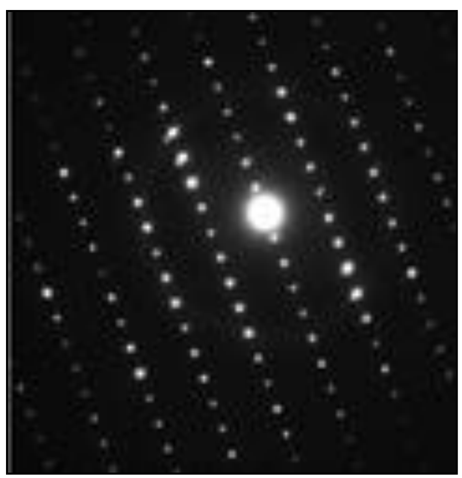




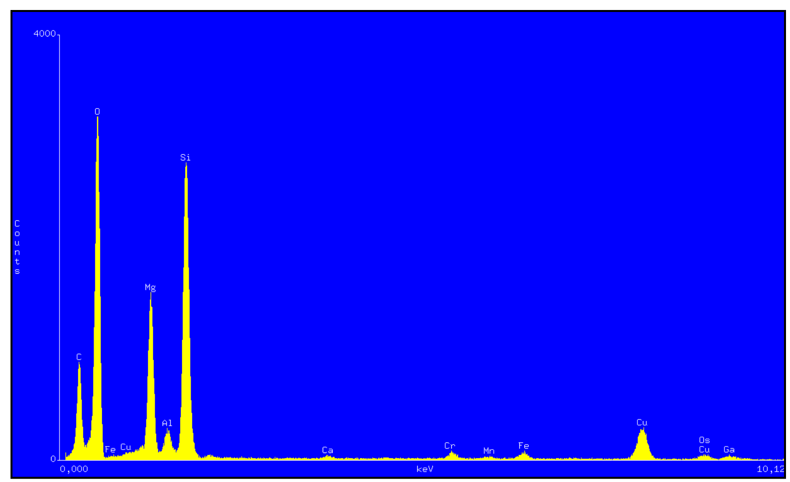
Conventional imaging



HRTEM (resolution = 1-2 Å)

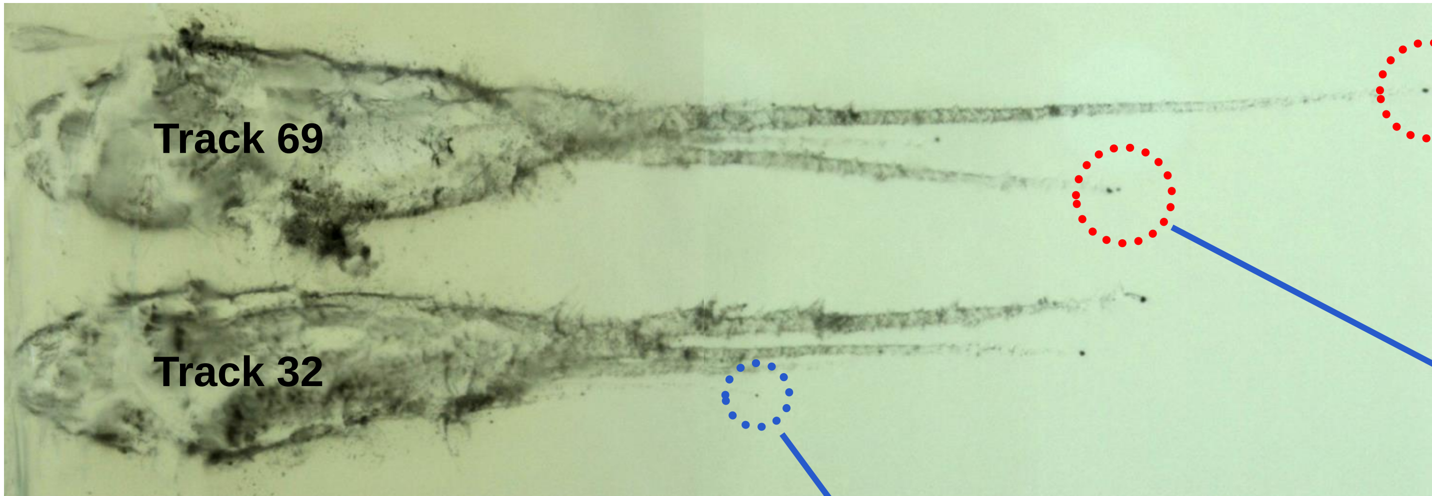


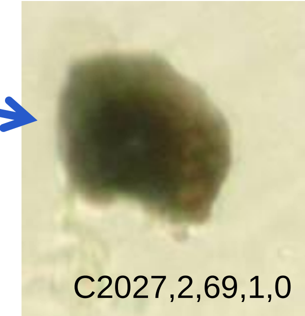
Electron diffraction

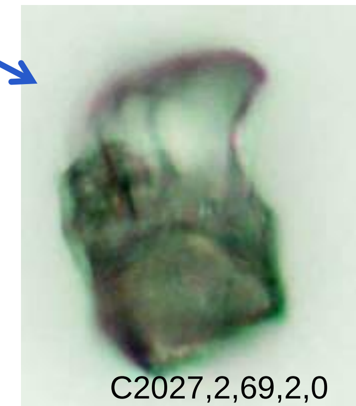


Nano-analysis

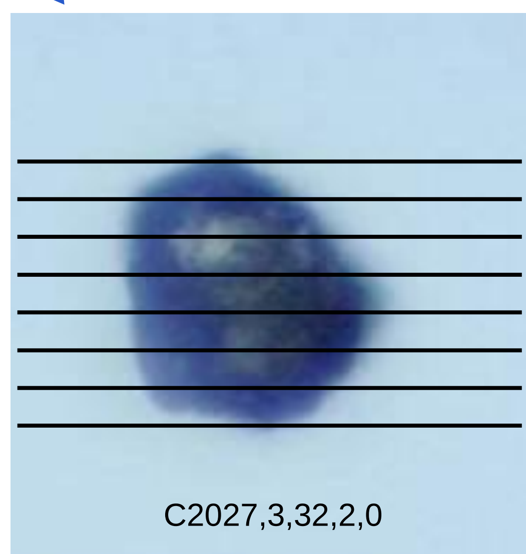
Sample preparation







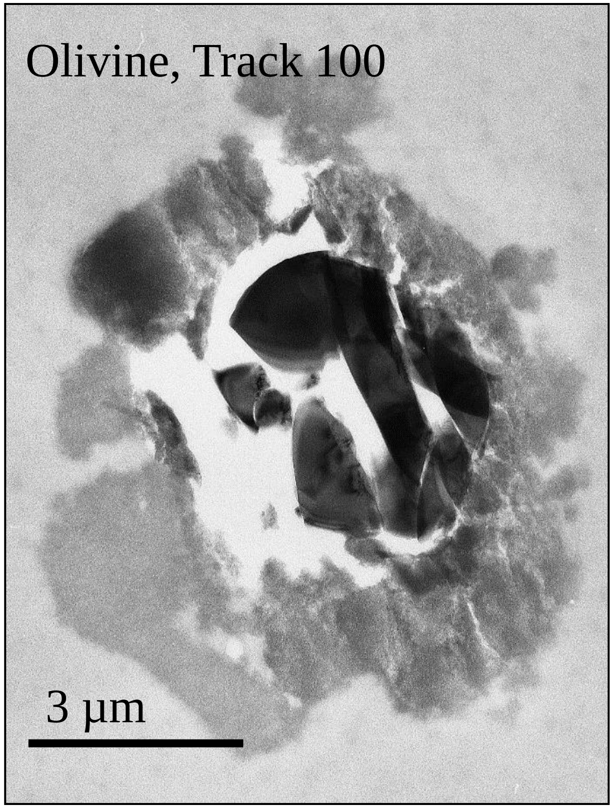
Extraction and preparation are made at the NASA Johnson Space Center by micromanipulation and ultramicrotomy

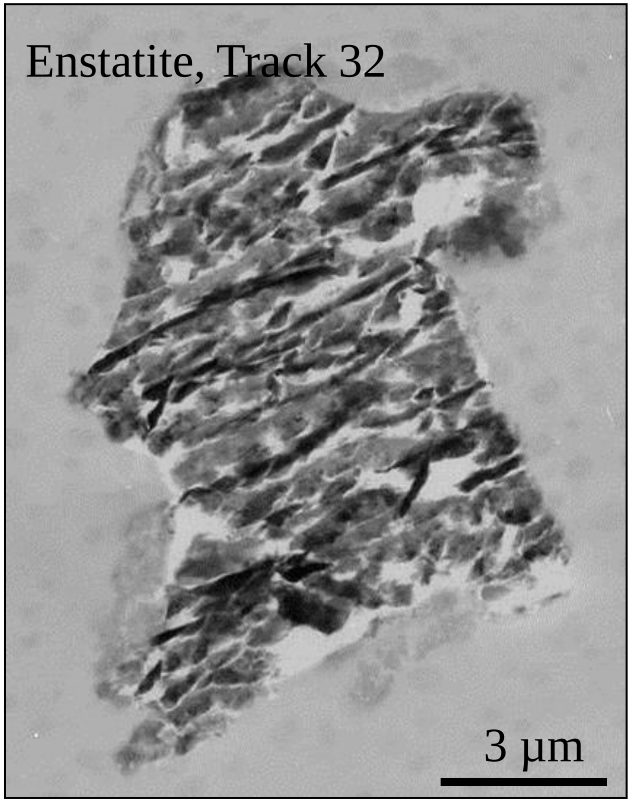


} ≈ 80nm

Zolensky et al. 2008

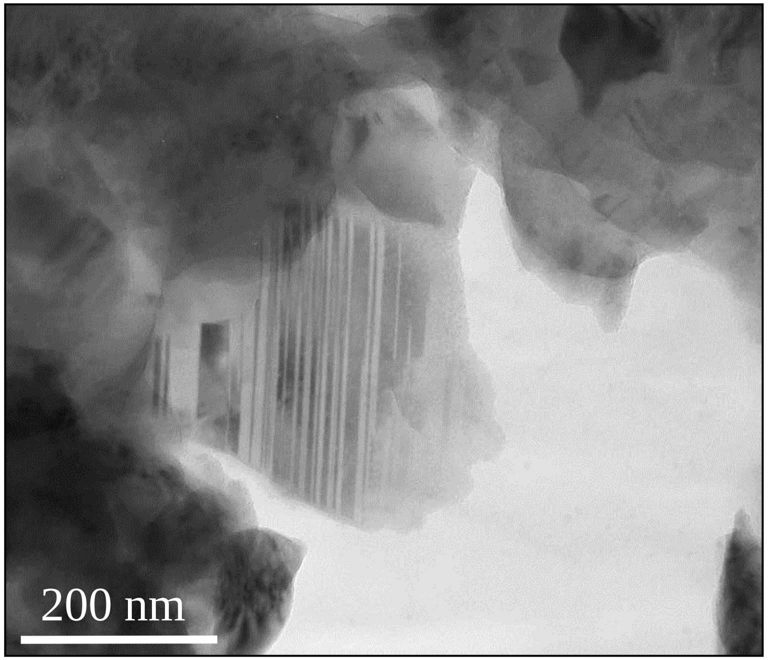
Terminal particles : coarse-grained fraction

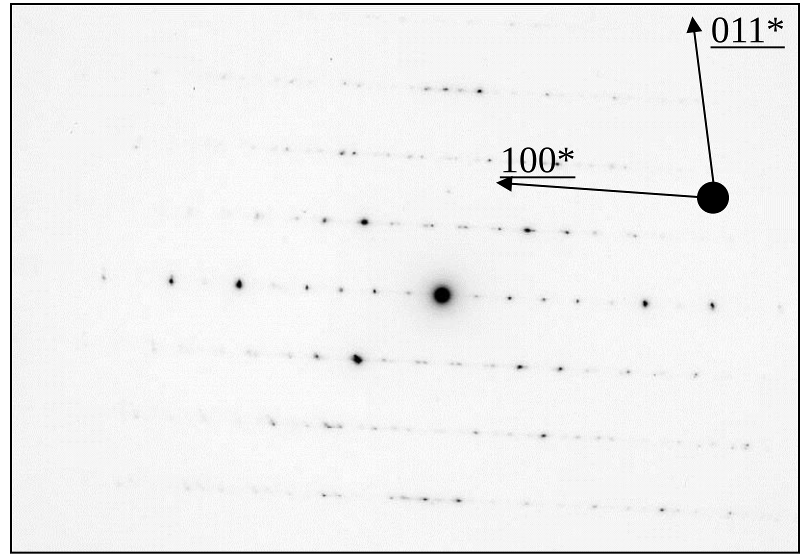


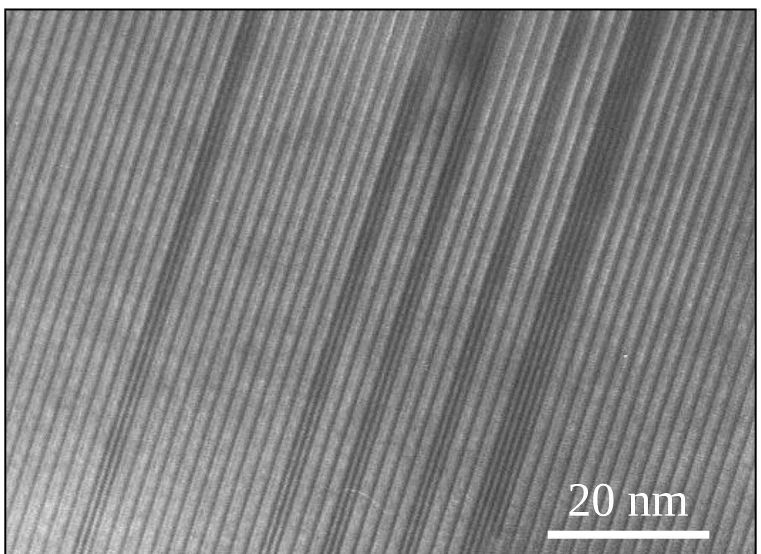


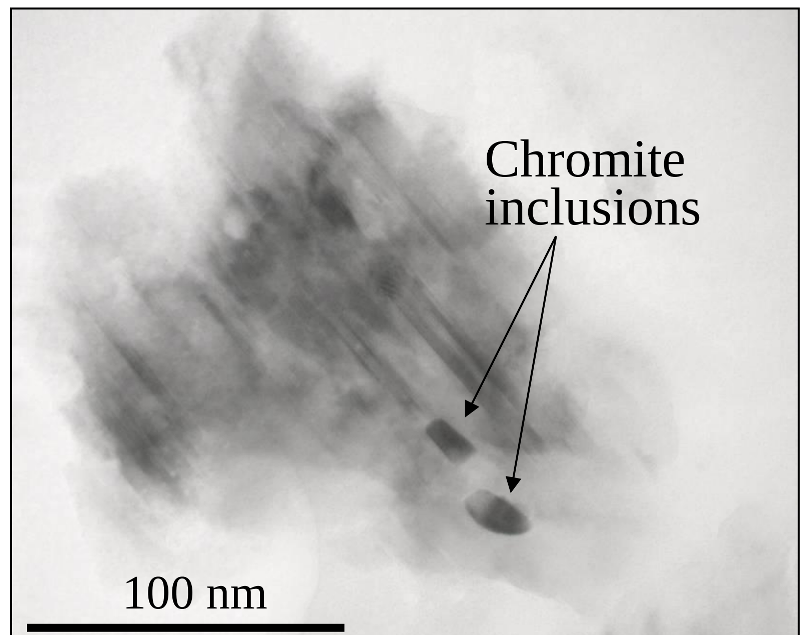
- ➢ Terminal particles are ‘coarse-grained’, frequently single crystals

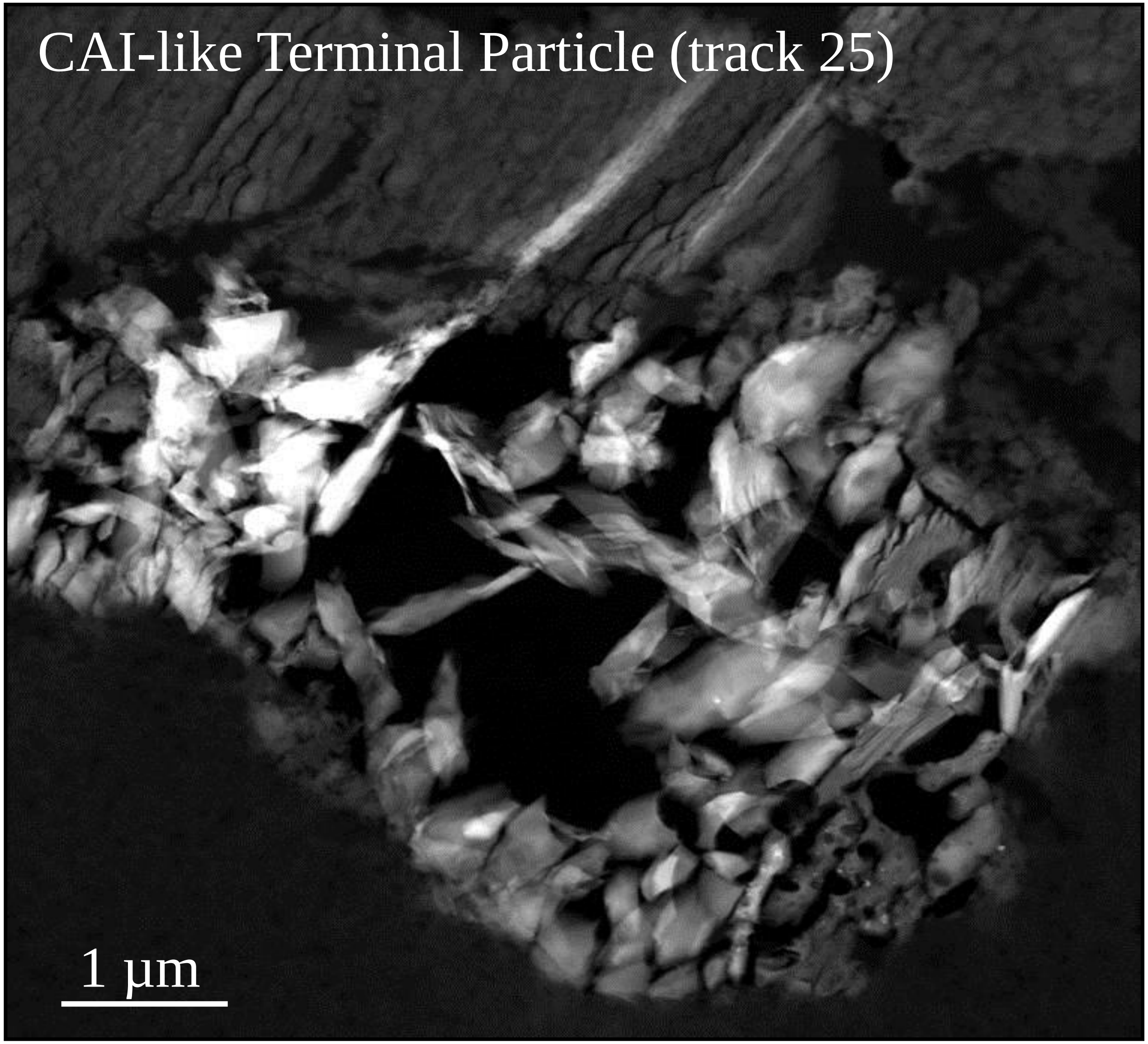
Microstructure of terminal particles by TEM







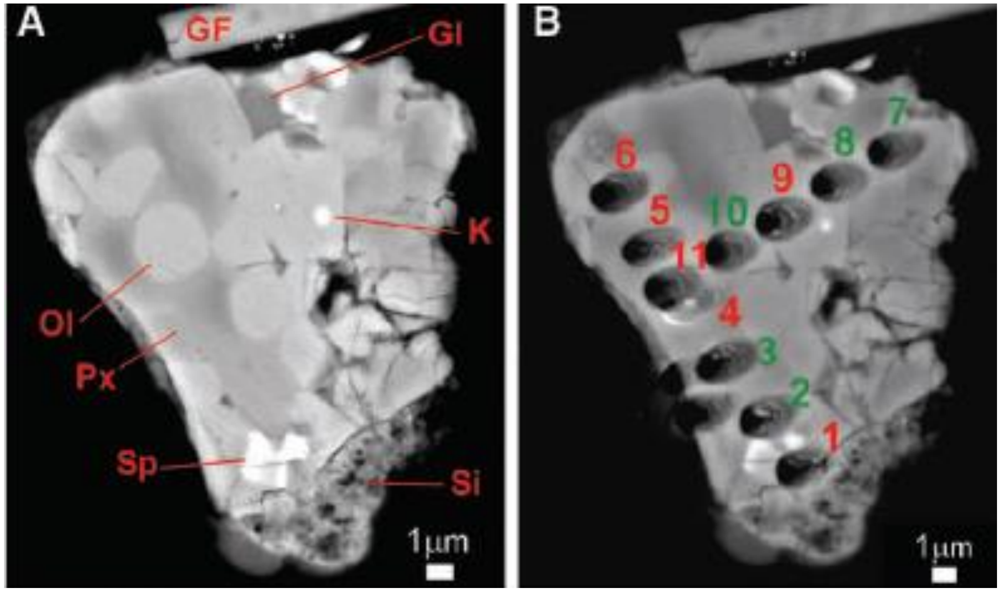




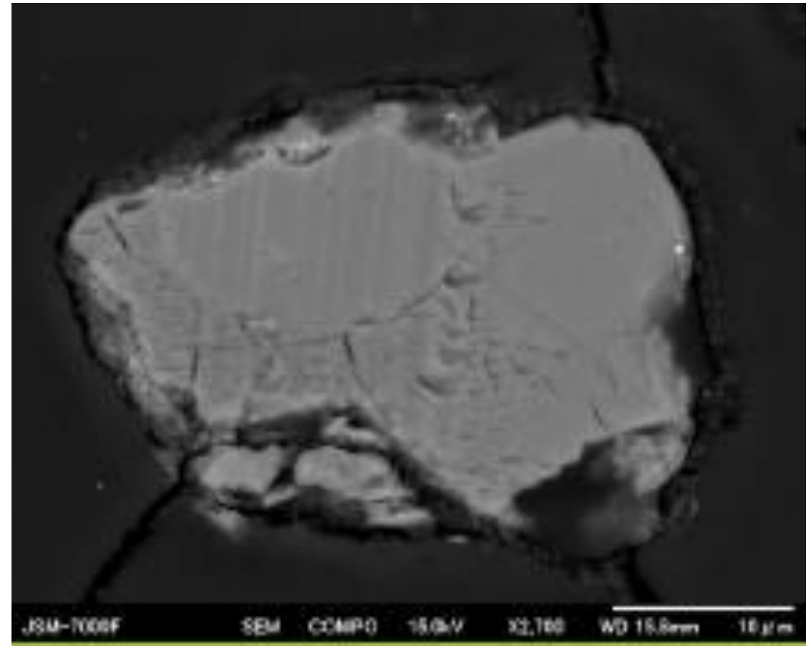
Micrograph by D. Joswiak

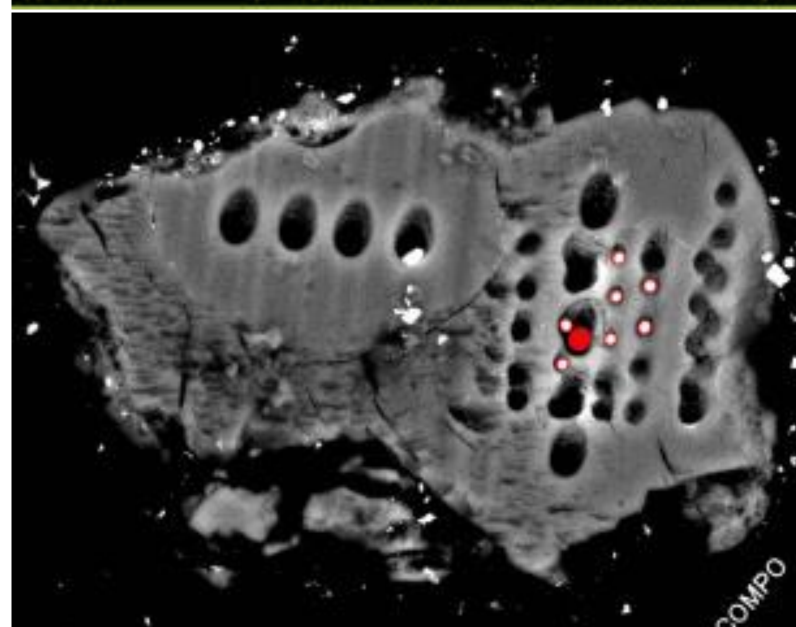
Anorthite, Diopside, Fassaite, Spinel, Gehlenite, Osbornite, ….

- Evidence for a HT mineralogy

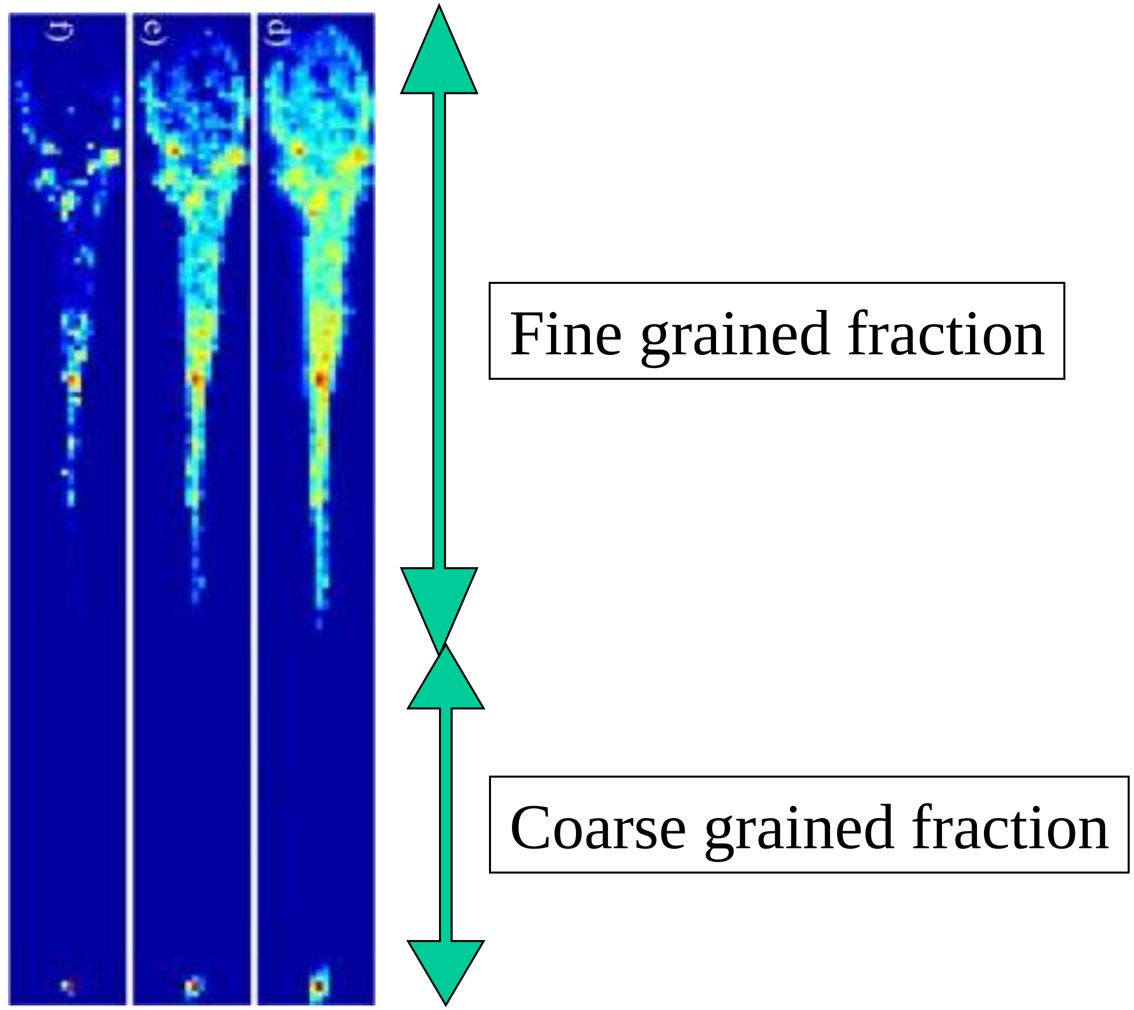


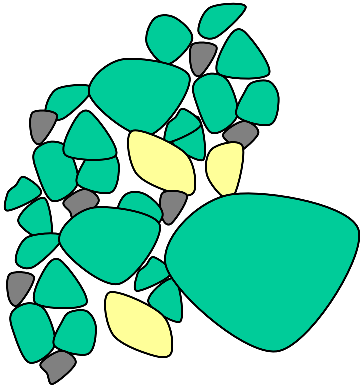
Nakamura et al. 2008



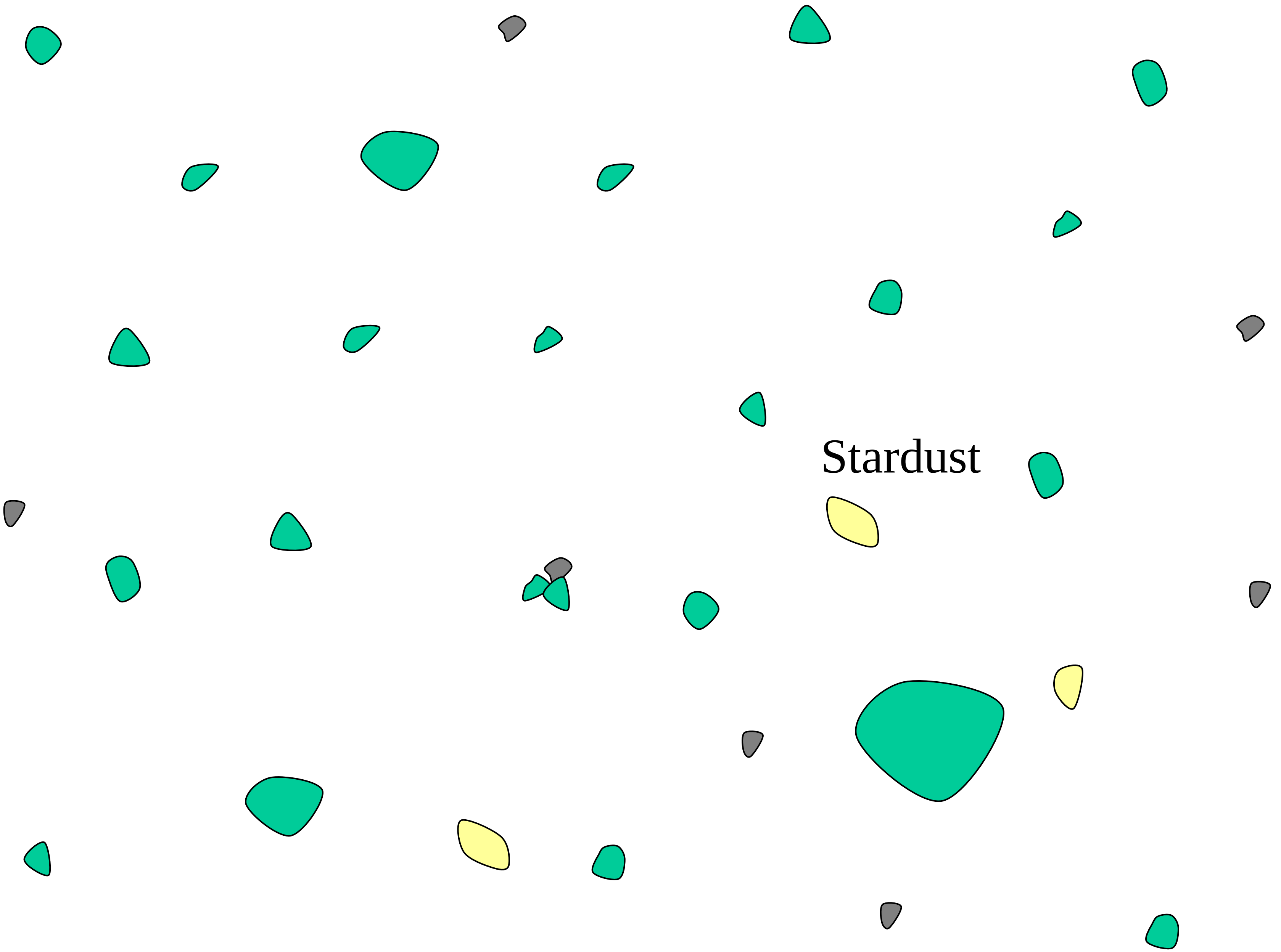


- Chondrule-like material

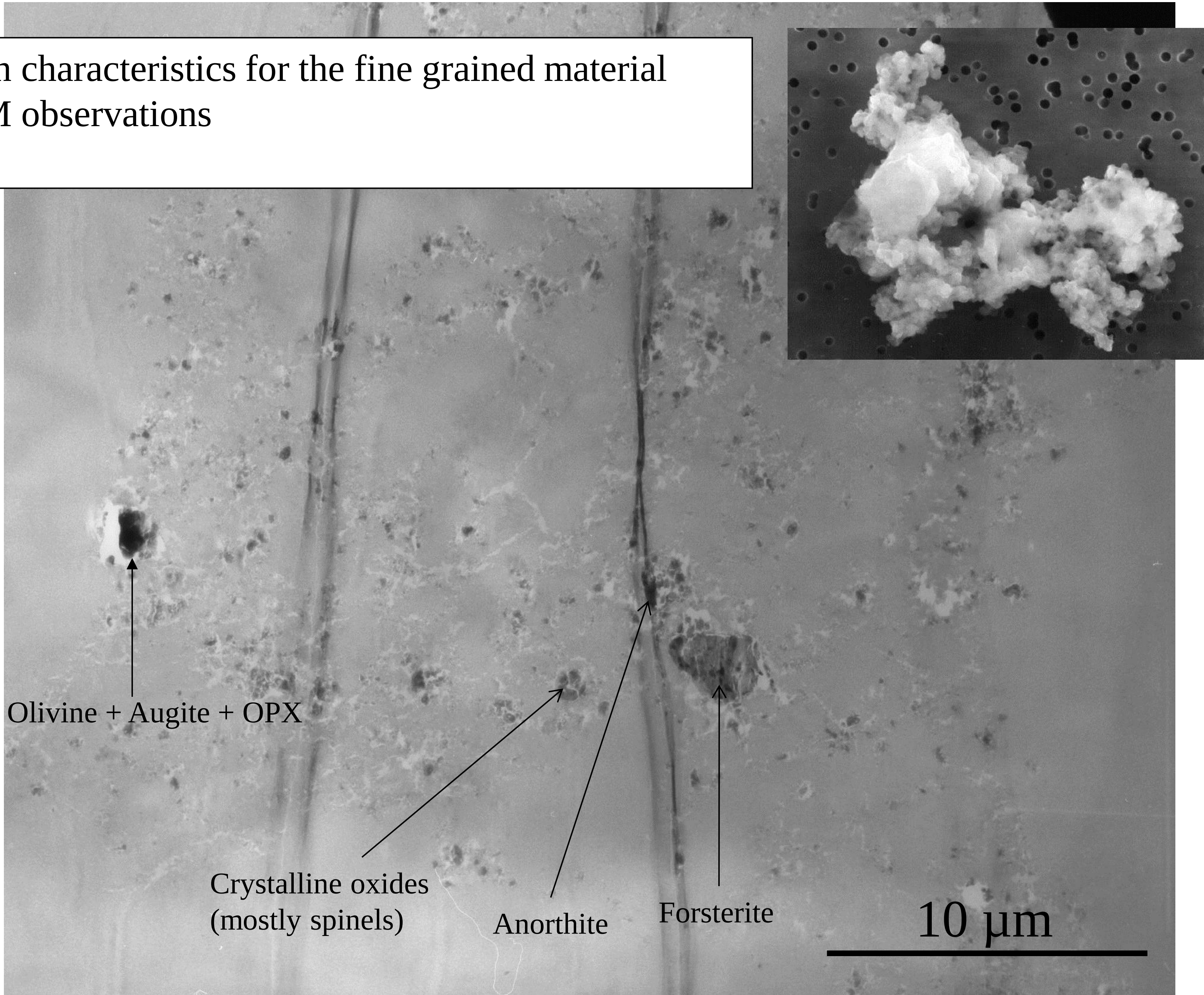

Fine grained fraction
Coarse grained fraction



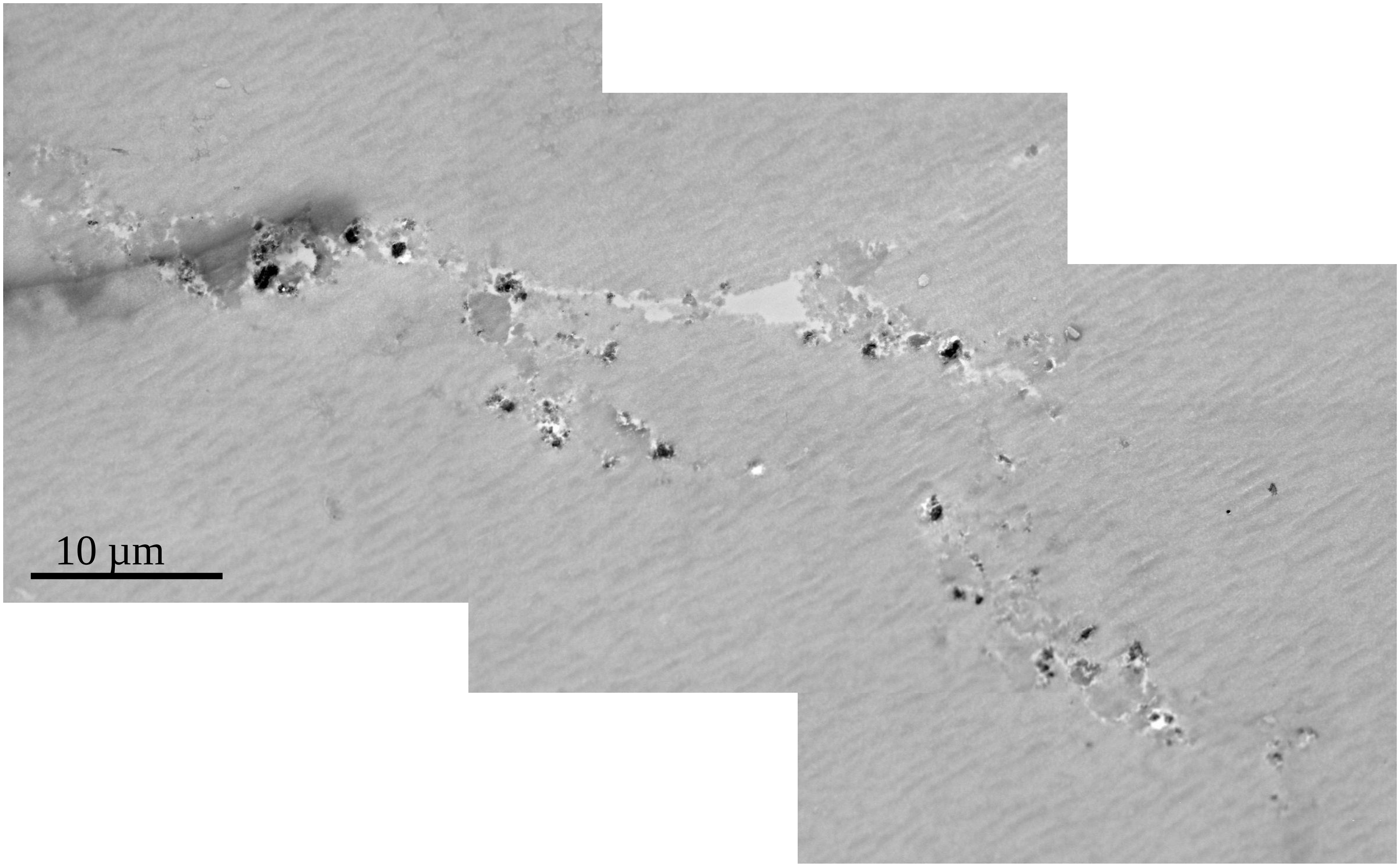
Wild 2

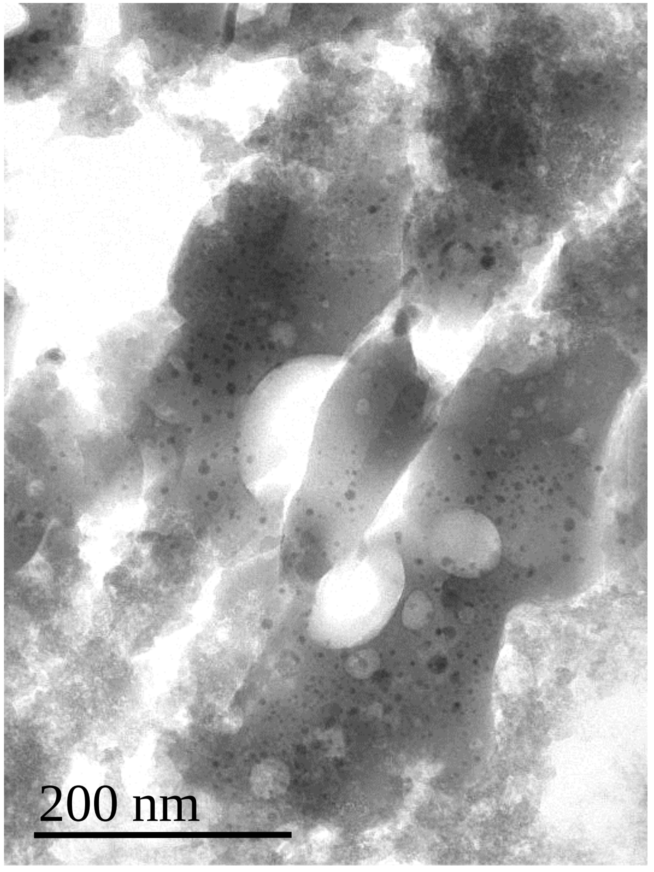

Stardust

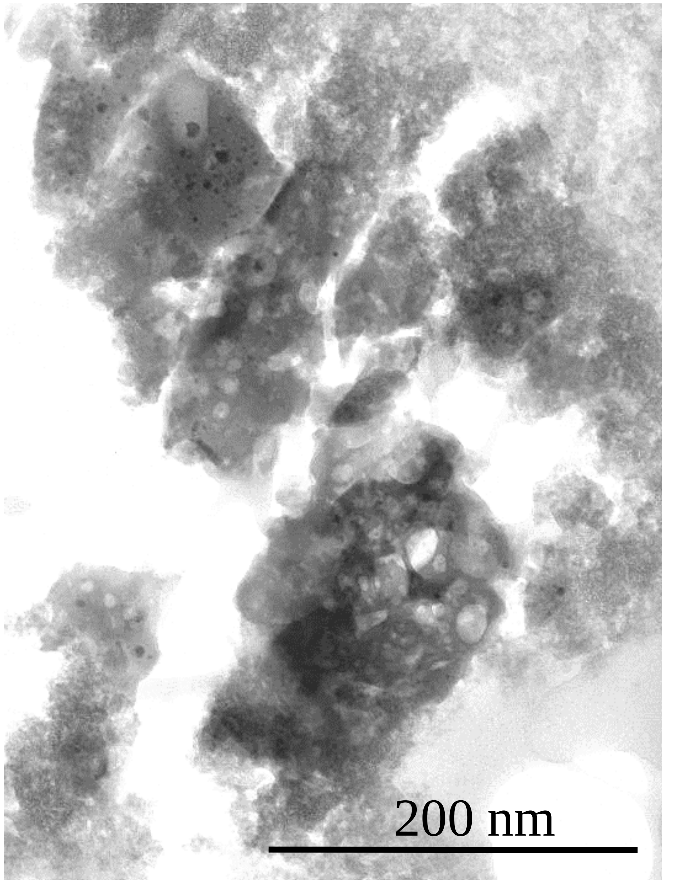
Main characteristics for the fine grained material
TEM observations



Micro-tracks in aerogel (somewhere in track 10)







The glass (melted material) is silica-rich

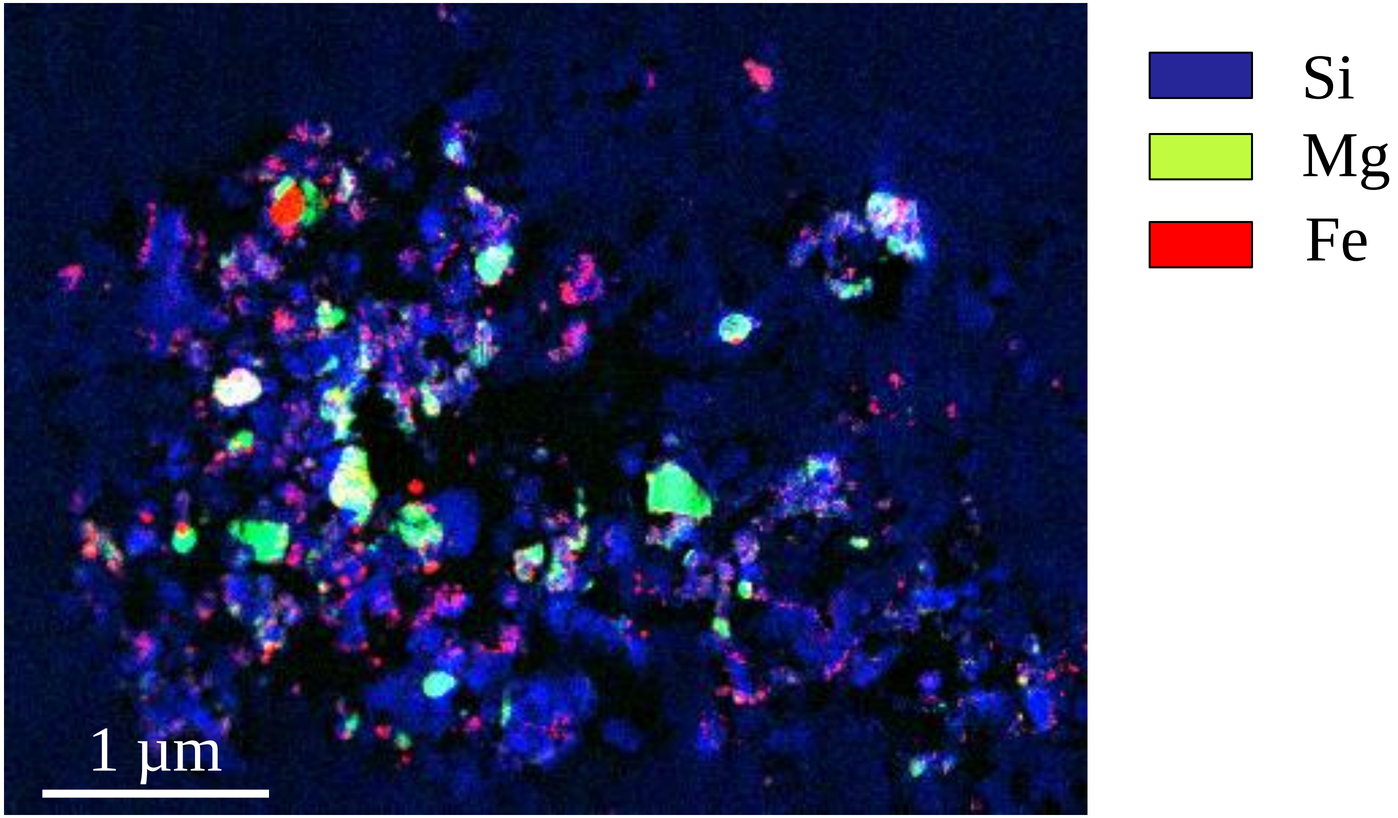
Fe, Mg, S: major elements from the comet
Si, O: major elements from the comet <u>and</u> aerogel

~ 90 % aerogel, ~ 10 % dust

Melting, mixing with melted aerogel and fast quenching

Element distribution in the glassy matrix

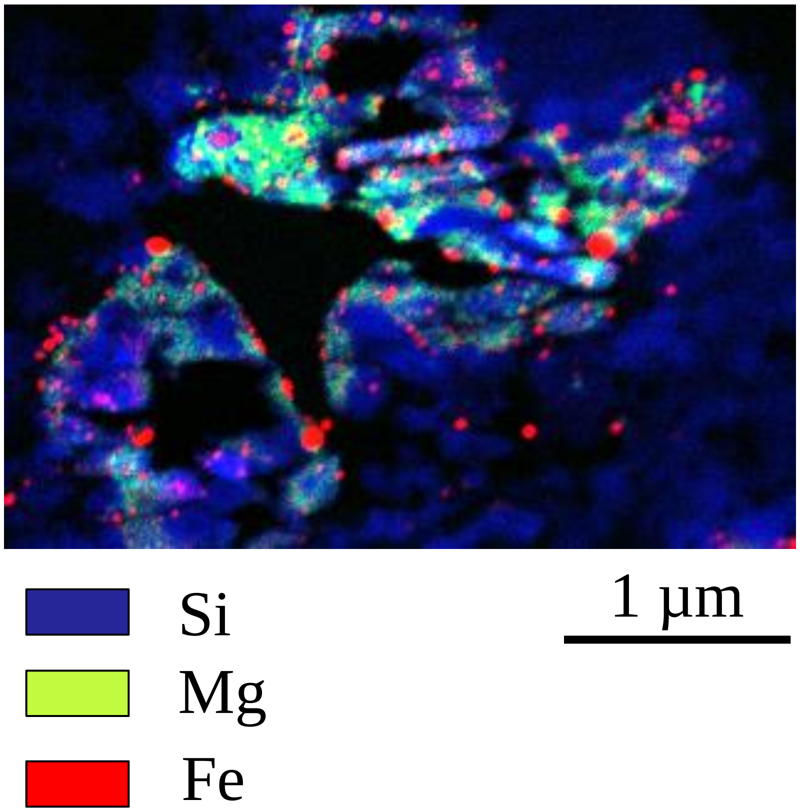
- X-ray intensity elemental distribution (EDS)

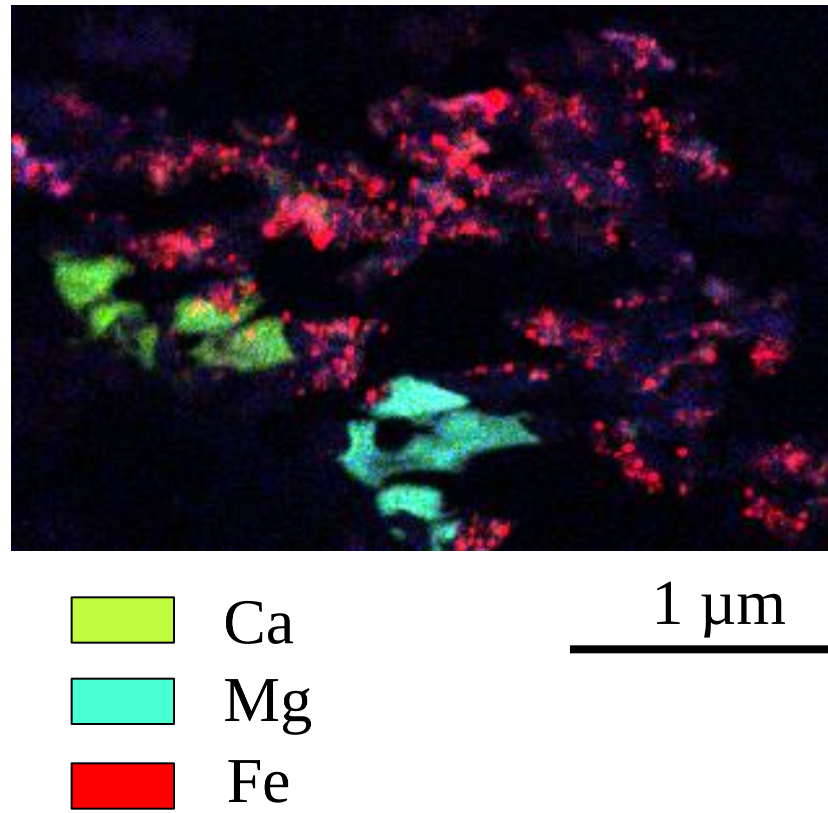


- Elements are not distributed homogeneously (incomplete mixing with aerogel) – ‘shadow’ grains

Element distribution in the glassy matrix

- X-ray intensity elemental distribution (EDS)





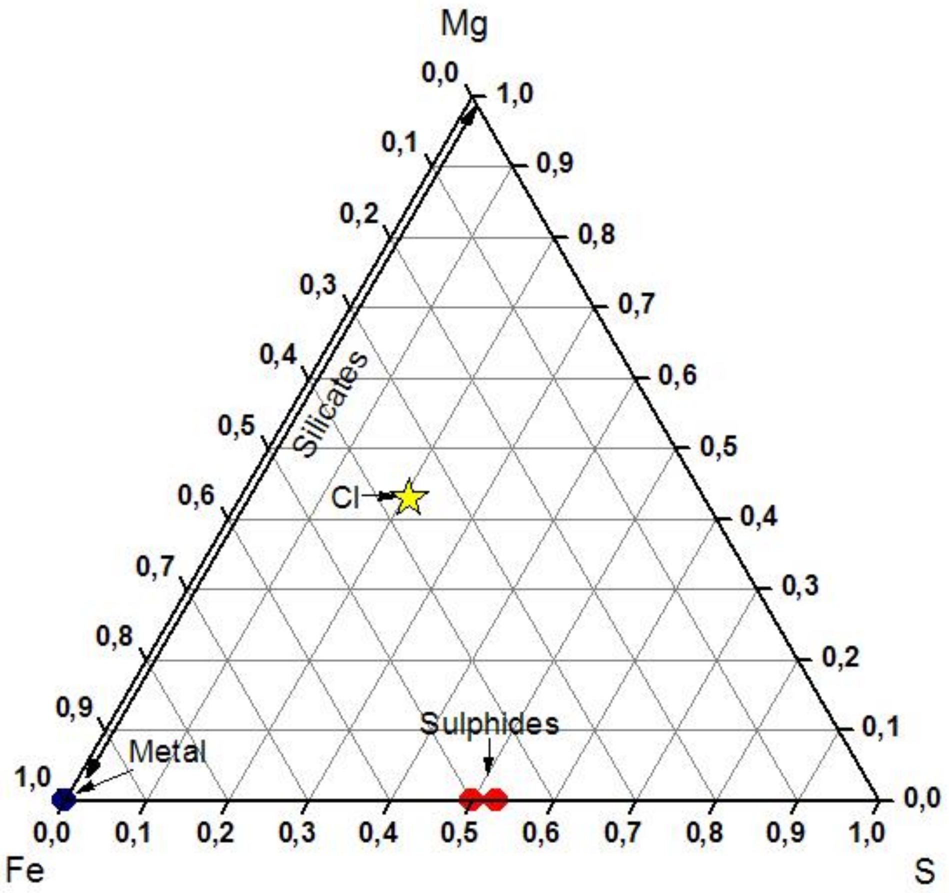
Composition of the samples: SiO_2 enriched (typically 90 %)

➢ A specific petrological groundwork: Fe-Mg-S ternary diagram

Mg: in silicates

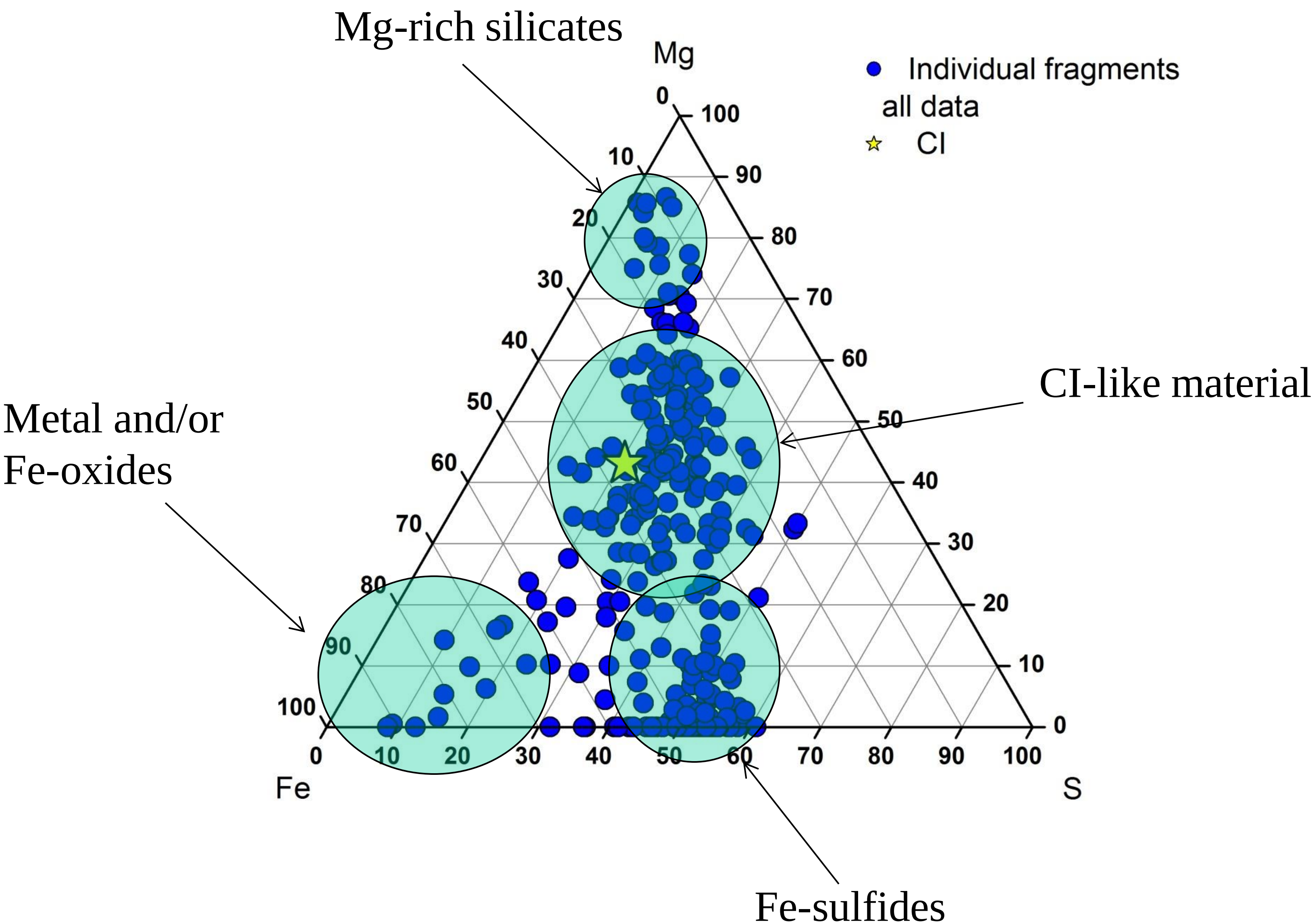
S : in sulfides

Fe : Silicates, metal and sulfides

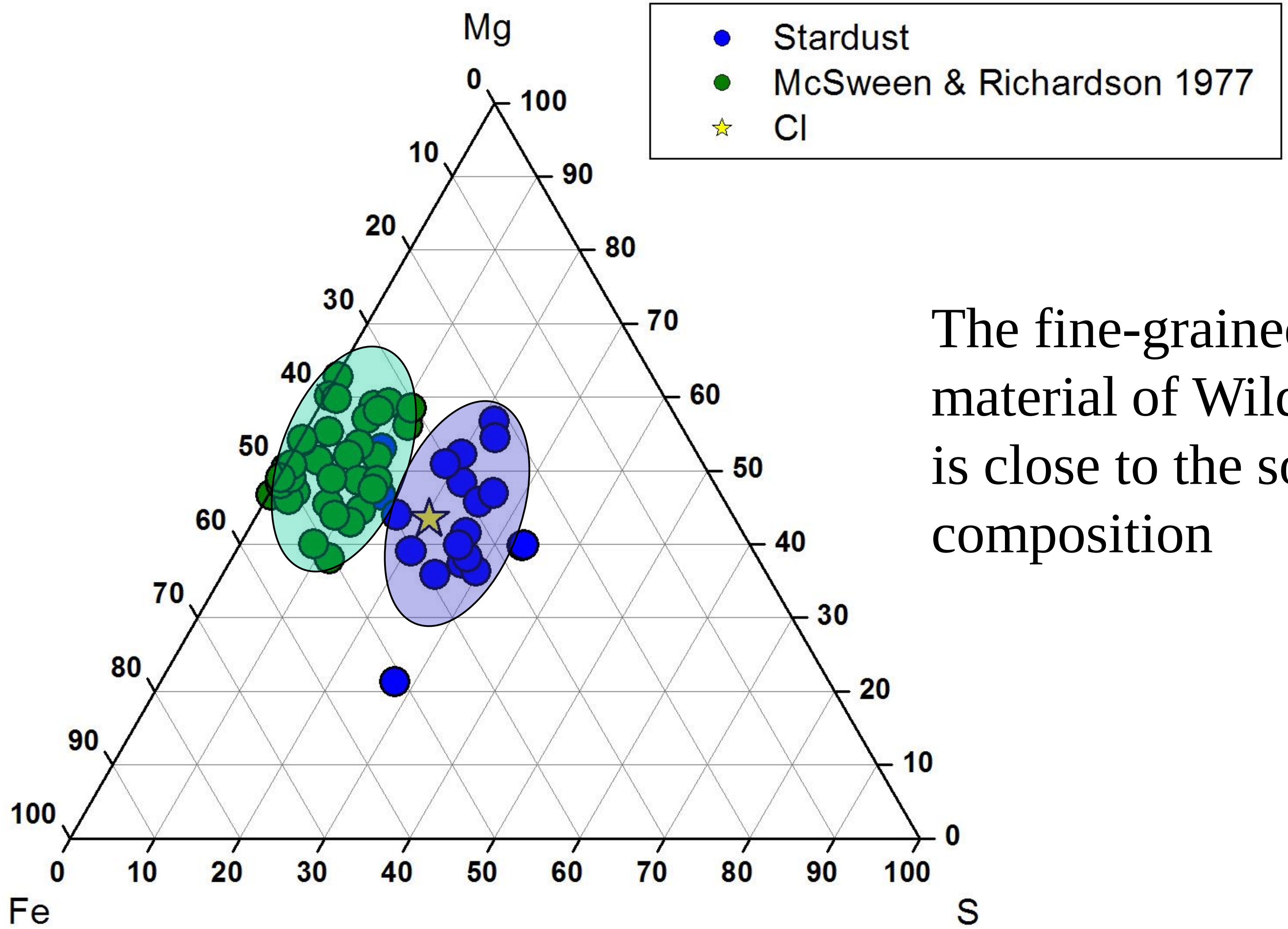


Leroux et al. 2009, GCA

Microanalysis of amorphous fragments in a TEM sample



Comparison with matrix in carbonaceous chondrites



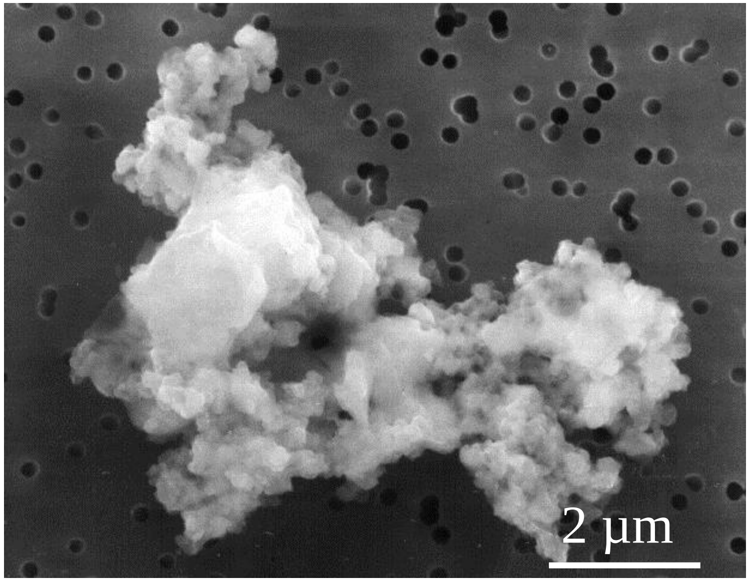
The fine-grained material of Wild 2 is close to the solar composition

Silicate mineralogy of Wild 2, summary

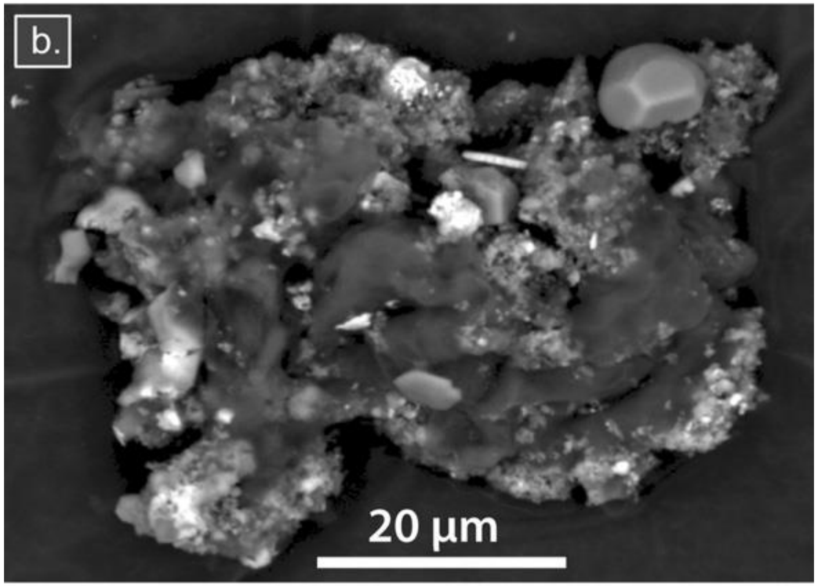
- Evidence for particles fragmentation, fine-scale dispersion, and deposition along the track walls: suggest the impact of fragile, fine-grained aggregates mixed with “large” crystalline nuggets.
- The coarse grains particles survived well, the mineralogy resembles to the one of chondritic meteorite.
- The fine grained material is thermally modified – strong impregnation by melted aerogel. The average composition is CI (primitive signature).

Part 2: Silicates in interplanetary dust particles (IDPs) and micrometeorites

- Focus on fine-grained objects



Chondritic-Porous IDPs



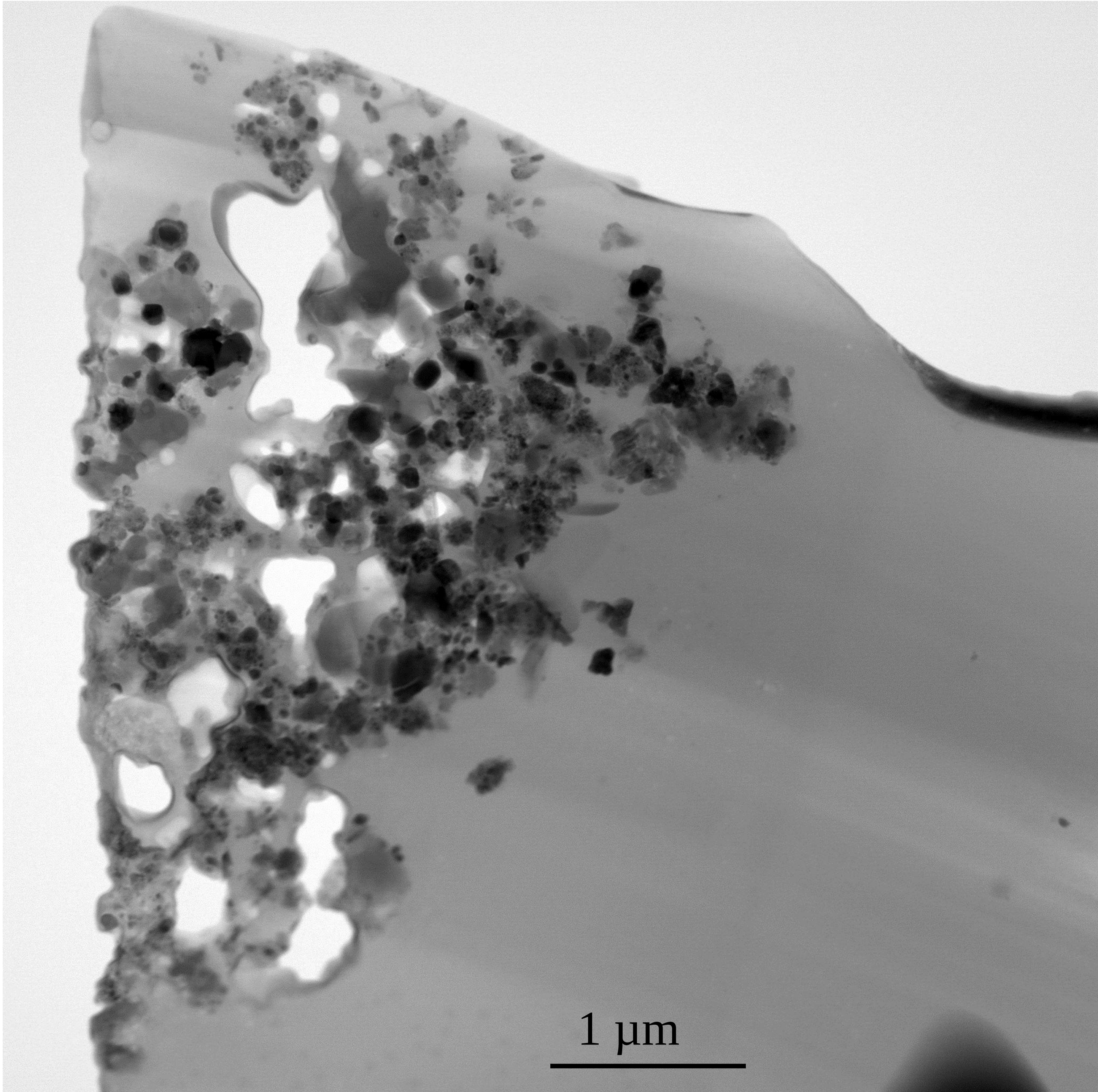
Fine-grained and friable micrometeorites and UCAMMs

Interplanetary dust particles (IDPs) and micrometeorites

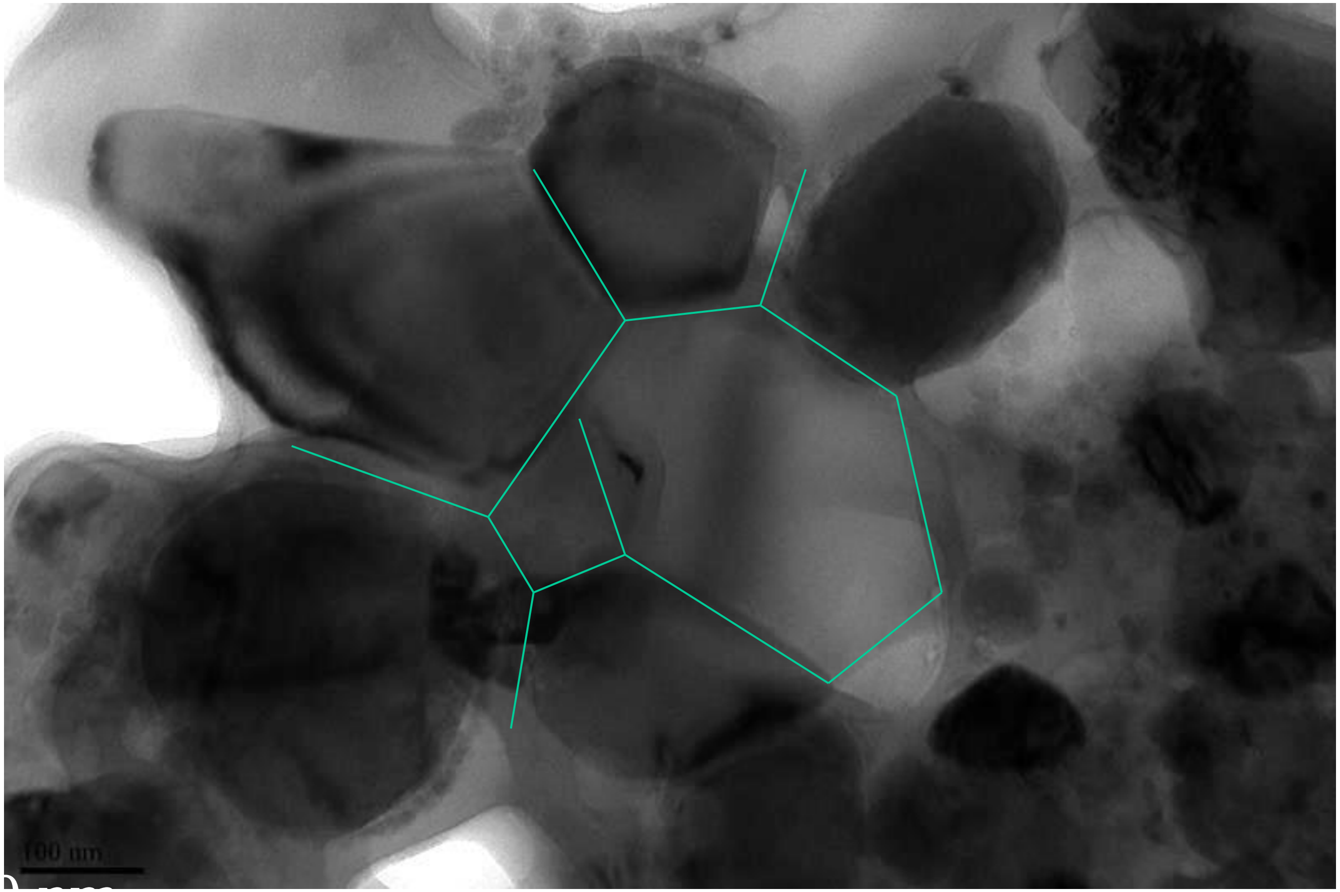
- Anhydrous and unequilibrated mineralogy
- Carbon-rich
- Volatil element rich
- Porous, fine-grained and friable

Cometary origin ?

Ultracarbonaceous micrometeorites (UCAMMs)

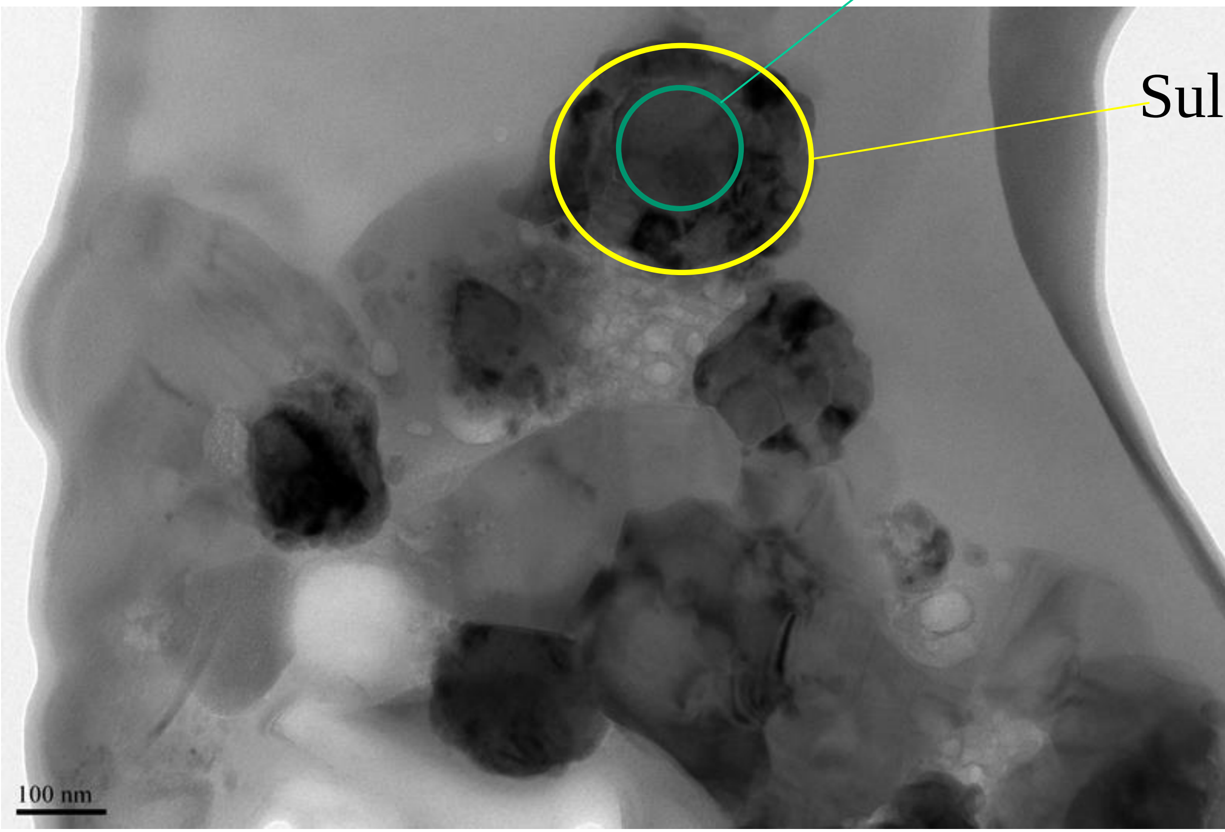


High temperature mineralogy



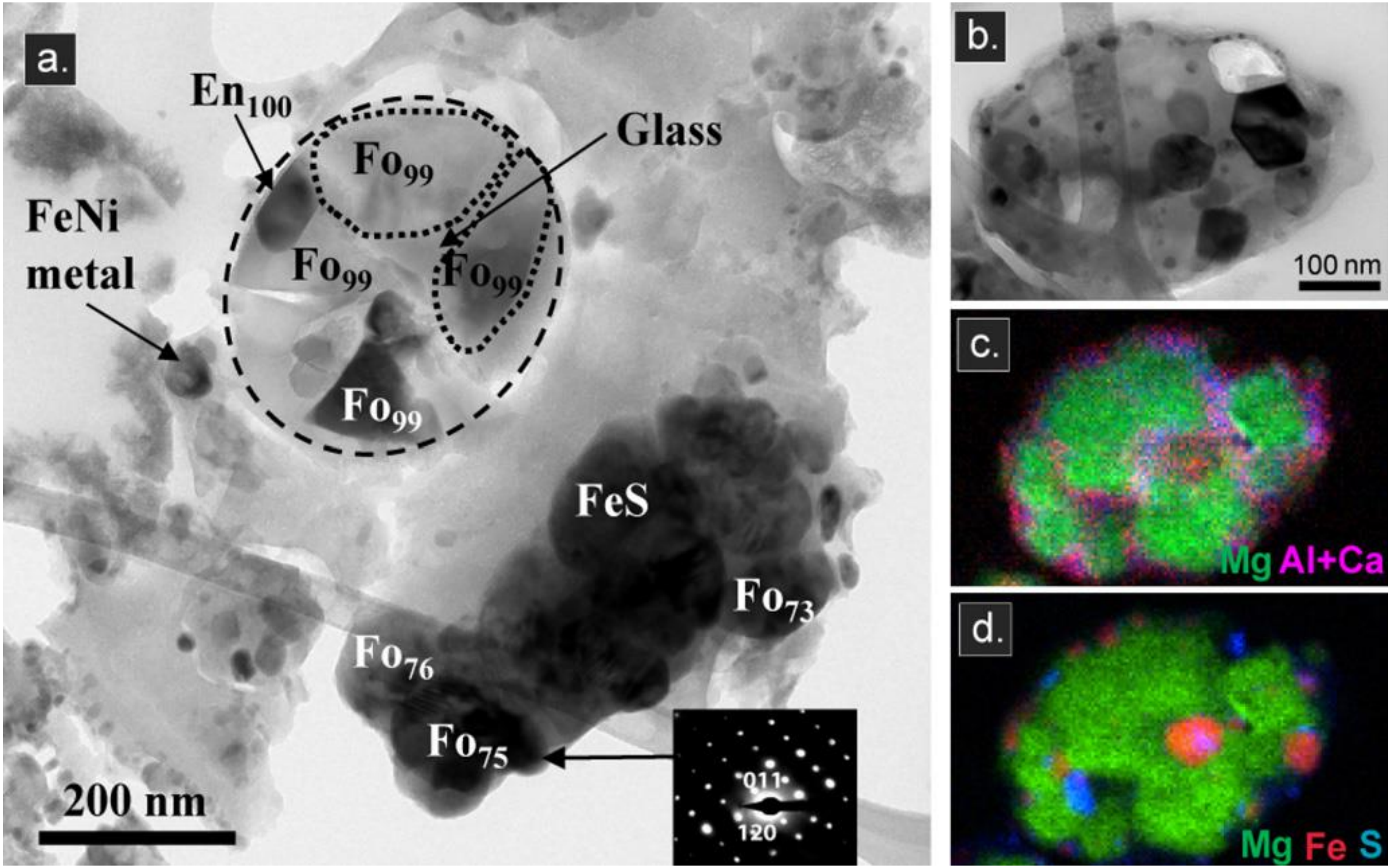
Olivine aggregate, equilibrated texture

High temperature mineralogy



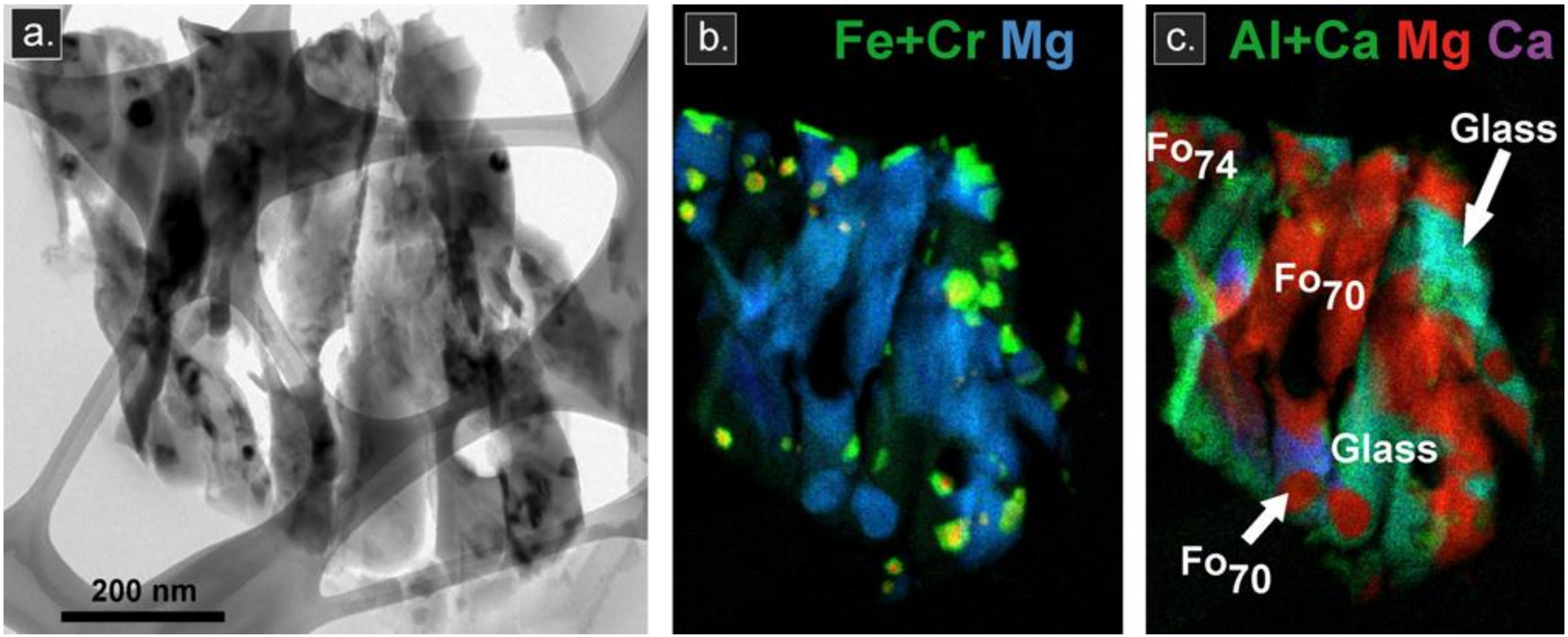
Crystalline grains (silicates, metal, sulfides, …)…

High temperature mineralogy



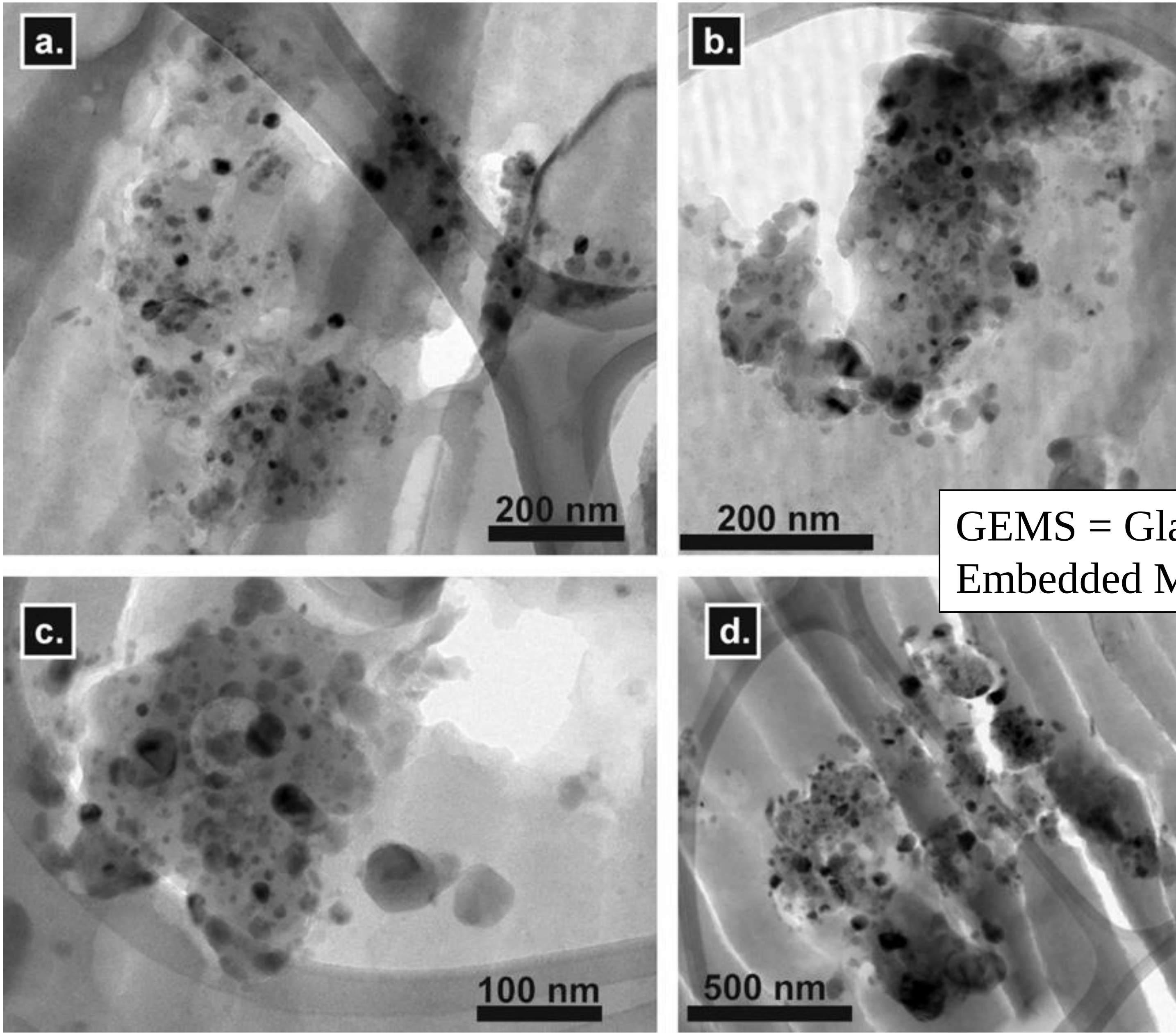
Dobrica et al. 2012

High temperature mineralogy



Dobrica et al. 2012

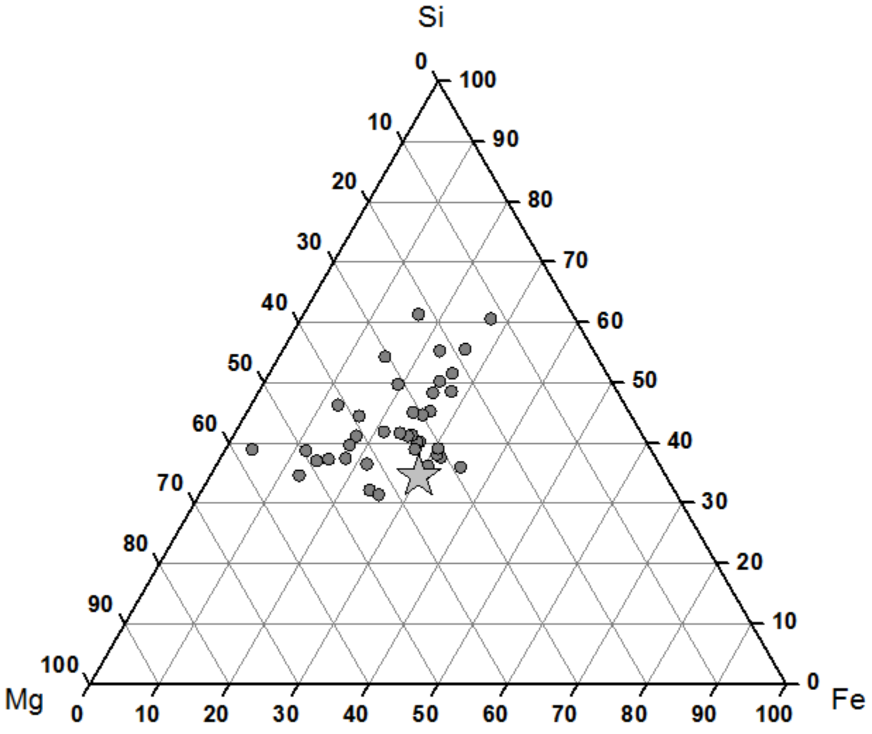
Low temperature mineralogy GEMS grains



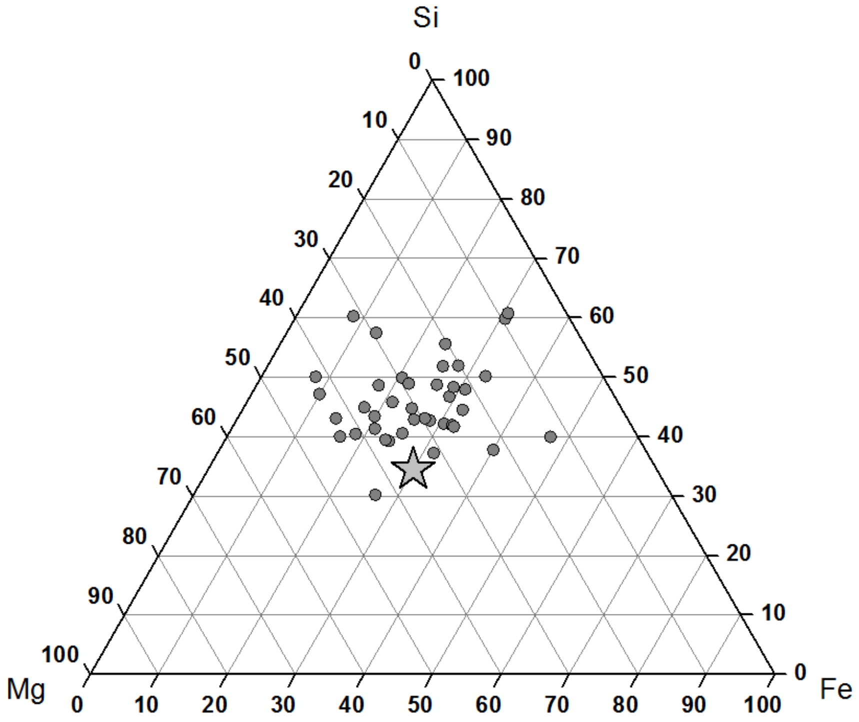
GEMS = Glass with Embedded Metal and Sulfides

Dobrica et al. 2012

Composition field of GEMS in UCAMMs



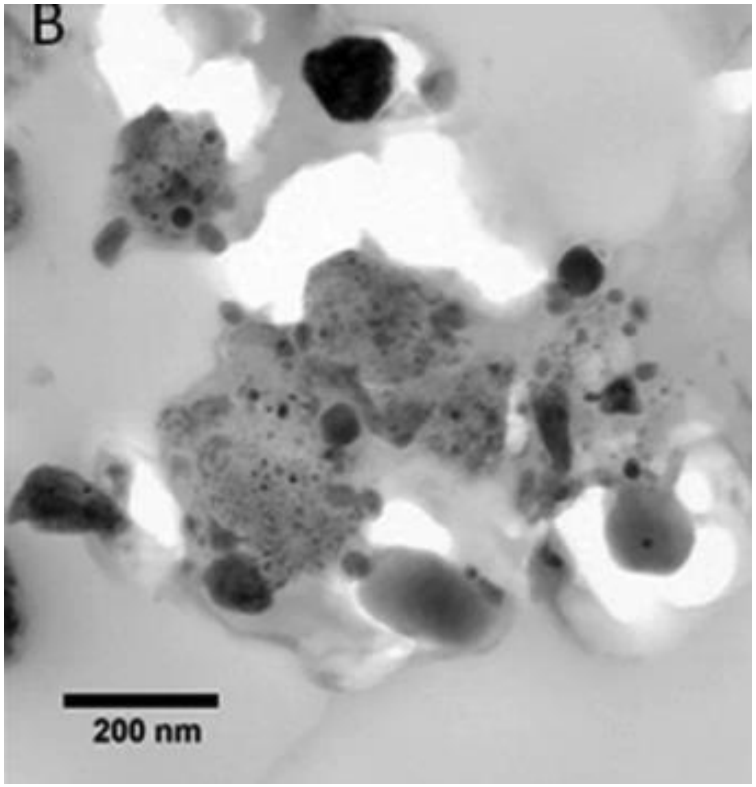
Dobrica et al 2012

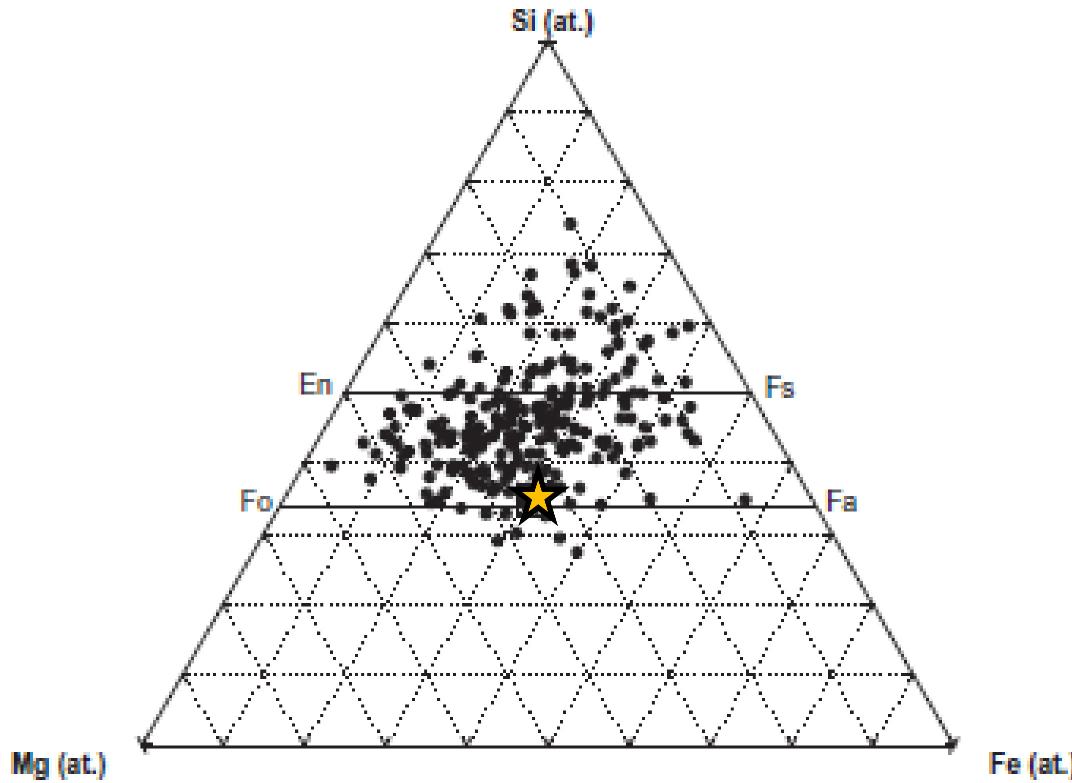


Recent study (unpublished)

GEMS in IPDs

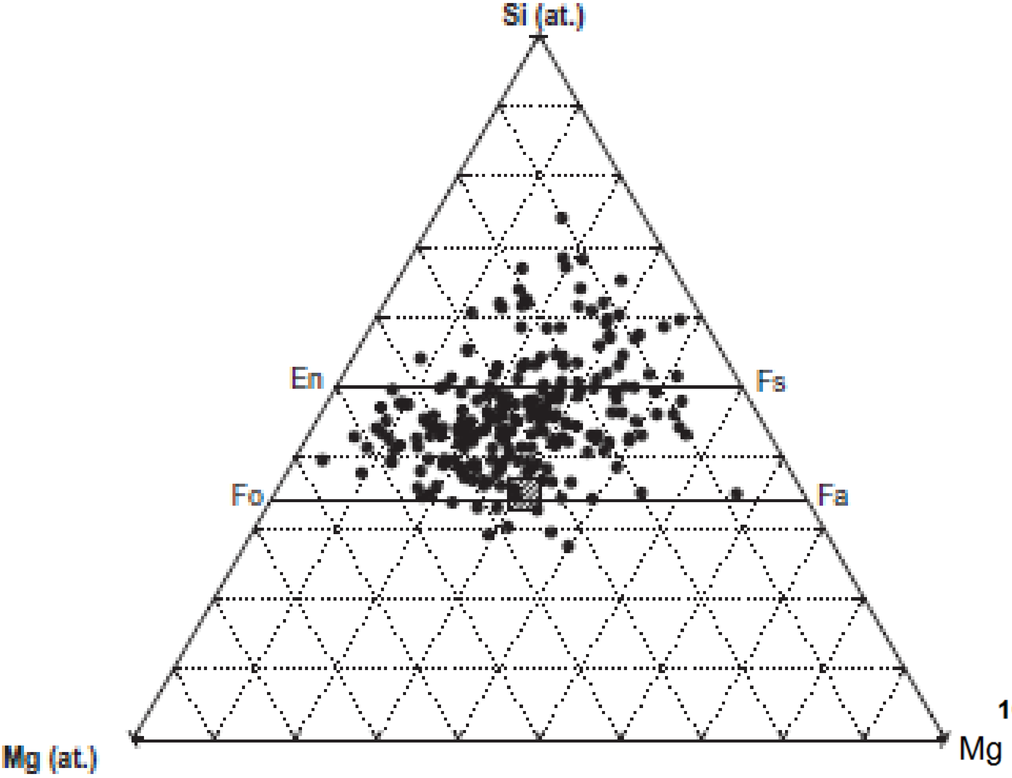
Bulk compositions of individual GEMS grains



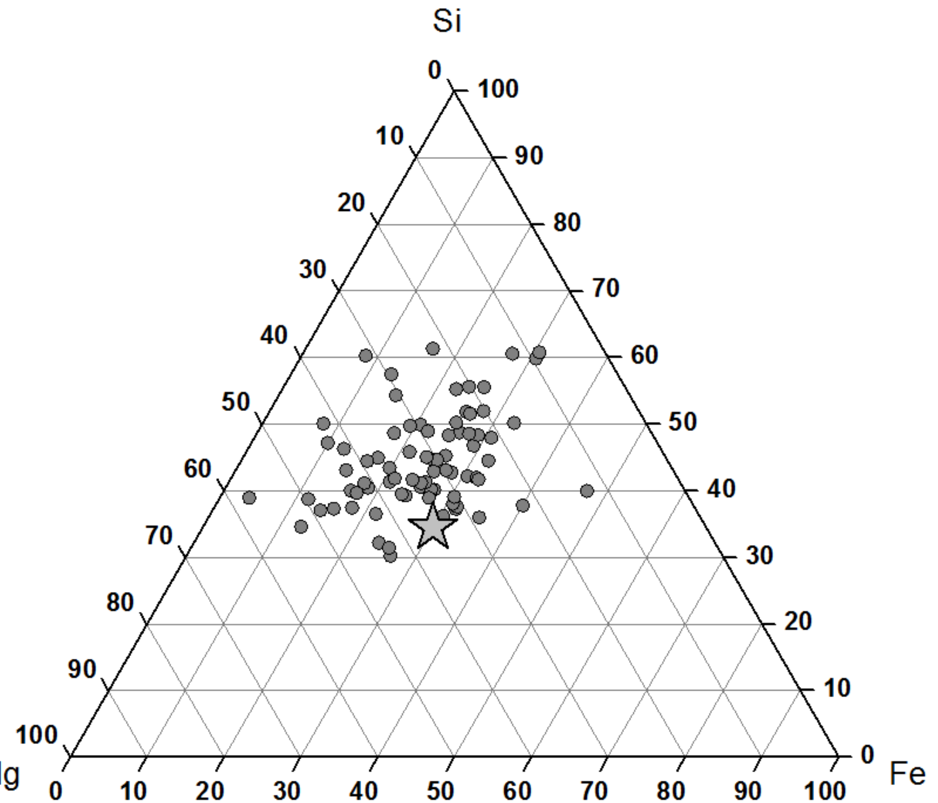


Keller and Messenger, 2011 GCA

Comparison of GEMS in IPDs and UCAMMs



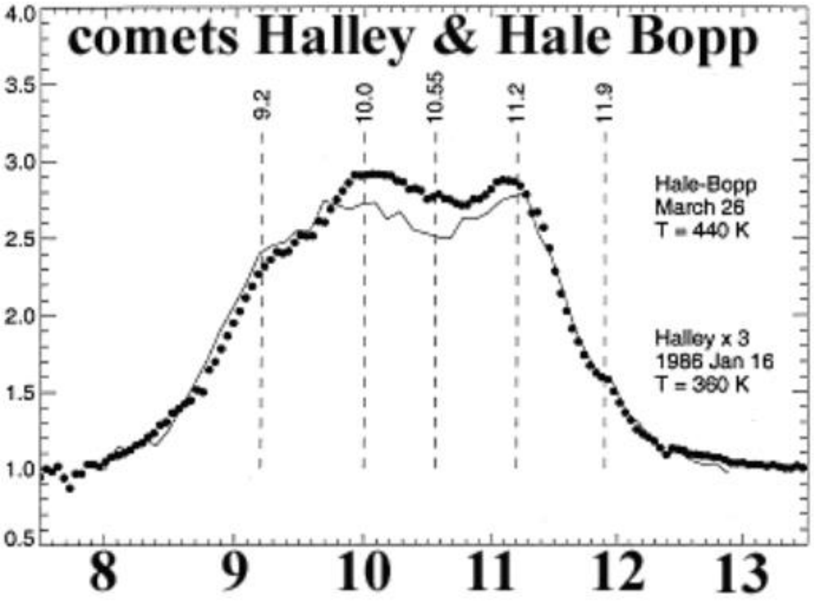
GEMS in IDPs



GEMS in UCAMMs

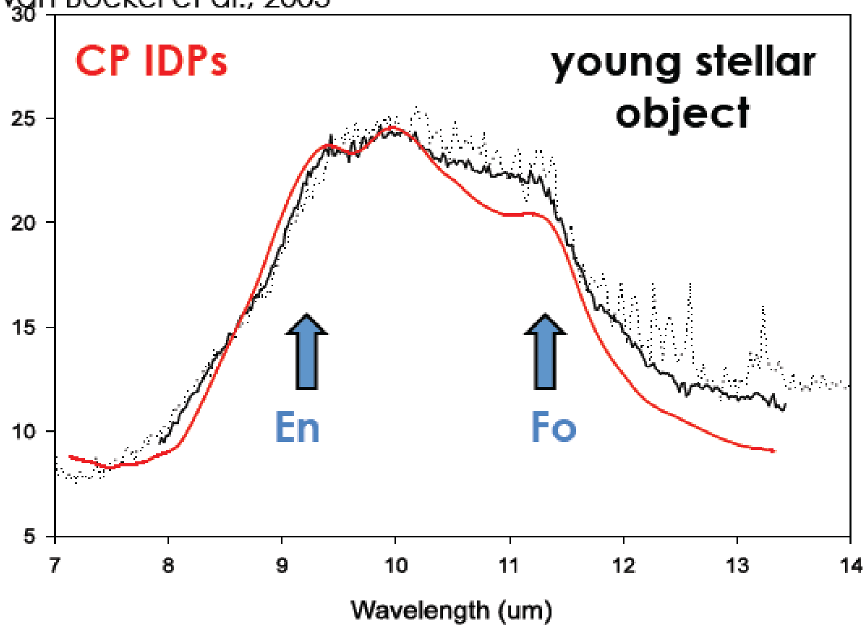
Keller and Messenger, 2011 GCA

Infrared signature of GEMS

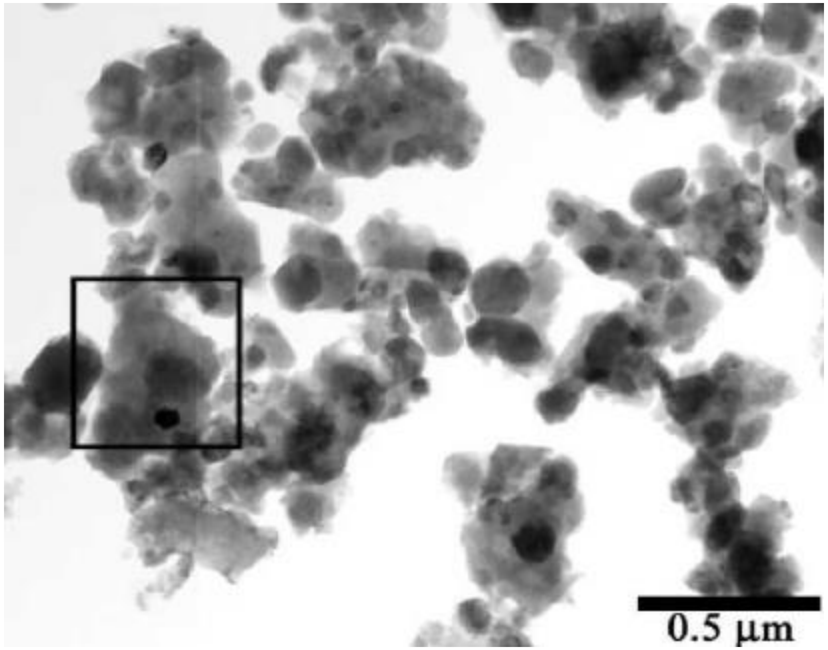


Hanner et al, 1999

Van Boekel et al., 2003

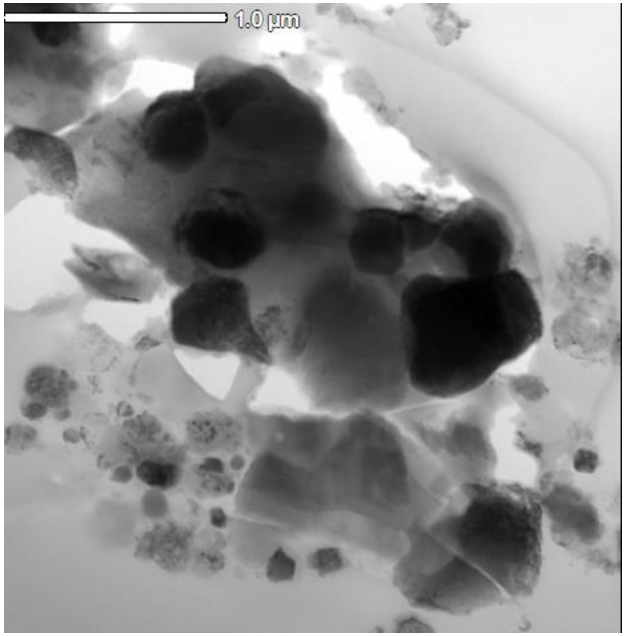


Equilibrated Aggregate IDPs

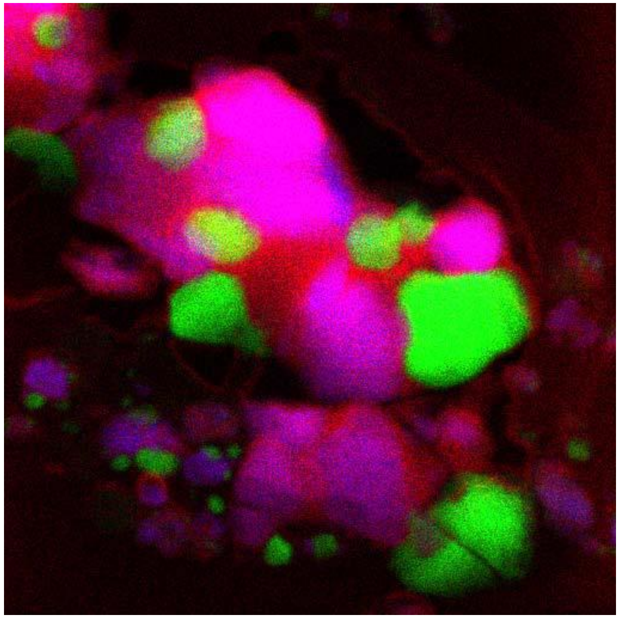


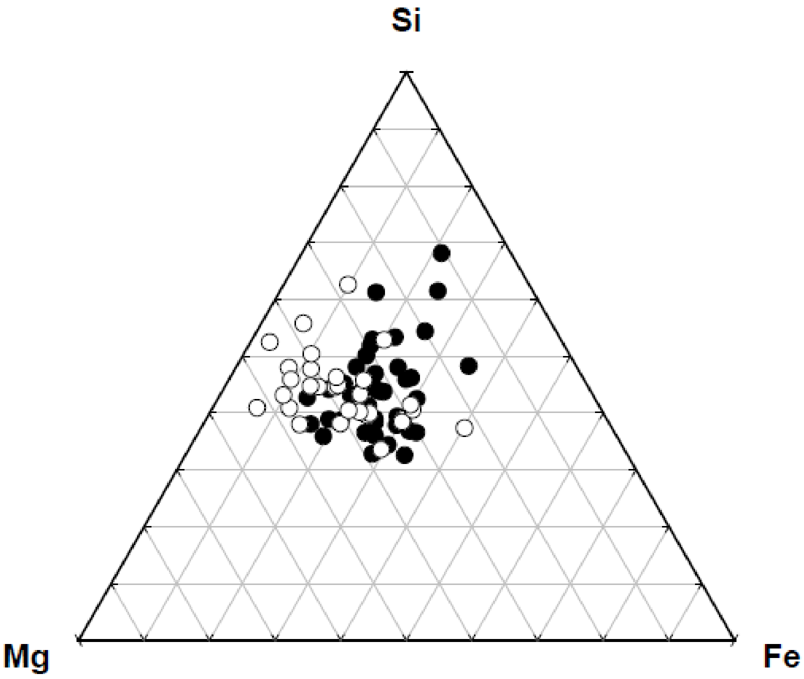
TEM image of a equilibrated aggregate IDP containing a presolar grain

Nguyen et al. 2010



TEM image of a equilibrated aggregate in an IDP ; X-ray map of the same area where the magenta colored grains are enstatite ($MgSiO_3$), while the green grains are pyrrhotite ($Fe_{1-x}S$). The red areas correspond to the interstitial SiO_2-rich mesostasis.

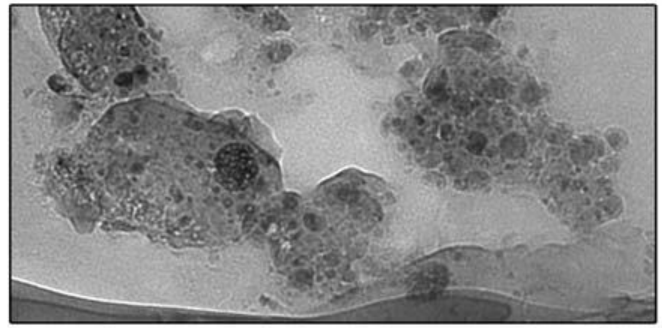




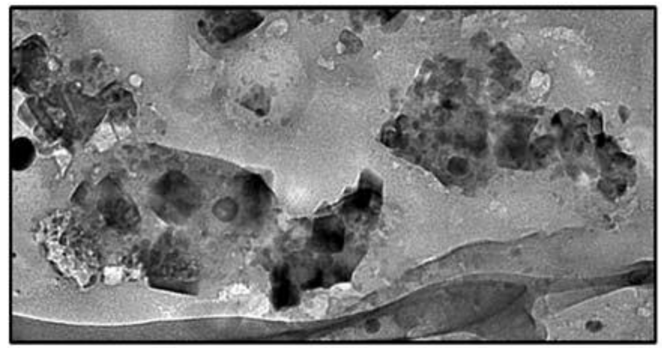
Mg-Fe-Si ternary plot (at%) showing the compositions of equilibrated aggregates (open circles) compared to GEMS grains in the same particles (filled circles).

Keller and Messenger, 2009

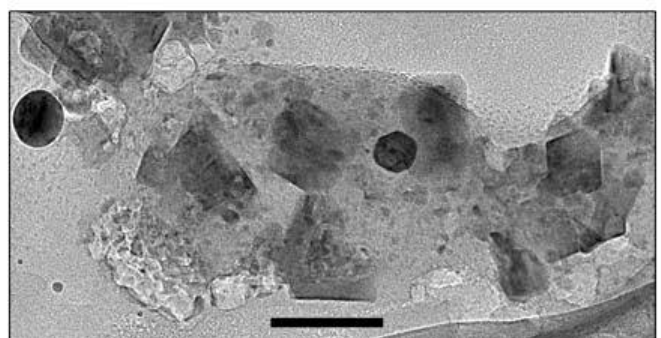
Cooked GEMS



Initial - U217B19 GEMS13



After heating to 970K



Enlargemen of above   bar = 100nm

Brownlee et al, 2005

Summary

- GEMS grains are probably the building blocks of the object growing in the protoplanetary disk

- But the origin of GEMS is not fully understood (direct interstellar grains or late-stage nonequilibrium nebular condensates)

- GEMS grains are more or less modified by thermal annealing at subsolidus temperatures. There is a continuum from porous GEMS to equilibrated (crystalline) aggregates

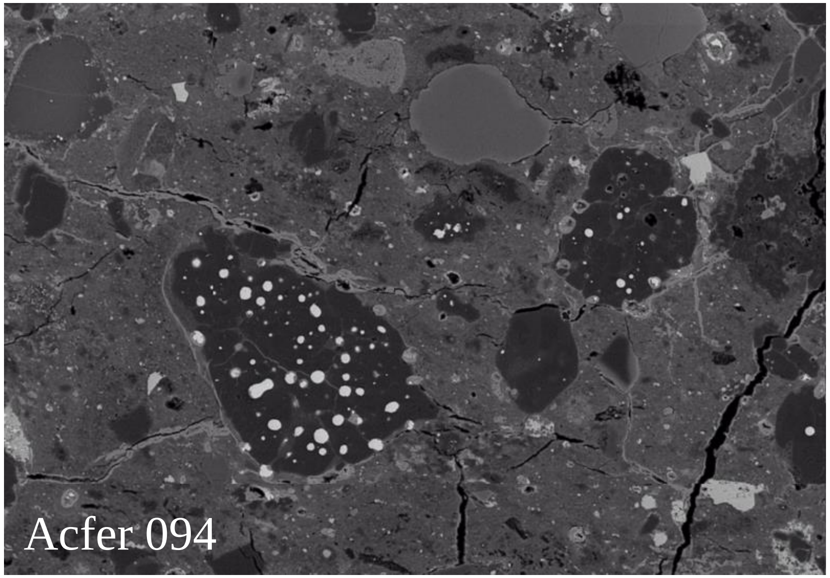
- IDPs and friable micrometeorites contain a mixture of high temperature minerals and low temperature minerals : a proof for radial mixing ?

Part 3: Silicates in fine-grained matrix of primitive chondrites

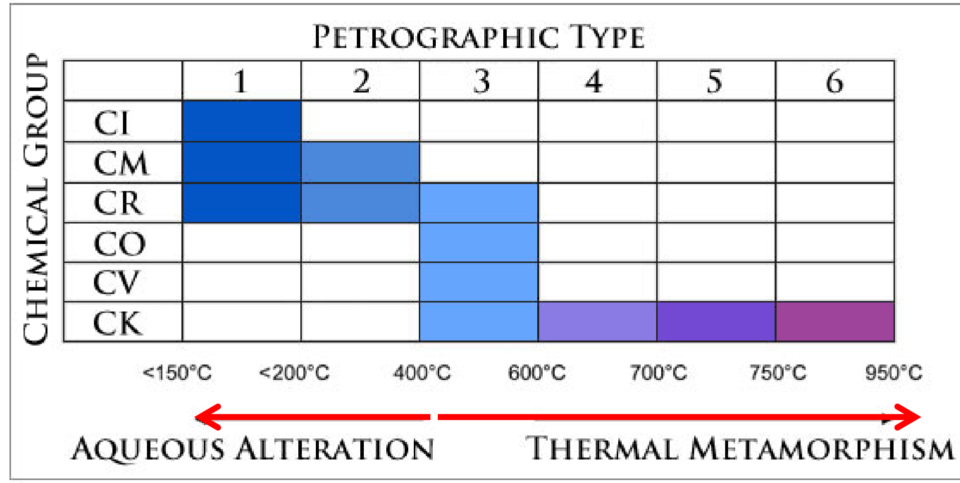
The most primitive meteorites are constituted by millimeter-size chondrules embedded in a matrix of fine-grained material

https://dslauretta.com/2014/11/20/the-science-of-bennus-journey/

The fine-grained matrix of carbonaceous chondrites



Classification of Cabonaceous Chondrites



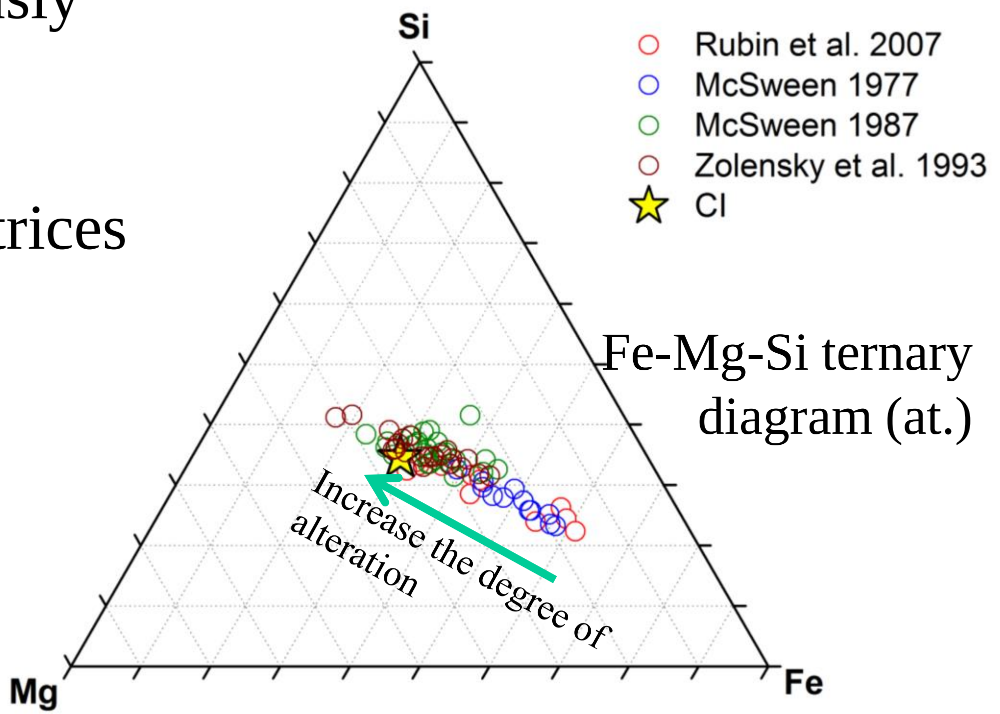
(Adapted from Sephton, M. A. (2002) *Nat. Prod. Rep.*, v. 19, p. 292-311. doi: 10.1039/b103775g)

CM chondrites:

- Most CM are highly aqueously altered chondrites
- Fine-grained matrices are dominated by phyllosilicates

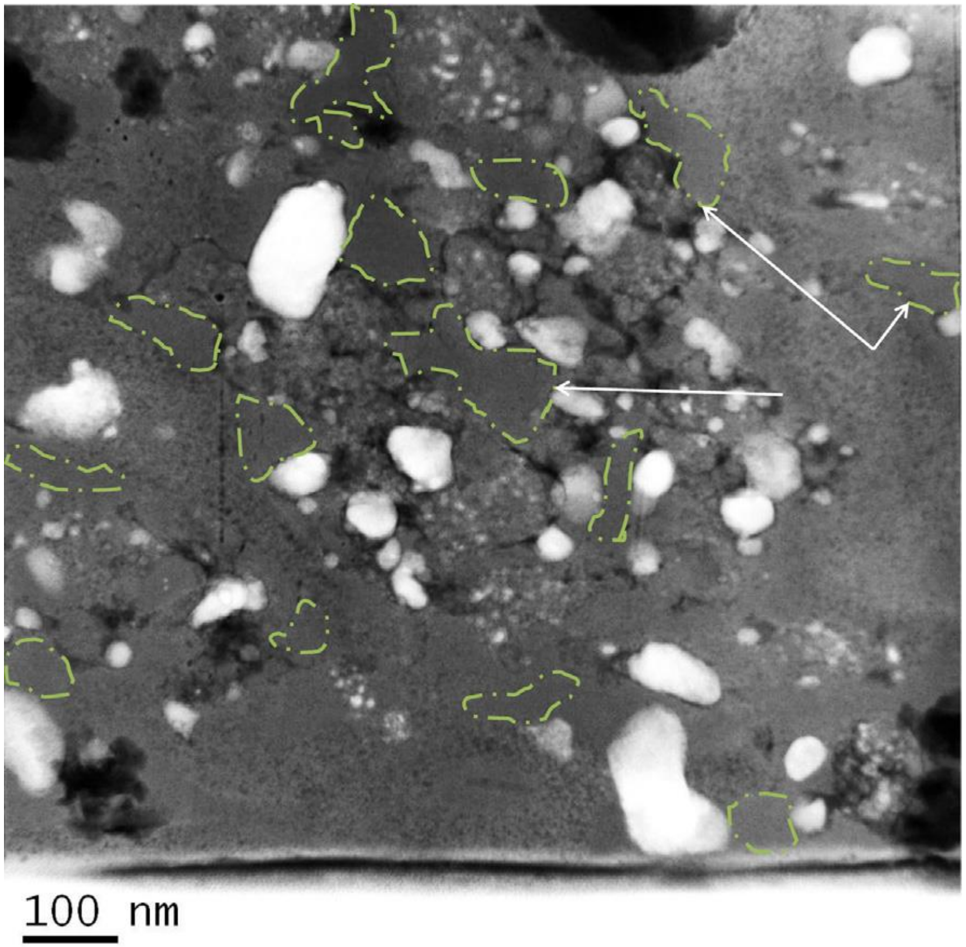
Mineralogy and compositions of matrices in CM

- Most CM are highly aqueously altered
- Silicates in fine-grained matrices are transformed into phyllosilicates
- Composition of matrices are roughly distributed along a line (from CI to the Fe endmember)



Fe-Mg-Si ternary diagram (at.)

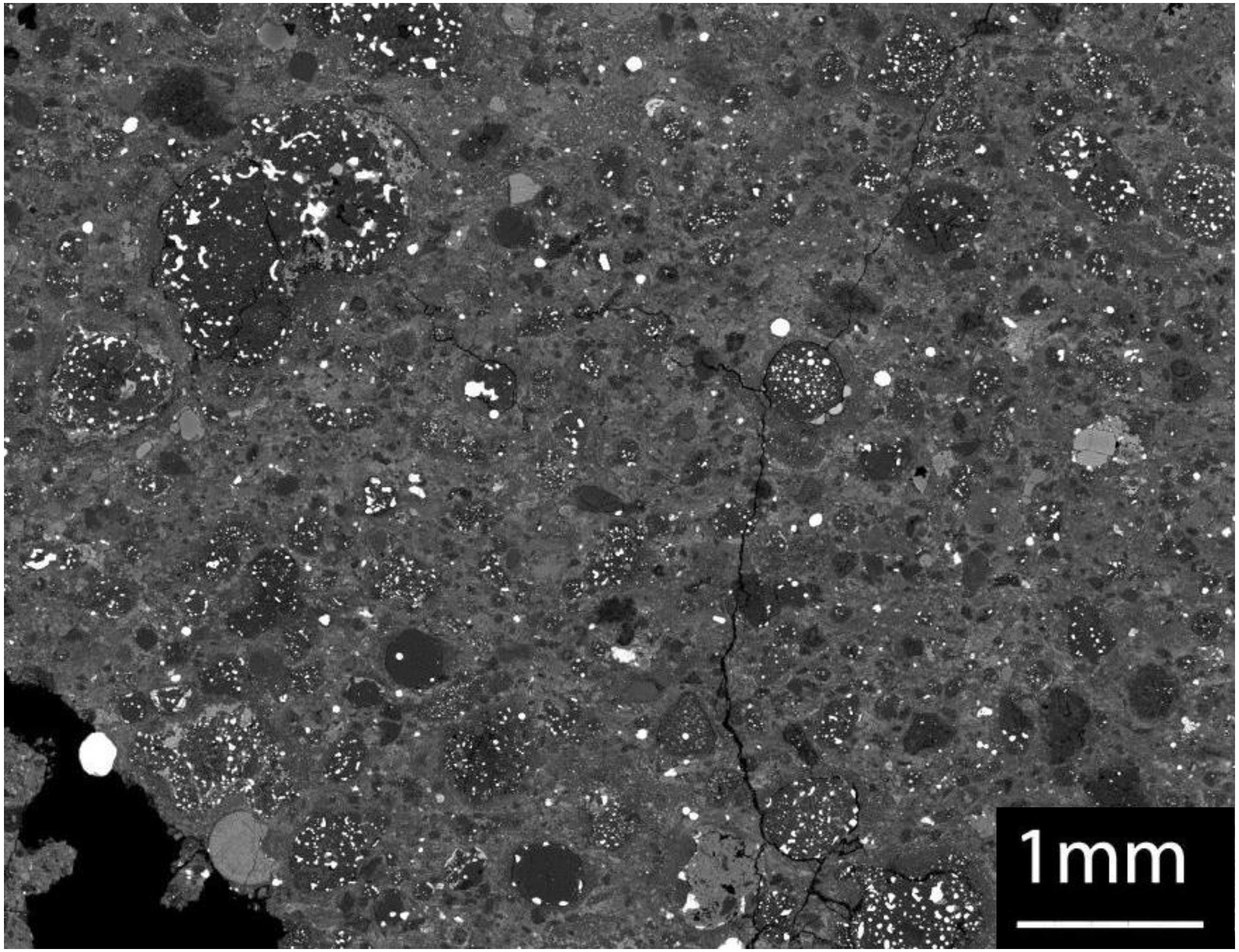
Fine-grained silicates in the matrix of primitive chondrites



Dark-field STEM image showing the textural differences between compact amorphous silicate (dashed lines) and finer grain sized, porous nanophyllosilicate (most of the other areas of the image). Bright areas are FeNi – sulfides. Dark areas are organic matter particles, which are preferentially associated with phyllosilicates.

Le Guillou and Brearley, 2014

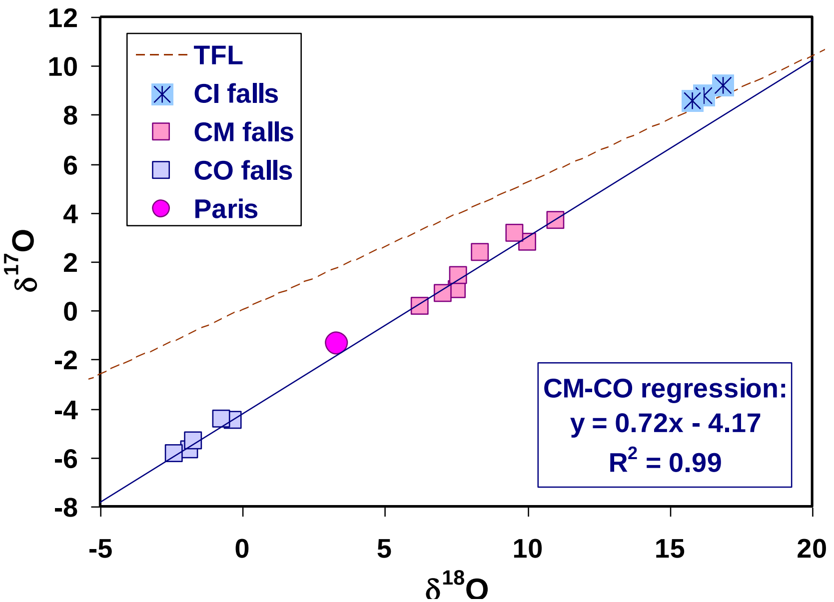
- Study of a less altered CM chondrite: Paris

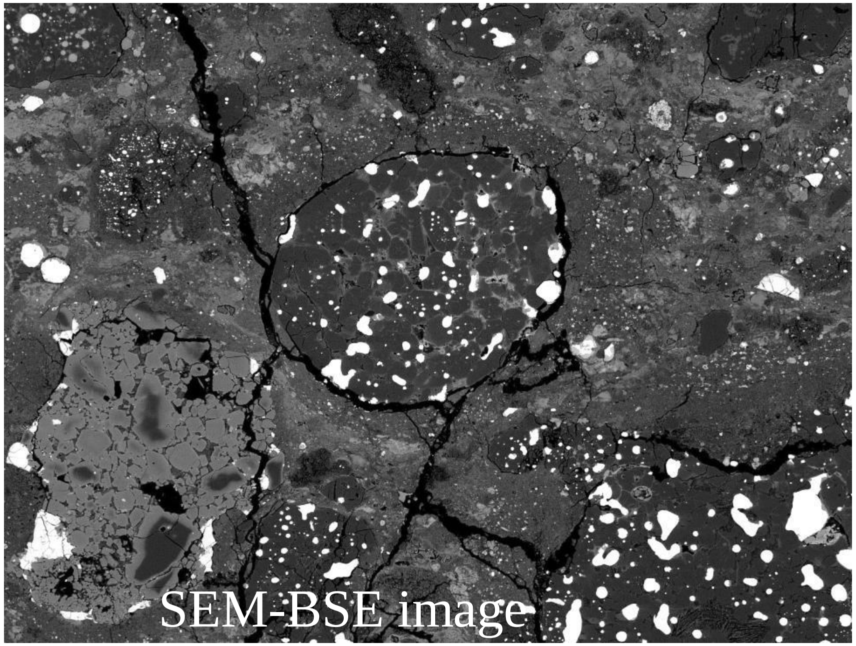


SEM image of the Paris carbonaceous chondrite

Paris : a less altered CM chondrite

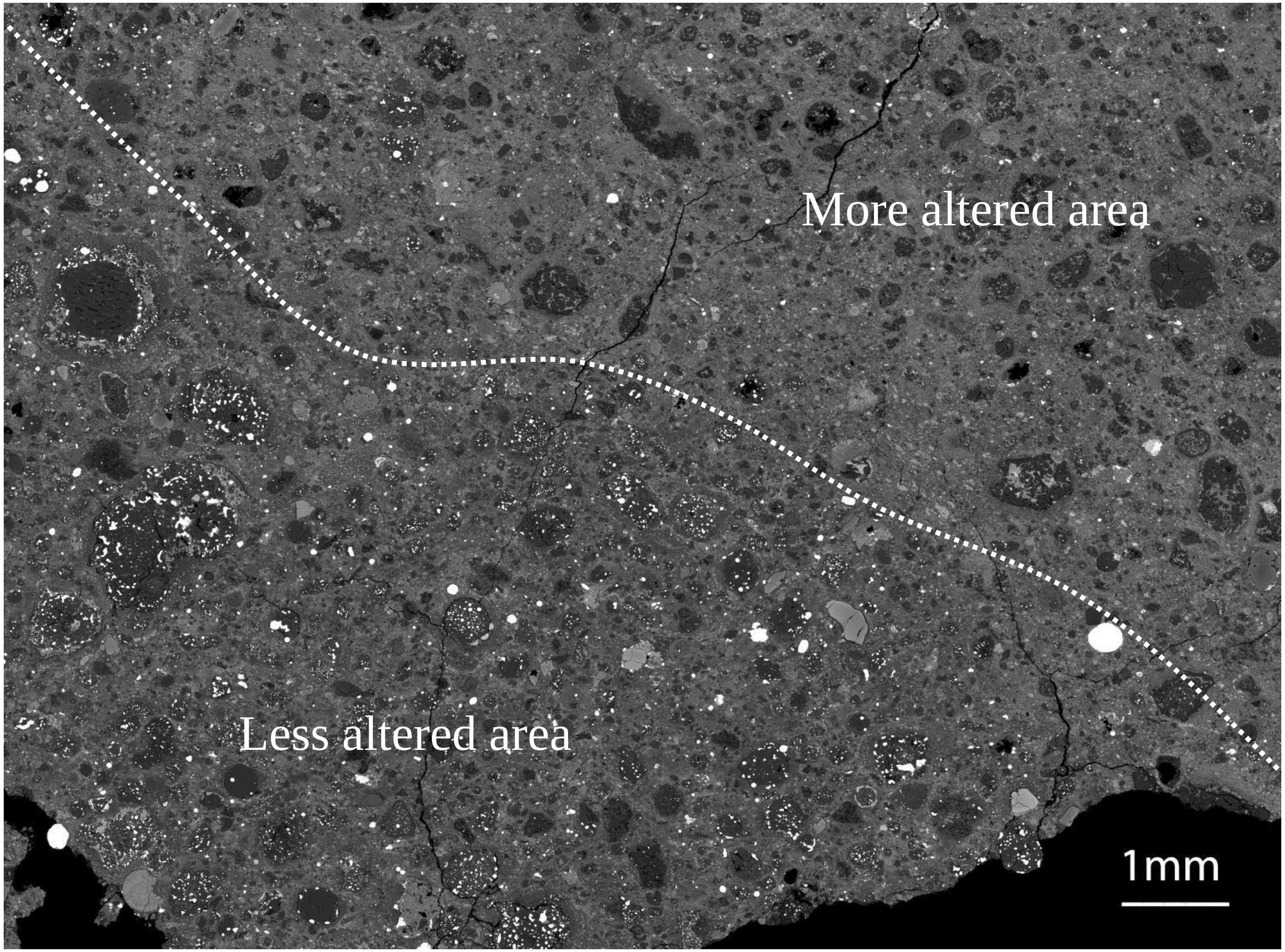
- O isotope mixing line passes through CM2 and CO3 falls
- Abundant metal (metal alteration stage 1)
- No signs of diffusion in chondrule silicates due to metamorphism





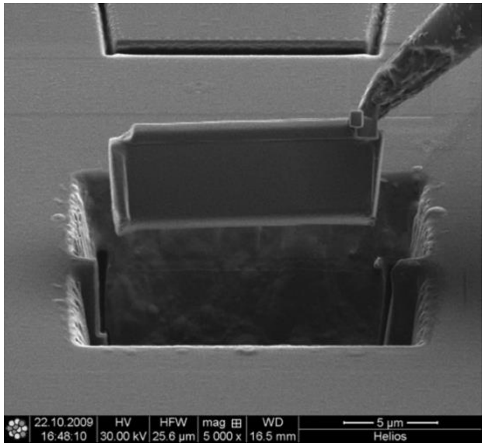
Data from Hewins et al, 2014

Paris : a less altered CM chondrite

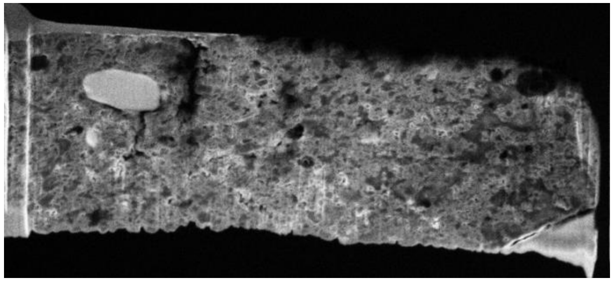


SEM - BSE image of a section of the Paris CM chondrite

➢ Extraction by FIB of TEM sections from altered areas to less altered areas



➢ Analytical transmission electron microscopy (TEM) study

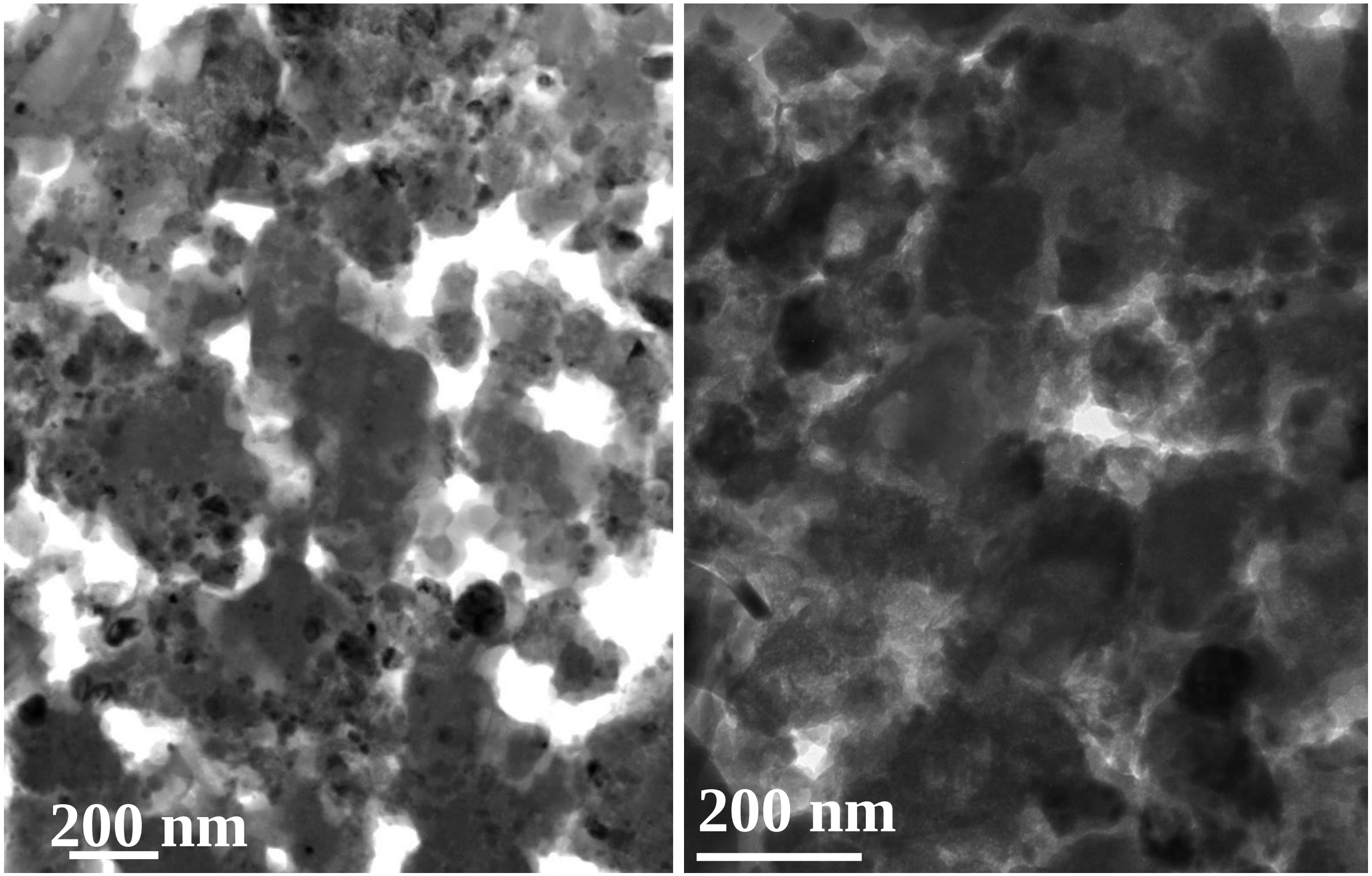


➢ Focus on the less altered areas:

⇨ Search for the ‘pristine’ pre-accretional material
⇨ decipher the first stages of alteration

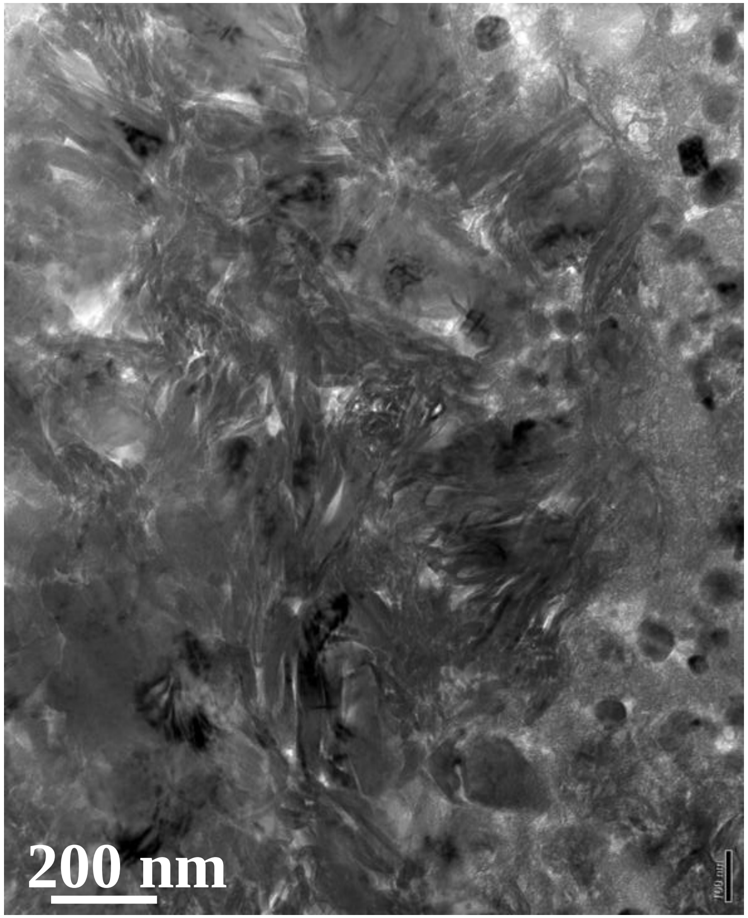
TEM results : less altered areas

‘GEMS-like’ components, highly porous

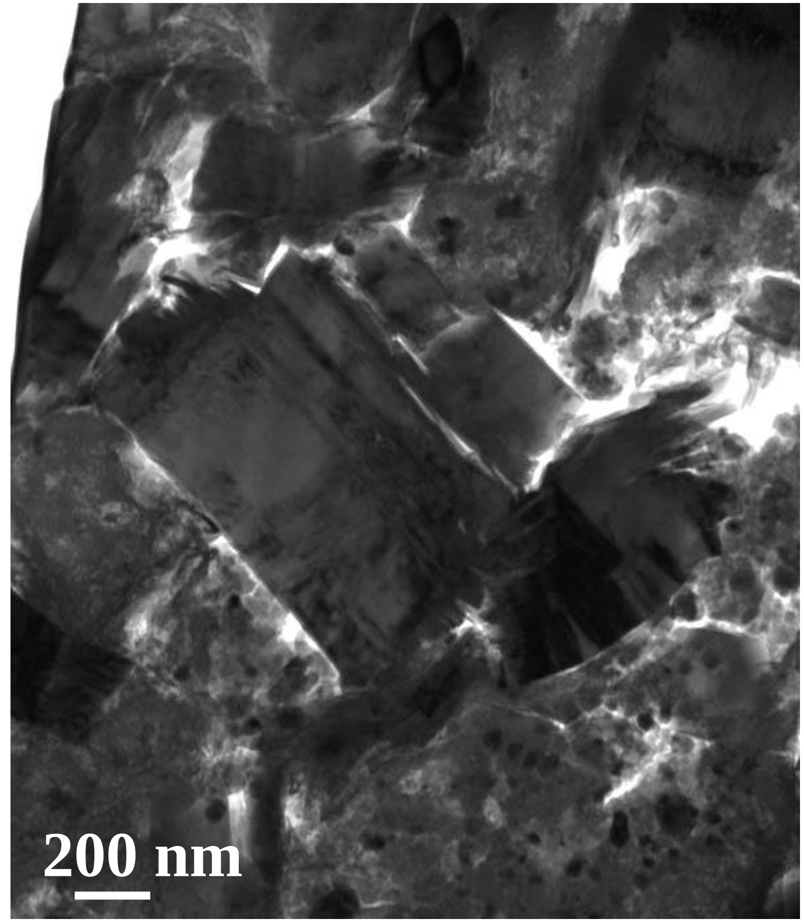


From amorphous « blocks » to fine-fibrous material (poorly crystallized)

TEM results: altered areas

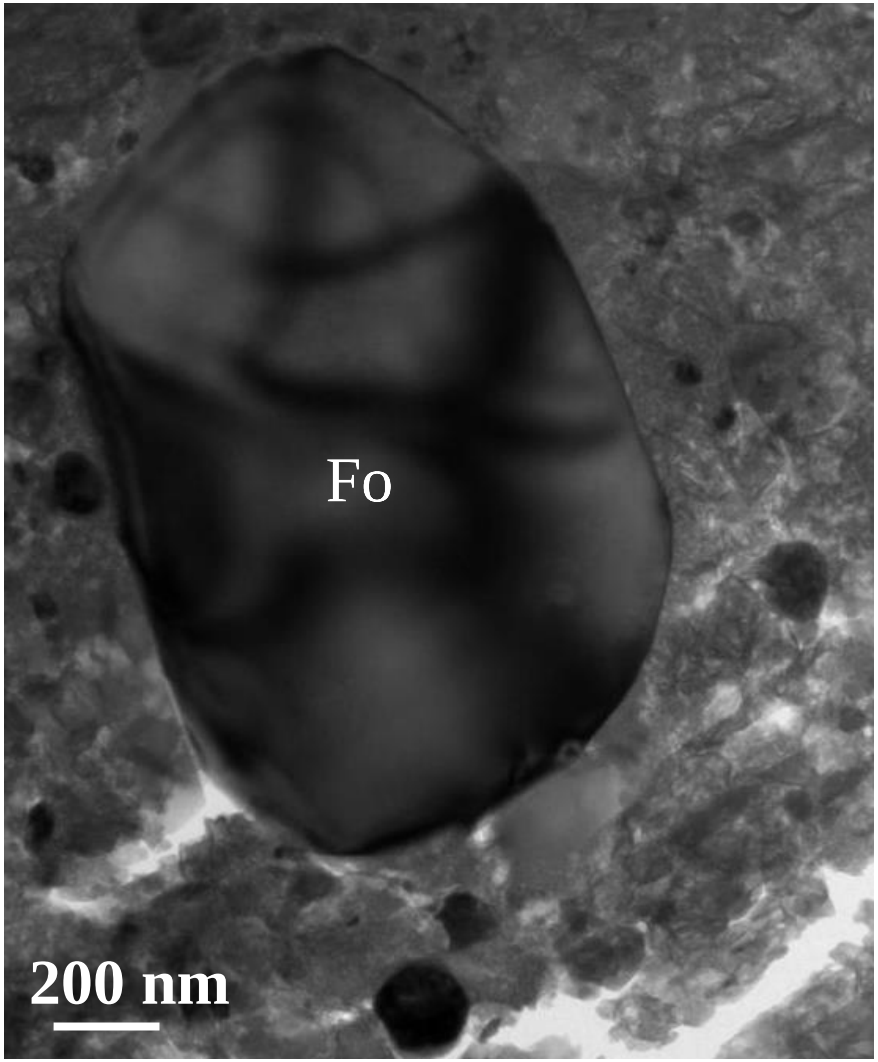


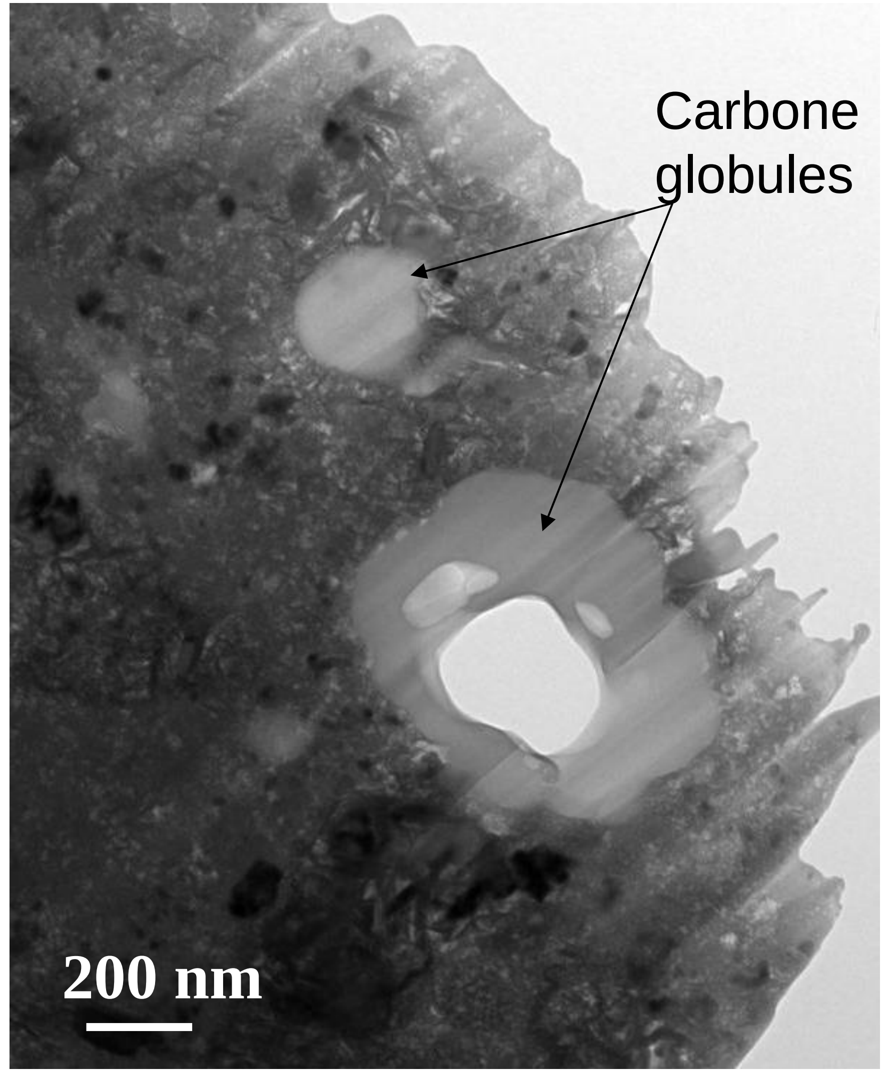
Coarse fibrous phyllosilicates (Fe-rich) – no porosity.



Platy cronstedtite (Fe-rich and Al-rich)
Interlayer of tochilinite

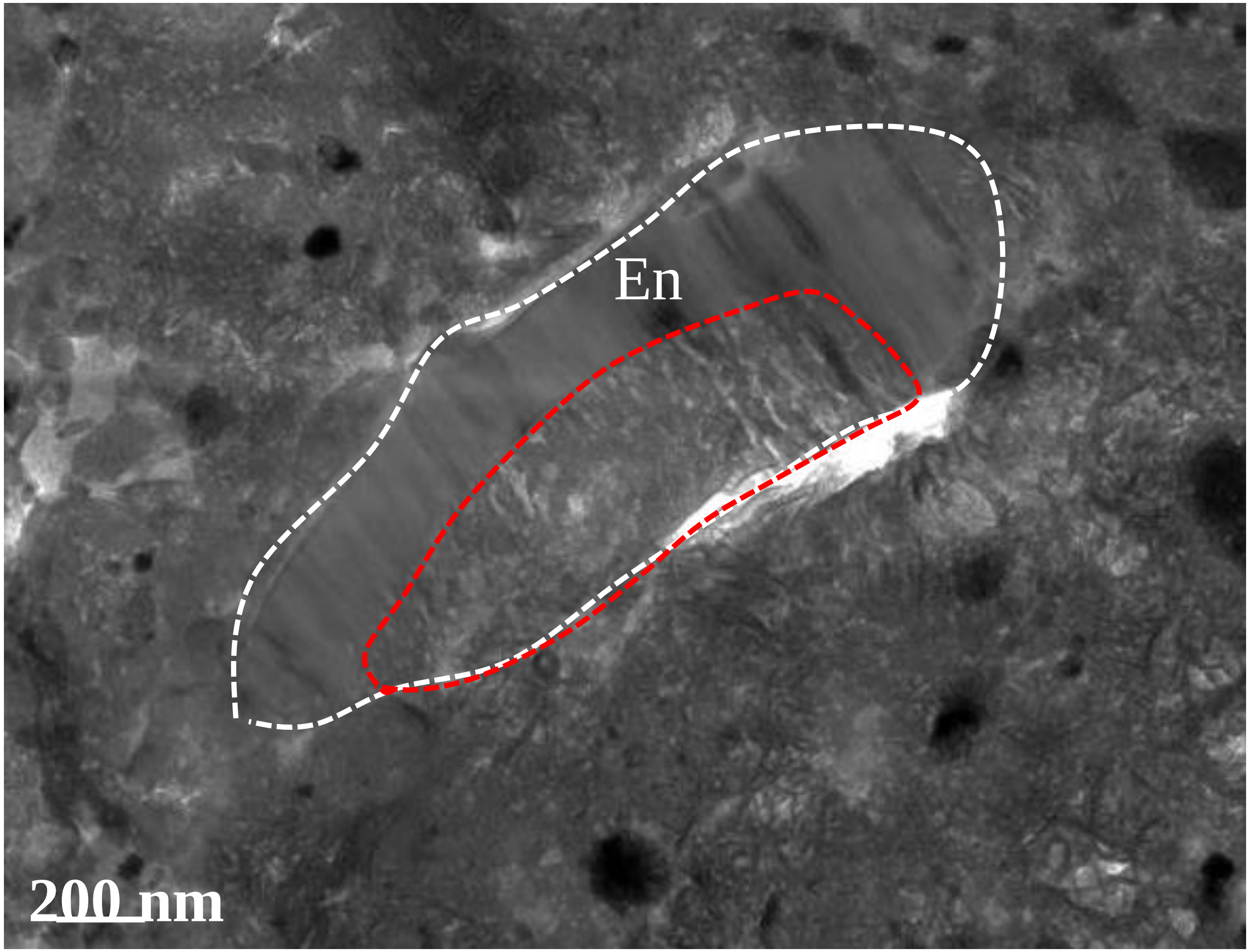
TEM results : accessory phases





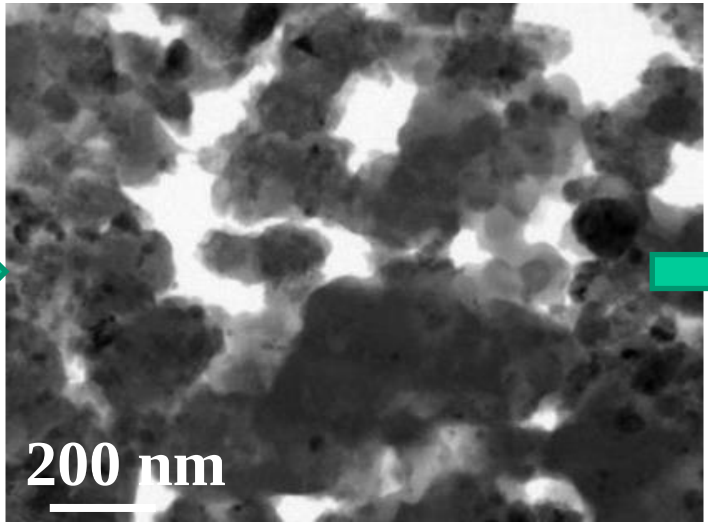
Most frequent accessory phases: pure Mg-silicates (forsterite and enstatite) and carbon material. Very limited signs of aqueous alteration.

TEM results : accessory phases

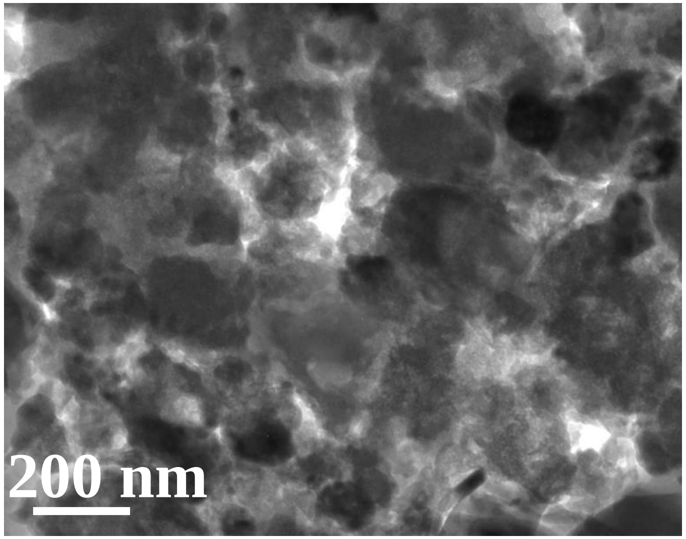


In altered areas, some Mg-silicates are partially converted into Fe-rich fibrous material

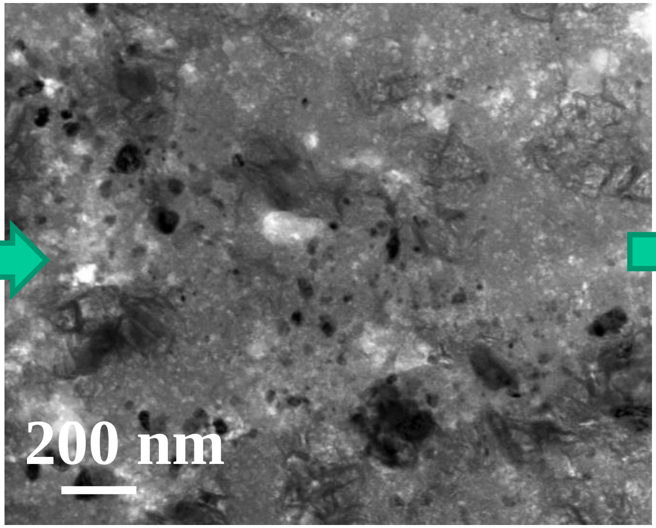
TEM results : from less altered areas to altered areas



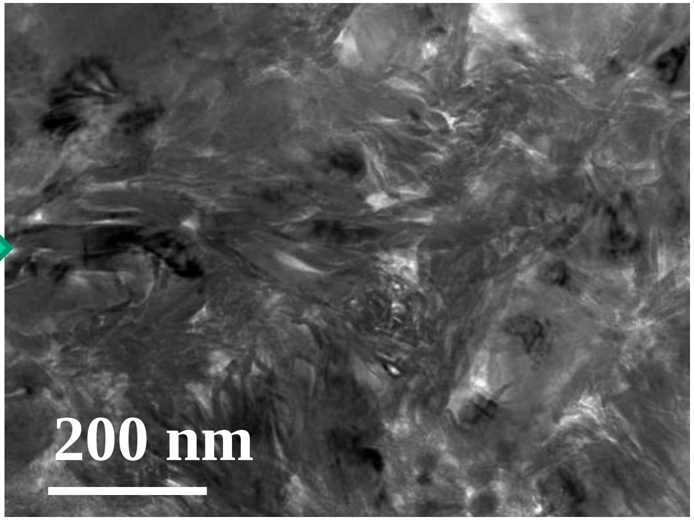
Amorphous blocks, highly porous



Amorphous to fine-grained fibrous phyllosilicates

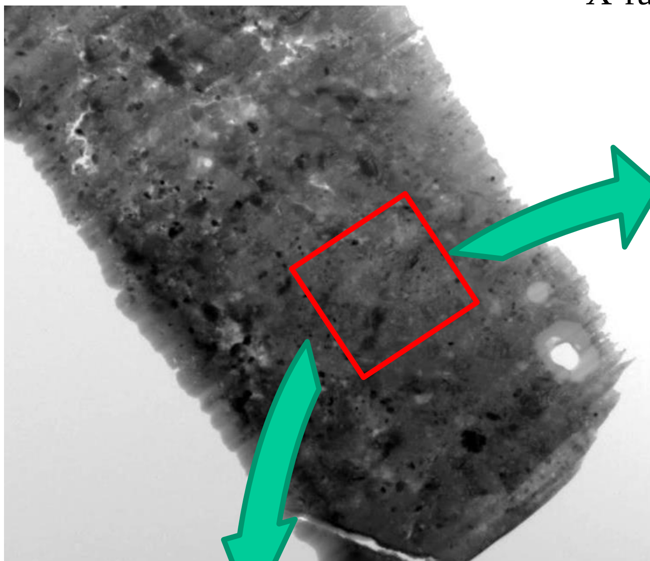


Fine to coarse grained fibrous phyllosilicates

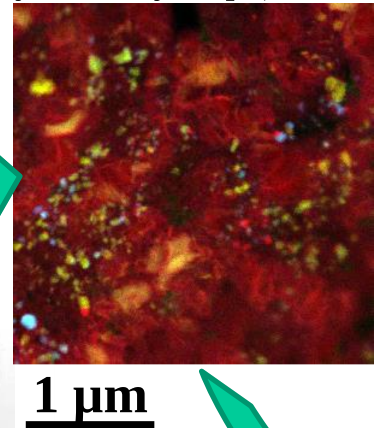


Coarse fibrous phyllosilicates

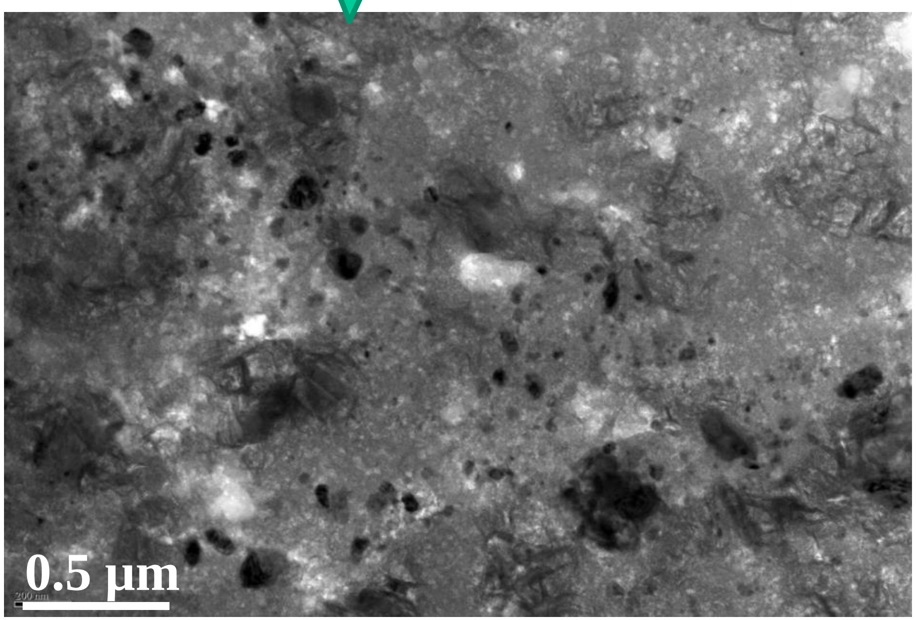
Partialy altered material

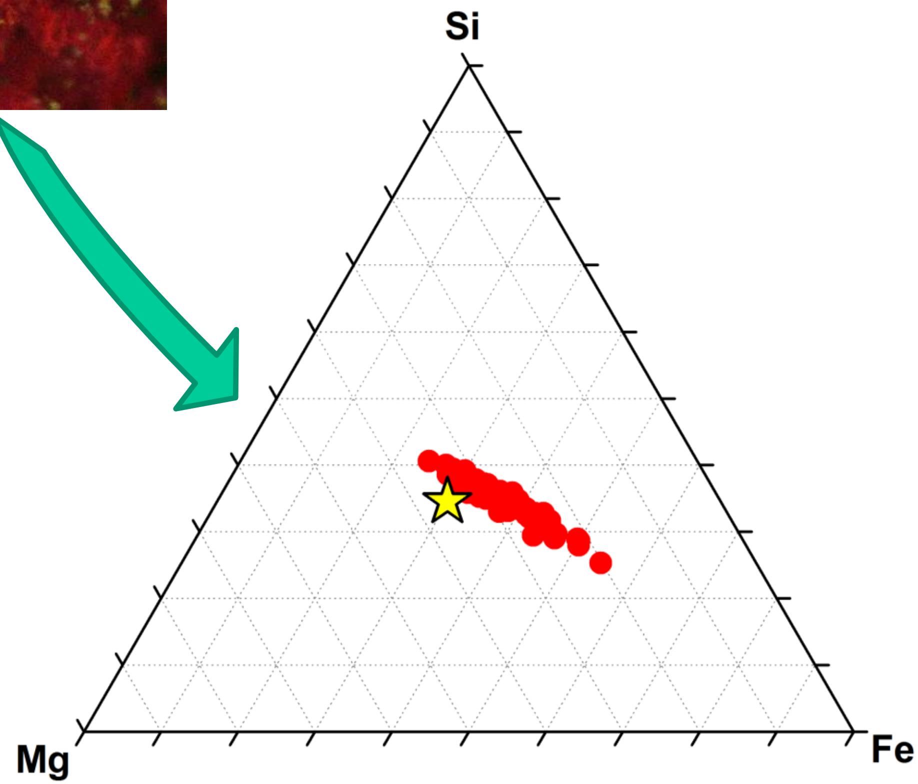


X-ray intensity map (false color)



Methodology: the full surface area is scanned by windows 300*300 nm^2.



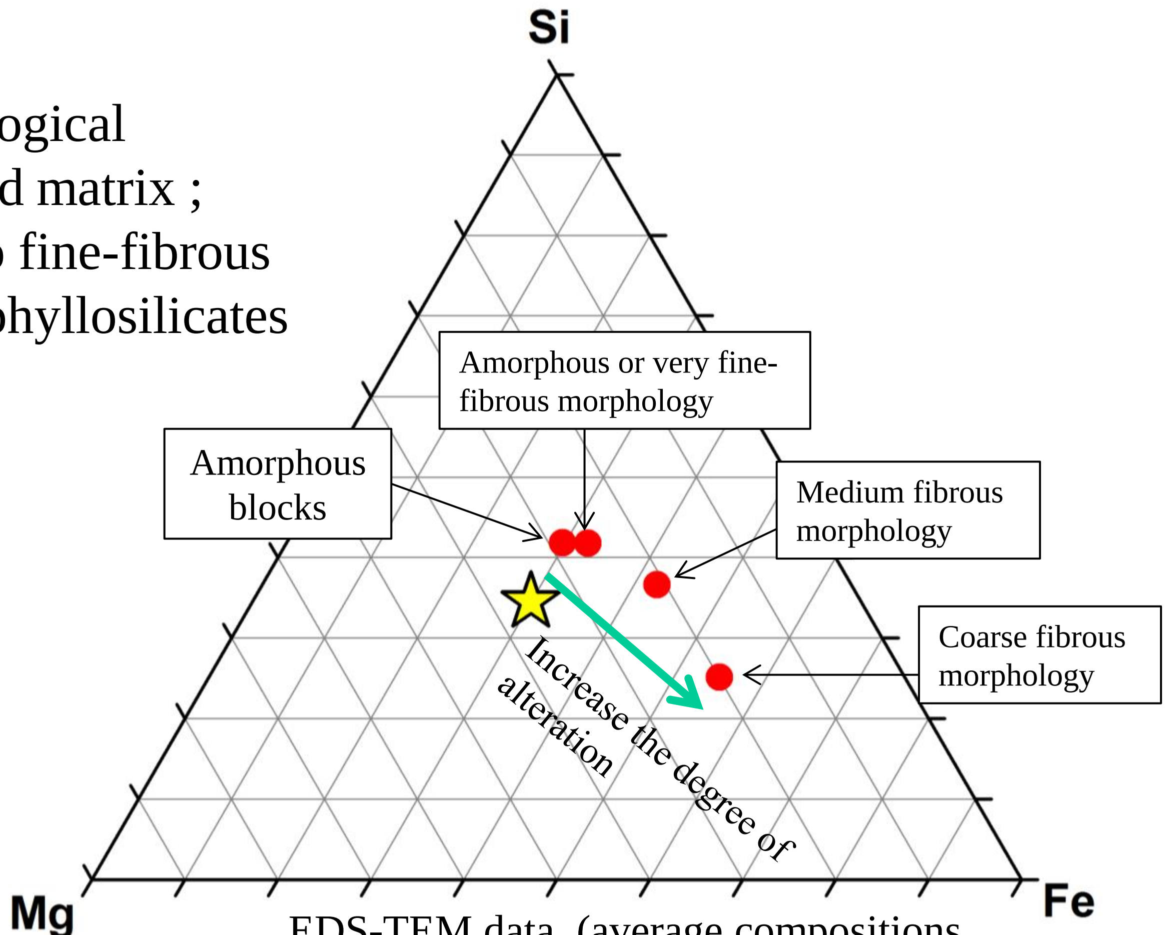


- Compositions lie along a line, from ≈ CI toward the Fe endmember

TEM results : compositional evolution

- Mineralogical and morphological evolution of the fine-grained matrix ; from amorphous silicates to fine-fibrous and then to coarse-fibrous phyllosilicates

- Composition : progressive incorporation of Fe in the silicate components in the matrix.

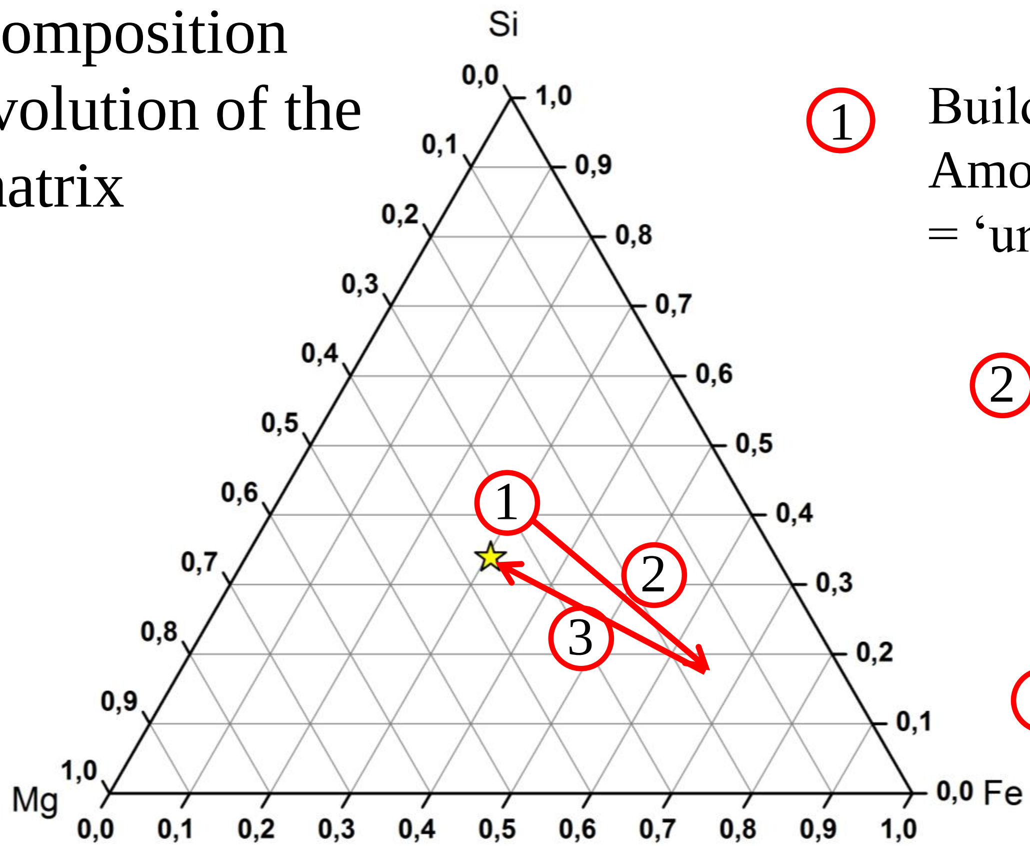


EDS-TEM data (average compositions from each type of morphology)

Fe enrichment of silicate components in the fine-grained matrix

Paris: from well preserved to altered material

Composition evolution of the matrix

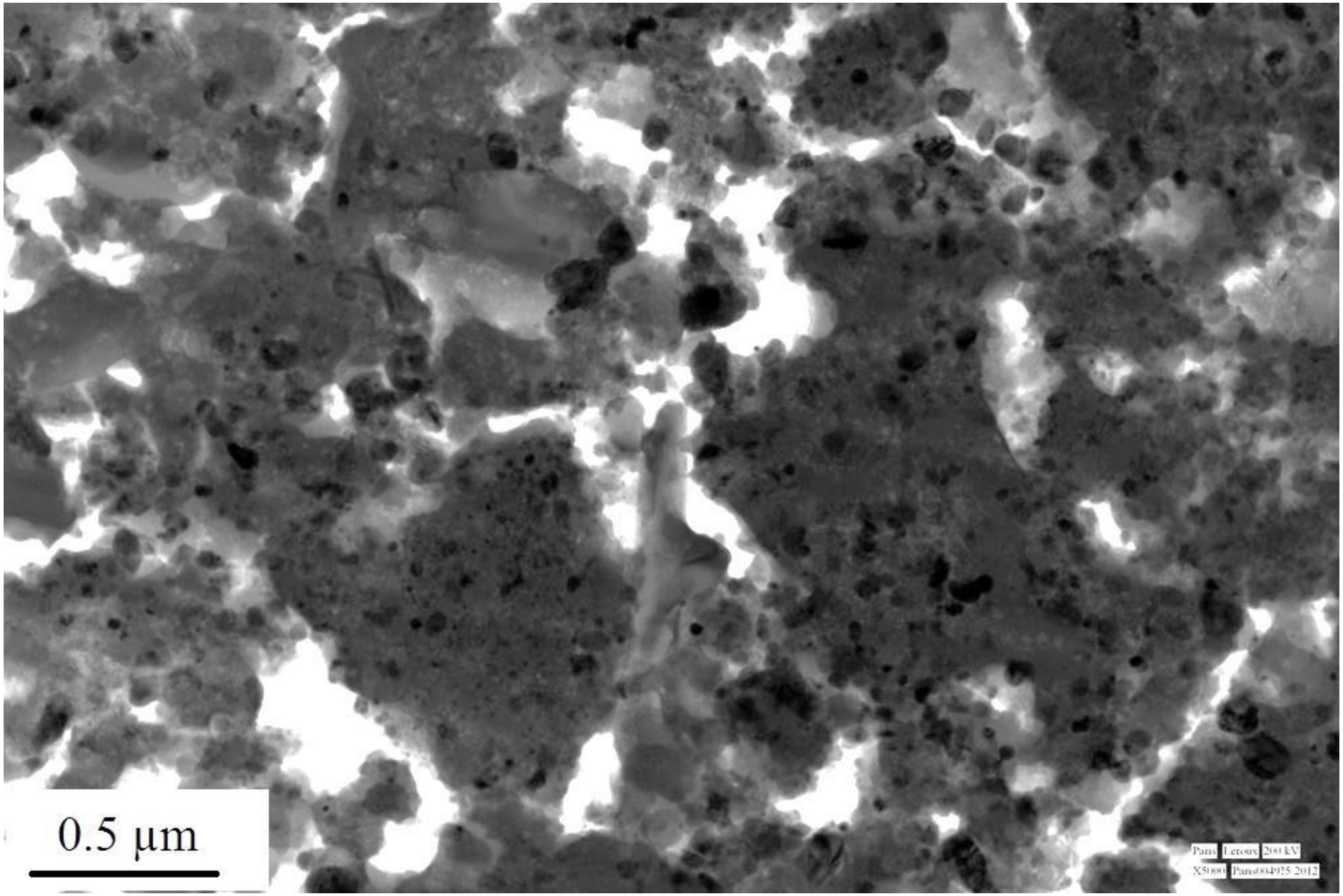


① Building blocks: 'GEMS-like' material
Amorphous assemblage, highly porous
= 'unmodified material' (pristine)

② Preferential and progressive alteration of metal and sulfide
=> Incorporation of Fe in the matrix

③ Progressive alteration of chondrules
=> incorporation of Mg in the matrix, + formation of magnetite and sulfides

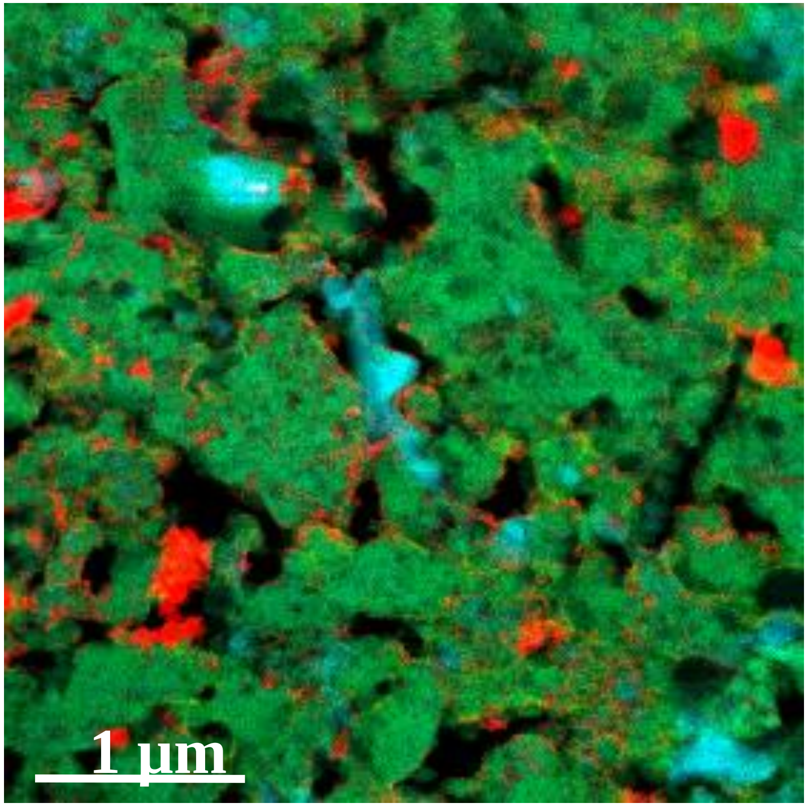
Focus on the less altered material

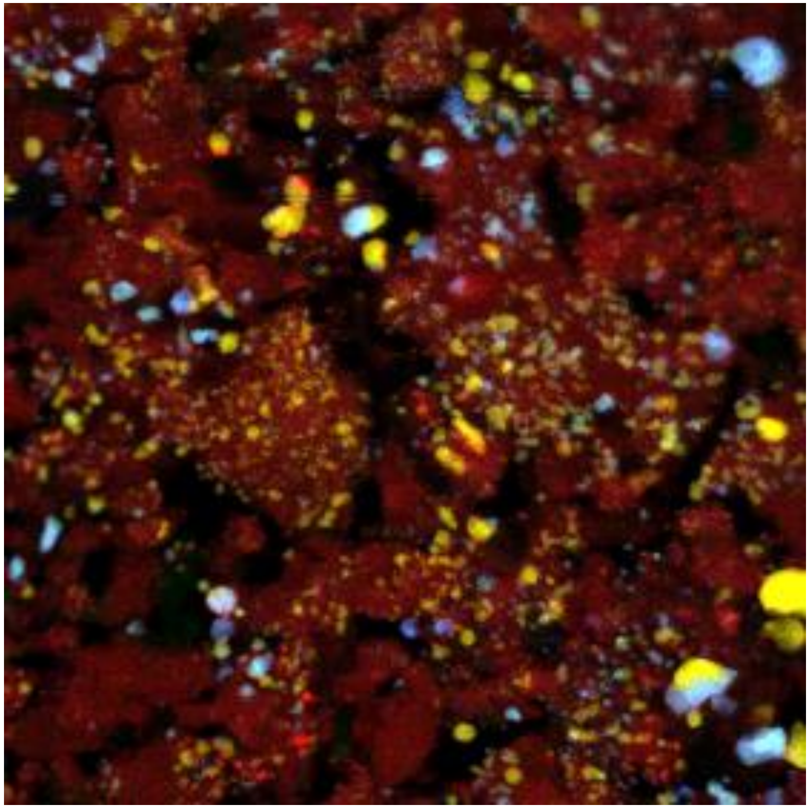


‘GEMS-like’ components, highly porous
(GEMS = Glass with Embedded metal and sulfides)

Focus on the less altered material

X-ray intensity map (false color)



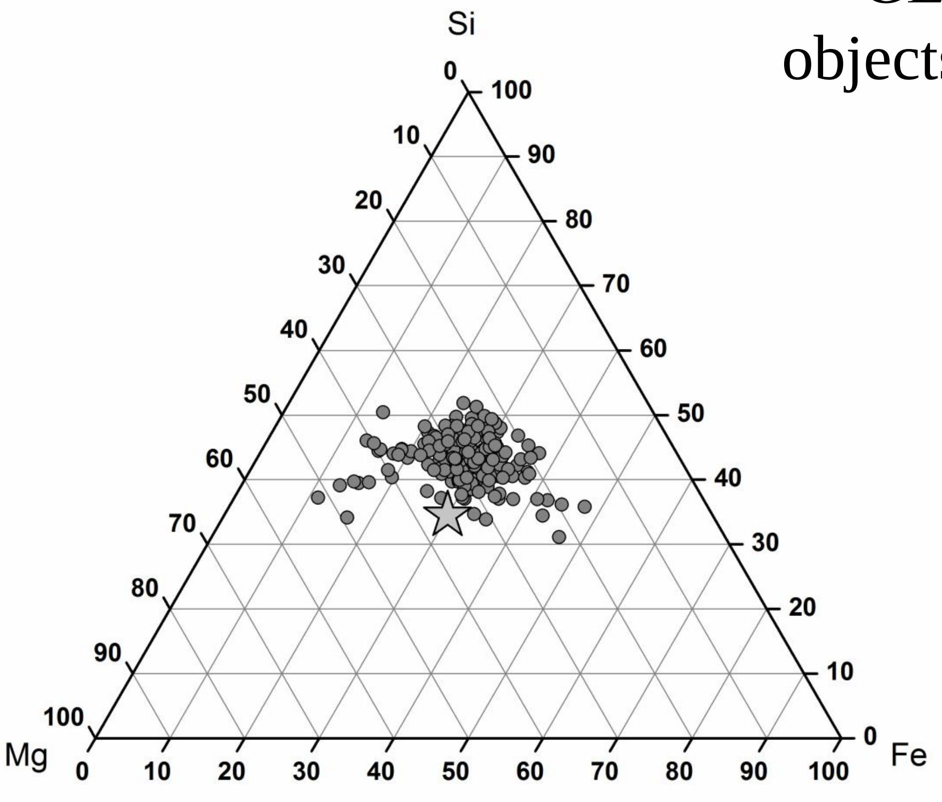


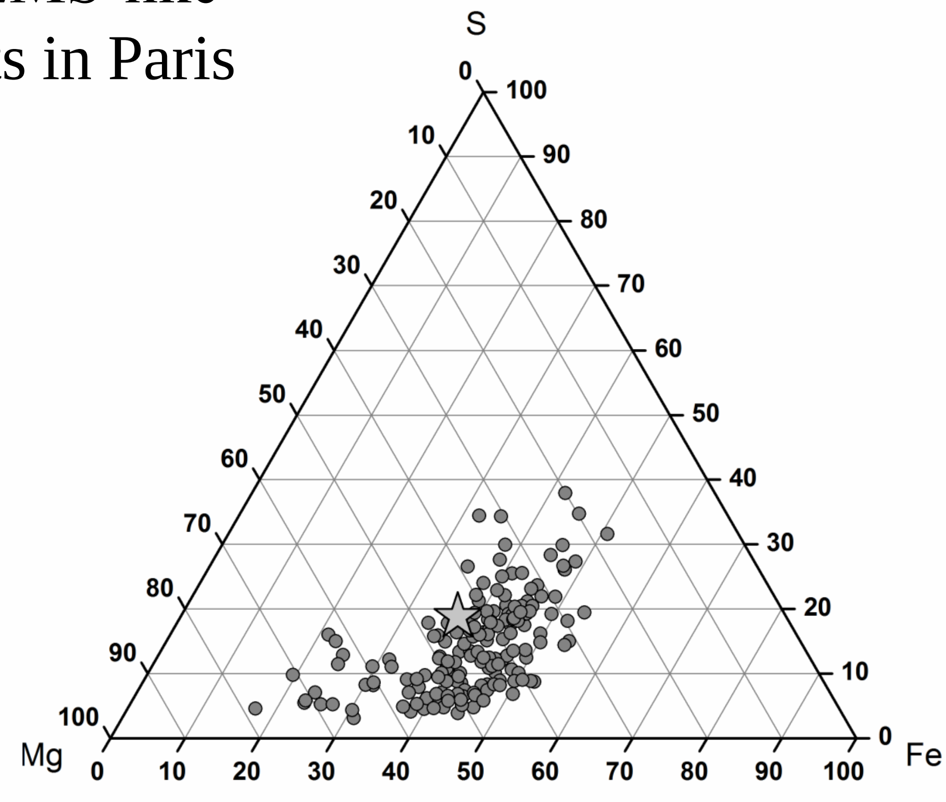
Silicate (amorphous, Fe-rich)
Carbon material
Mg silicates (forsterite and enstatite)

Fe in silicate
Fe-sulfides
Fe-Ni -sulfides
Fe in metal or Fe-oxides

Focus on the less altered material

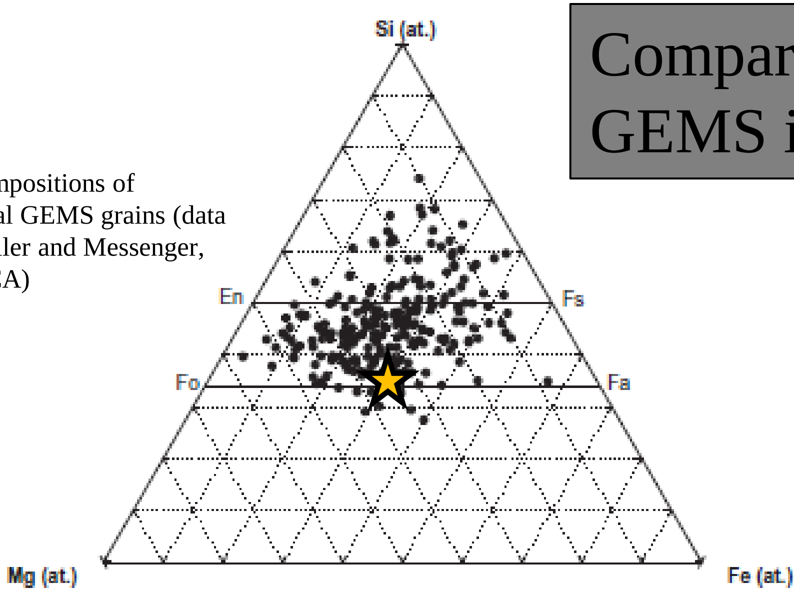
‘GEMS-like’
objects in Paris



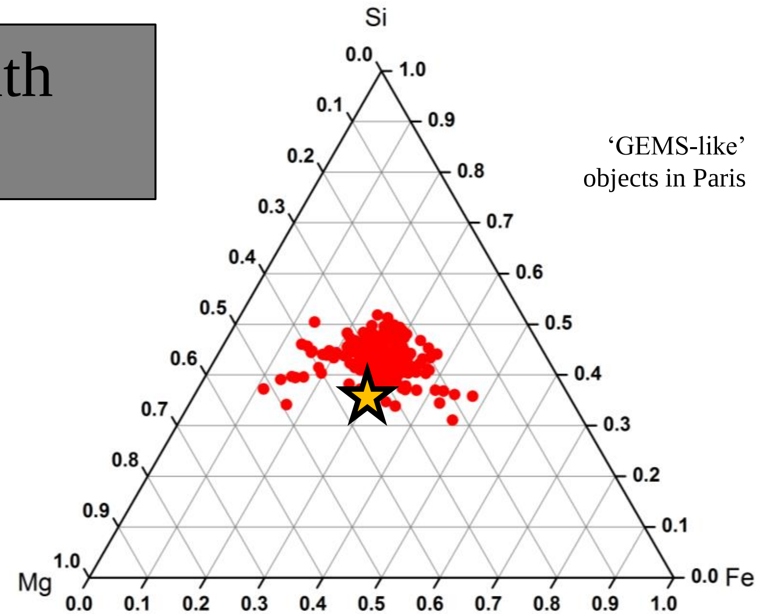


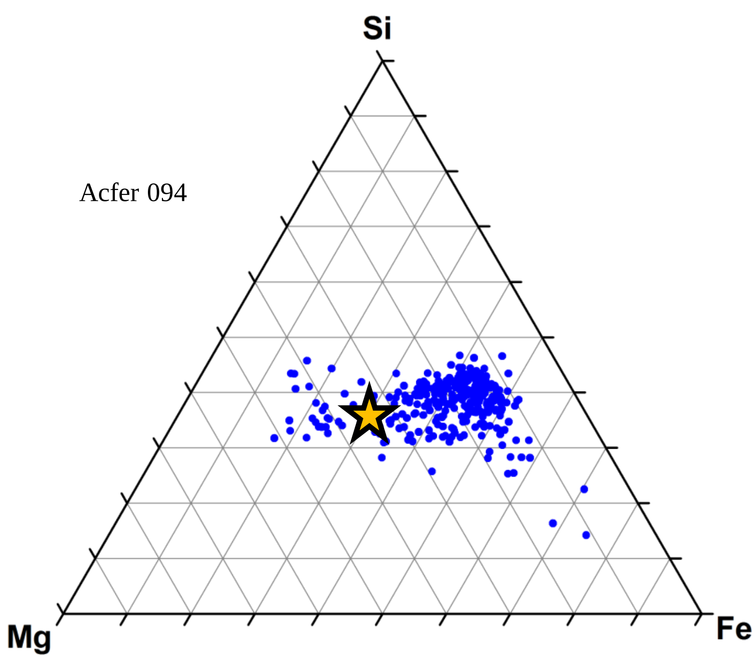
Matrix material in carbonaceous chondrite and CP-IDPs

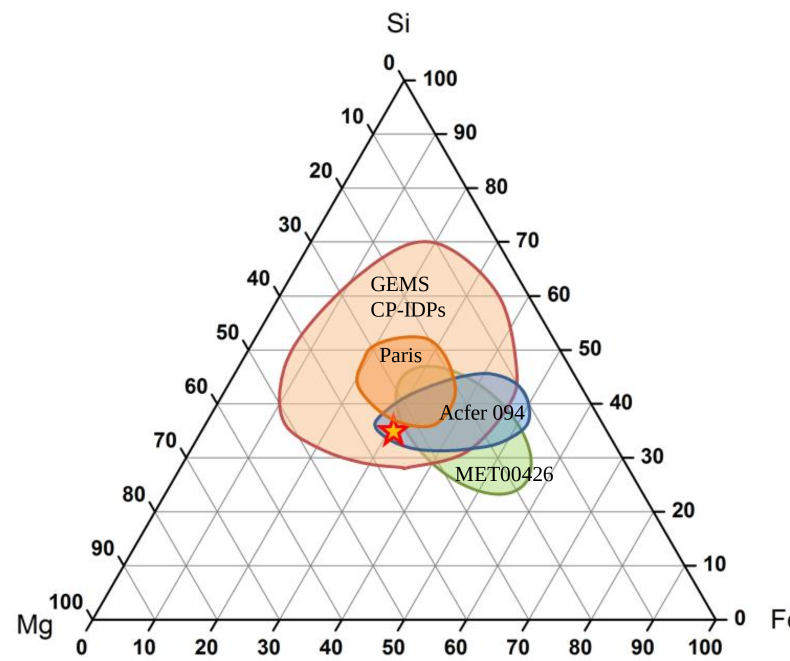
Comparison with GEMS in IDPs



Bulk compositions of individual GEMS grains (data from Keller and Messenger, 2011 GCA)





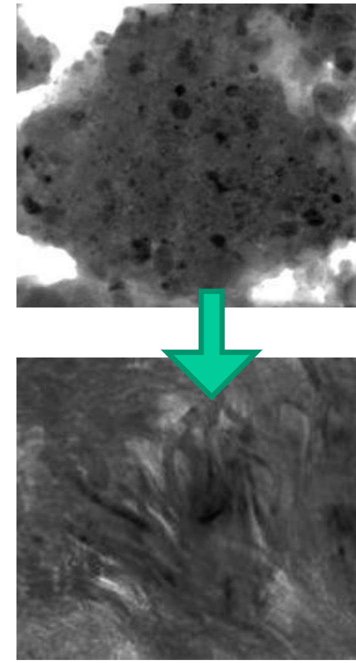


Summary

- Paris is a weakly altered CM chondrite. Some areas are well preserved from alteration

- The alteration variability allows to draw a sequence for the early stage of alteration:

    - From amorphous grains to fibrous phyllosilicates
    - Porosity is lost
    - Fe-sulfides nanograins disappear (tochilinite)
    - Progressive enrichment in Fe



- The most preserved material consist of ‘GEMS-like objects’

- Many similarities with the GEMS in IDPs and micrometeorites (size, composition, texture, porosity, structural state)

- GEMS could have been the building blocks of the solar system

Conclusion

- The fine-grained silicates in primitive object consist of a mixture between high and low temperature assemblages

- Low temperature grains are quite rapidly altered on asteroid parent bodies

- High temperature minerals are found in abundance in comets => radial mixing ? Local thermal events ?

- GEMS grains are probably the building blocks of the object growing in the protoplanetary disk