Introduction into cosmochemistry - what the meteorites can tell us

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Wir erstaunen „metallische und erdige Massen, welche der Außenwelt, den himmlischen Räumen angehören: betasten, wiegen, chemisch zersetzen zu können“; [...]

Alexander von Humboldt (1844) „Kosmos“

(vol. III, p. 397, edition from 1874, Verlag der J. G. Cotta'schen Buchhandlung, Stuttgart)

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Origin of meteorites

- most meteorites source from the asteroid belt
- 28 meteorites are thought to come from Mars and 27 from the Moon
- a single possibly came from Mercury (NWA 011)*

Falls (~900): Observed meteorite falls, quickly recovered, little terresitial alteration

Finds (~21000): Finds of ancient meteorites, those from the cold and hot deserts show only little terrestial alteration

*Palme, H. (2002) Science, 296, 271-272

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meteorite find in the Lybian desert

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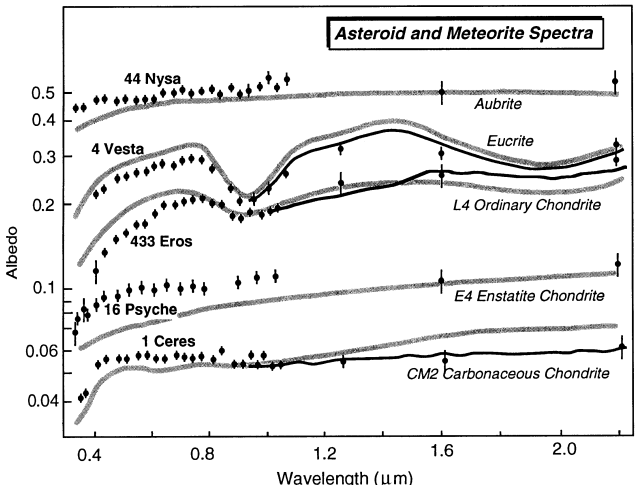

- albedos of individual asteroids can related to certain types of meteorites

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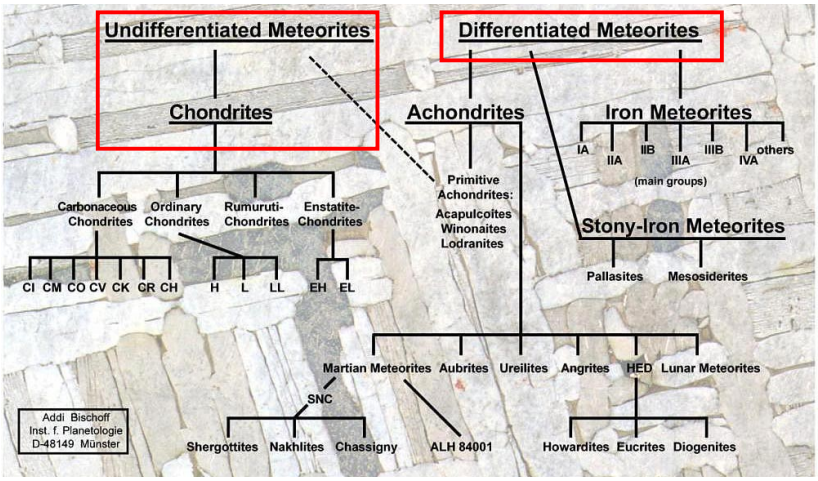
Meteorite classification



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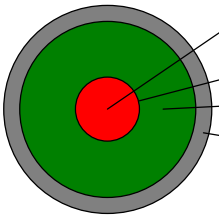
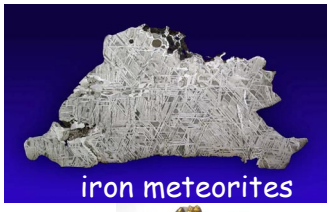
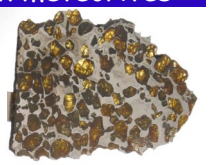
Differentiated meteorites

- from large parent bodies (with core formation)
  - iron meteorites
  - stone/iron meteorites
  - stone meteorites (achondrites)





pallasites



mantle rocks?

eucrites (basaltic crustal rocks)

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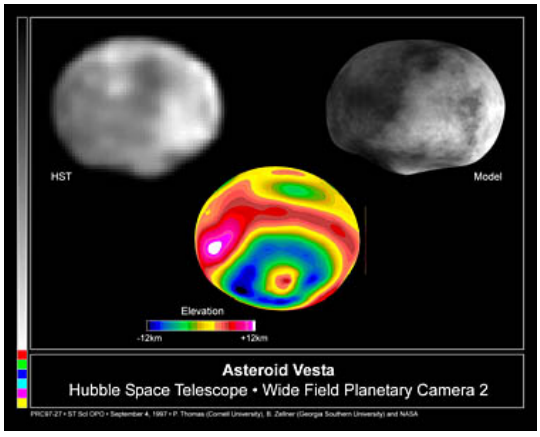
- differentieated meteorites ("HED"-group*) are thought to come from the asteroid Vesta ("eucrite like" albedo)



*howardites, eucrites and diogonites

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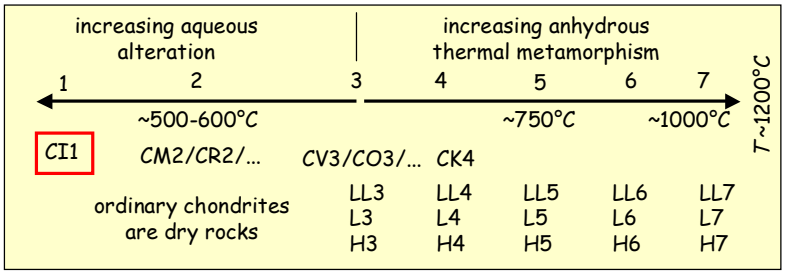
Undifferentiated meteorites (chondrites)

- no separation of metal and silicates (no core formation)
- source from small asteroids (T_{max} < ~1200°C)
- chondrites are primitive meteorites



- Type-1 (CI or C1): Chemically most primitive (e. g. Orgueil)

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Orgueil CI carbonaceous chondrite

- fell May 14, 1864, total mass ~12 kg
- black color is due to ~3-4 wt.% C (graphite, amorphous)
- contains 18 wt.% H_2O (bond in minerals)
- one of five known CI chondrites (n = 22000 meteorites)

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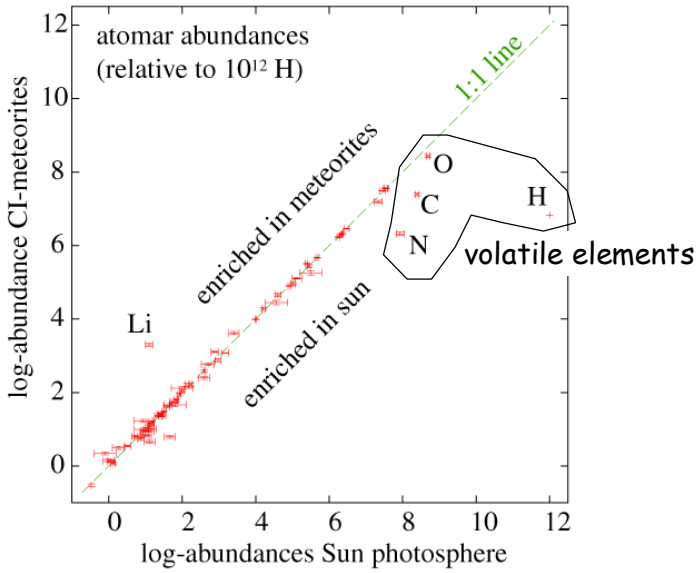
What does chemically most primitive mean?



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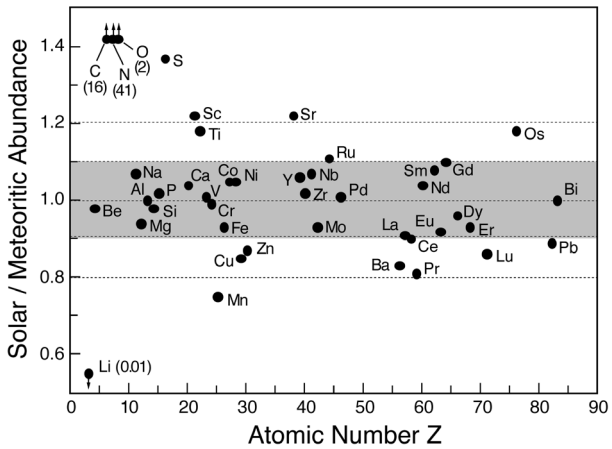

- Sun and CI meteorites have within ±10-20% the same composition
- highly volatile elements are depleted in CIs

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- Sun contains >99% of the mass of the solar system
  - Sun's composition representative for the solar system
  - CI chondrites have a composition representative for the "bulk" solar system

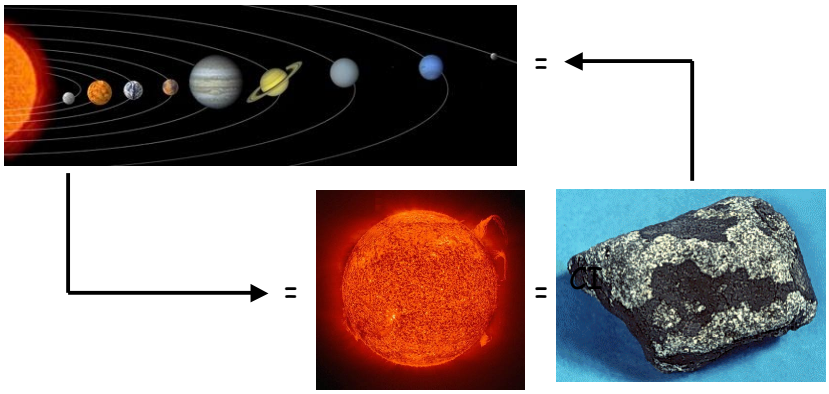

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Table 1. *Cosmochemical classification of the elements*

	elements	
	lithophile (silicate)	siderophile + chalcophile (sulphide + metal)
refractory	T_c = 1850–1400 K Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu	Mo, Ru, W, Re, Os, Ir, Pt
main component	T_c = 1350–1250 K Mg, Si, Cr, Li	Fe, Ni, Co, Pd
moderately volatile	T_c = 1230–640 K Mn, P, Na, Rb, K, F, Zn	Au, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S
highly volatile	T_c < 640 K B, Cl, Br, J, Cs, Tl, C, O, Ne, Ar, Kr, Xe	In, Bi, Pb, Hg, H

T_c denotes condensation temperatures at a pressure of 10^{-4} bar.

Ca,Al-rich phases (CAIs)

forsterite Mg_2SiO_4

Fe,Ni metal (~7% Ni)

decreasing T_c

- cosmochmical classification of the elements according to their condensation temperature

see also Ebel and Grossman, GCA (2000)

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- first major condensate is olivine (Mg_2SiO_4)
- was identified in circumstellas dust disks

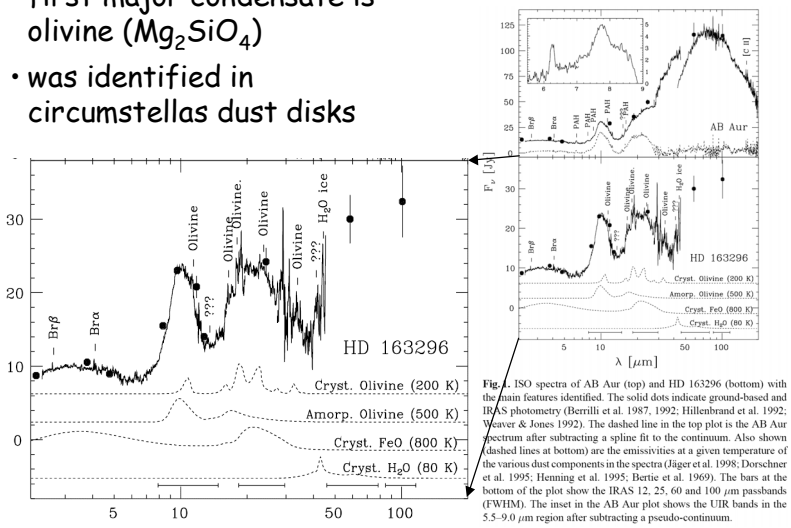

Fig. 1. ISO spectra of AB Aur (top) and HD 163296 (bottom) with the main features identified. The solid dots indicate ground-based and IRAS photometry (Berrilli et al. 1987, 1992; Hillenbrand et al. 1992; Weaver & Jones 1992). The dashed line in the top plot is the AB Aur spectrum after subtracting a spline fit to the continuum. Also shown (dashed lines at bottom) are the emissivities at a given temperature of the various dust components in the spectra (Jäger et al. 1998; Dorschner et al. 1995; Henning et al. 1995; Bertie et al. 1969). The bars at the bottom of the plot show the IRAS 12, 25, 60 and 100 μm passbands (FWHM). The inset in the AB Aur plot shows the UIR bands in the 5.5–9.0 μm region after subtracting a pseudo-continuum.

ISO spectra, v. d. Ancker et al. (2000) A&A 375, 325-329

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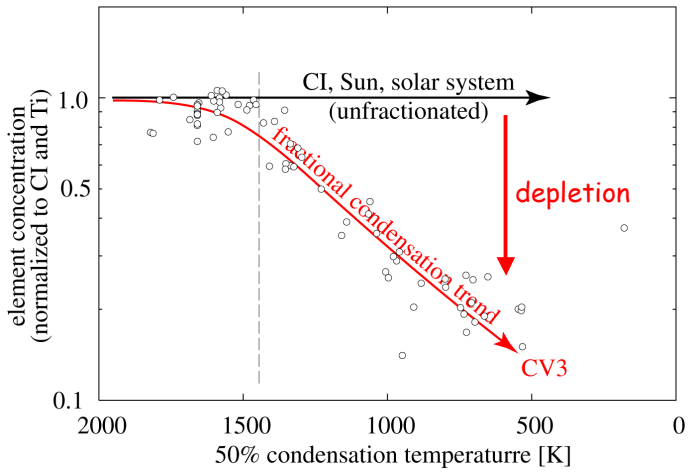
Element fractionation in CV3 chondrites



- CV3 chondrites are systematically depleted in moderately volatile elements (fractional condensation)

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Composition of other carbonceous chondrites (major groups: CI, CM2, CO3, CK3, CV3)

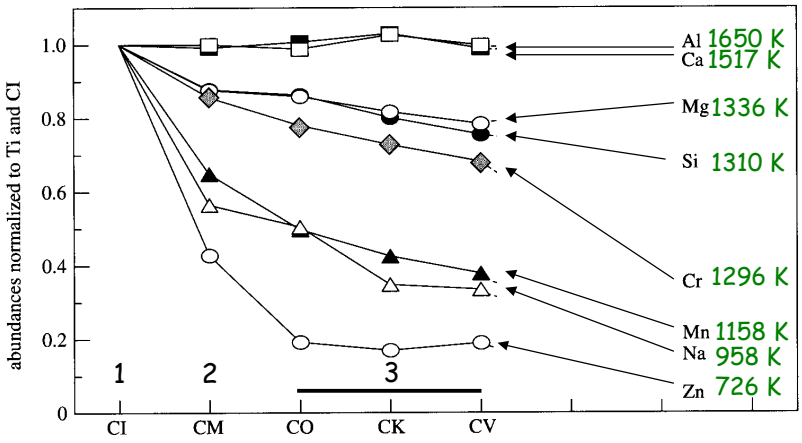

Figure 3. Major and moderately volatile elements in carbonaceous chondrites and in the Earth's mantle. Data from Wolf & Palme (2001) and O'Neill & Palme (1998).

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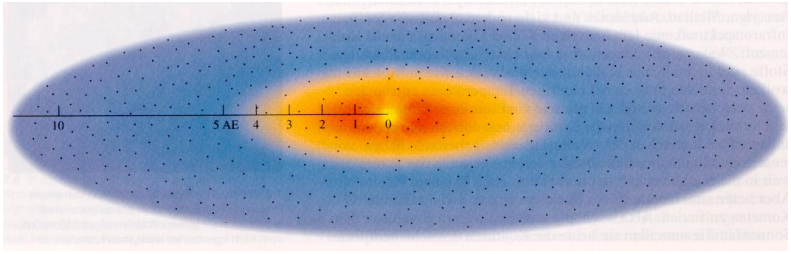
Chemistry of terestial planets and asteroids



- composition of carbonaceous chondrites and planets (Earth, Mars, Mercury) established by fractional condensation
  - inner solar system was heated to temperatures exceeding ~1500 K
- first solids formed by condensation from the nebular gas

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Composition of other carbonceous chondrites (major groups: CI, CM2, CO3, CK3, CV3)

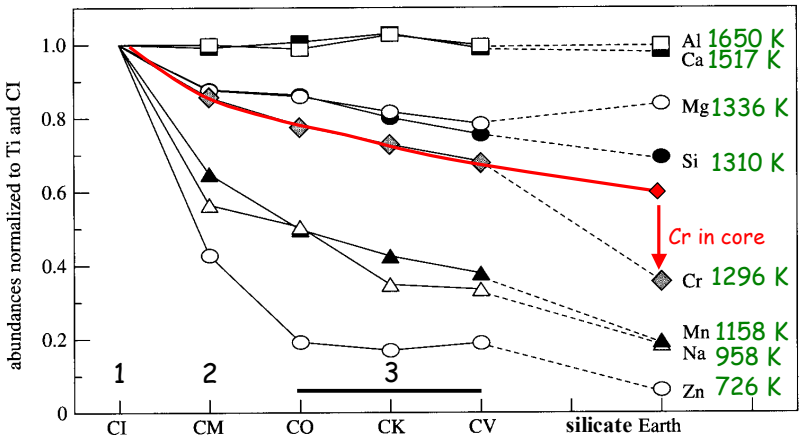

Figure 3. Major and moderately volatile elements in carbonaceous chondrites and in the Earth's mantle. Data from Wolf & Palme (2001) and O'Neill & Palme (1998).

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Formation & evolution of planetesimals

- planetesimals formed by accretion of material that formed by fractional condensation
- Earth accreted from material resembling that of carbonaceous chondrites
  - "bulk" Earth is strongly depleted in the moderatly volatile elements (incl. H_2O, more than CV3)
  - result of position at 1 AU
- element pattern of the silicate Earth indicates fractionation of Cr into the core
  - no indication for Si in the core

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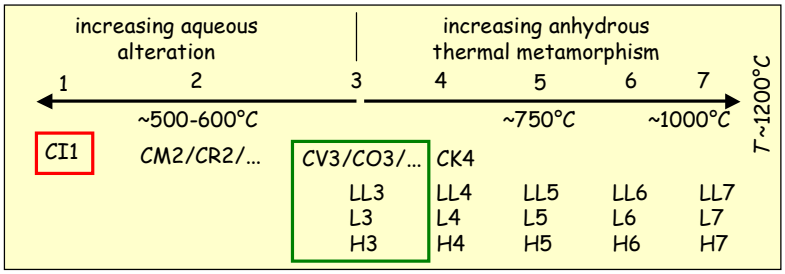
Classification of chondrites

- type-3 chondrites do not contain water
  - no or only little aqueous alteration of the "type-3" parent body



- type-1: Chemically most primitive (e. g. Orgueil)
- type-3: Texturally most primitive (e. g. Vigarano, Semarkona)

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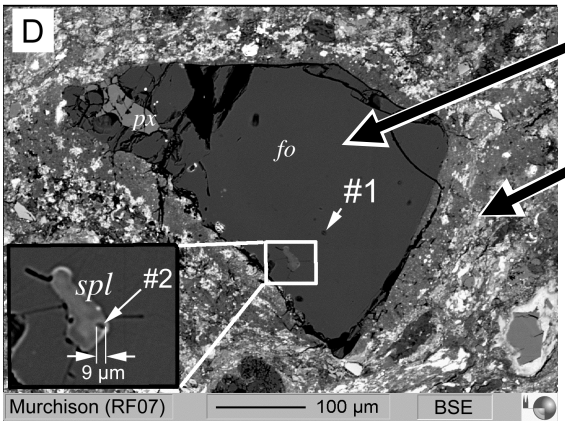
Texturally primitive: agglomerates of material that is chemically and texturally in dis-equilibrium



FeO-poor olivine crystal (<1% FeO)

FeO-rich fine grained matrix material (~30% FeO)

isolated olivine grain in Murchison (CM2), from Pack et al., *GCA*, submitted

[...]

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Components of chondrites

pre-solar grains (extremely rare: diamonds, SiC, truely exotic)

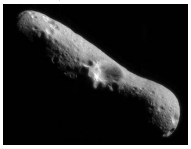
~4 vol.% high-T (~1700-1200 K) condensates (CAIs, forsterites, metal grains)

~48 vol.% main components (ol, px, metal) material (chondrules)

~48 vol.% low-T (~1000-500 K) material (sulphides, phyllosilicates, organics)

*http://www.einkaufen-wiesbaden.de/Wiesanha/hauptseiten/thema/thema_hilfenimalter.htm

accretion



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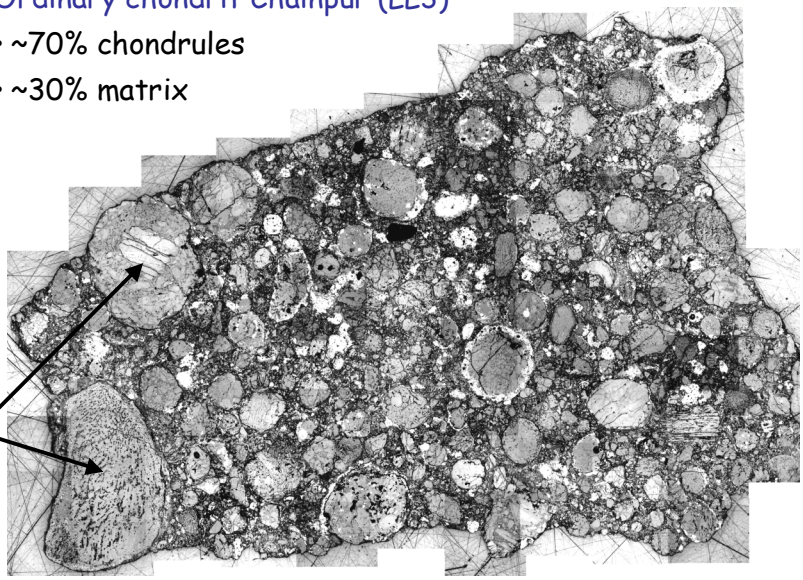
Ordinary chondrit Chainpur (LL3)

- ~70% chondrules
- ~30% matrix



chon-drules

reflected light micrography image map, width ~2 cm

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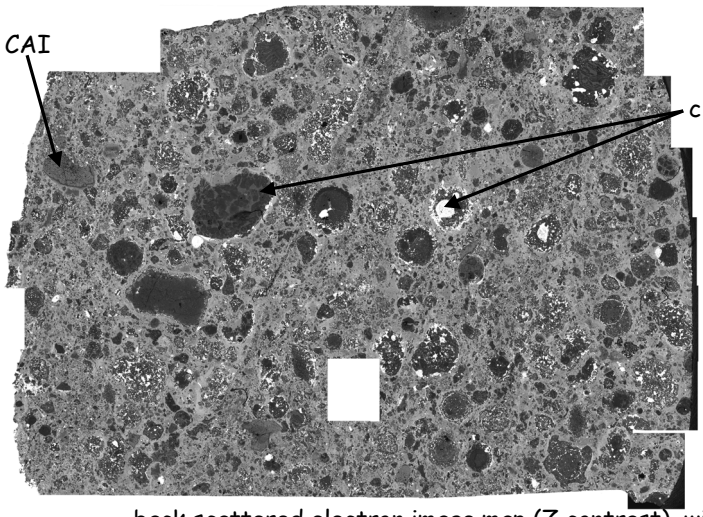
Carbonaceous chondrite "Vigarano" (CV3)

- ~44 vol.% chondrules, ~42vol. % matrix, ~4 vol.% CAIs



back scattered electron image map (Z contrast), width ~2 cm

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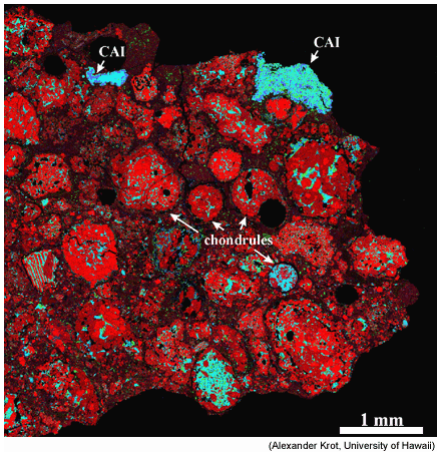
False color image of CR2 chondrite PCA 91082



(Alexander Krot, University of Hawaii)

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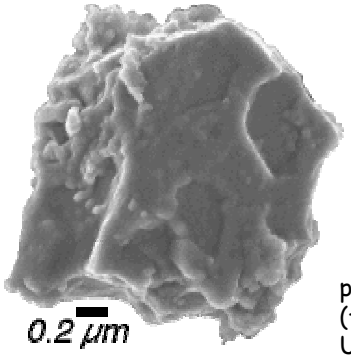
Pre-solar grains

- exotic grains of highly refractory phases (<1 µm)
- have extreme isotope anomalies
  - result of stellar processes
- chondritic material is isotopically homogenuous even on smalles scale (only exception: oxygen)



pre-solar SiC grain
(from Ernst Zinner's webpage, Univ. of St. Louis)

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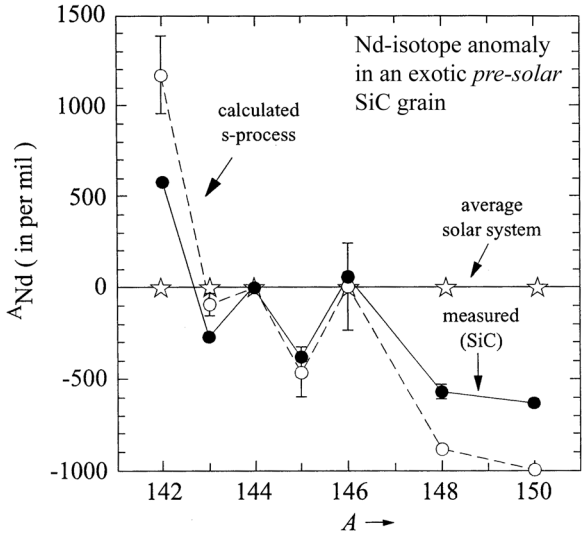
Nd-isotope anomaly in presolar grain (SiC)



from Palme and Jones (2003)

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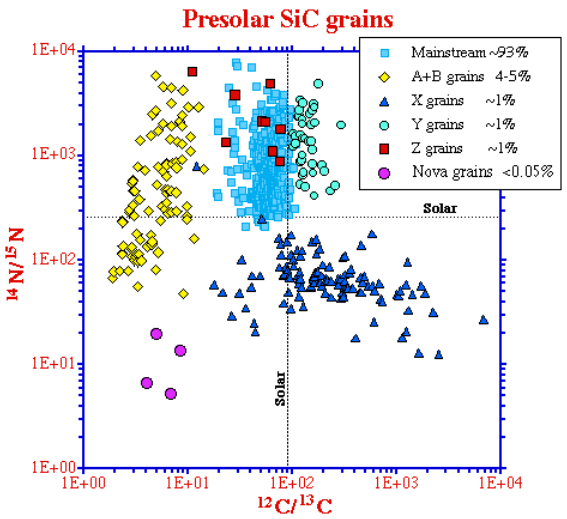
Extreme N and C-isotope anomalies in presolar grains



(from Ernst Zinner's webpage, Univ. of St. Louis)

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Pre-solar grains are truely exotic!

- rare (<<1%)
- highly refractory (diamond, SiC, corundum)
- pre-solar grains have inherited extreme isotope heterogeneity of the ISM material
- isotopic anomalies can be related to stellar nucleosynthesis processes

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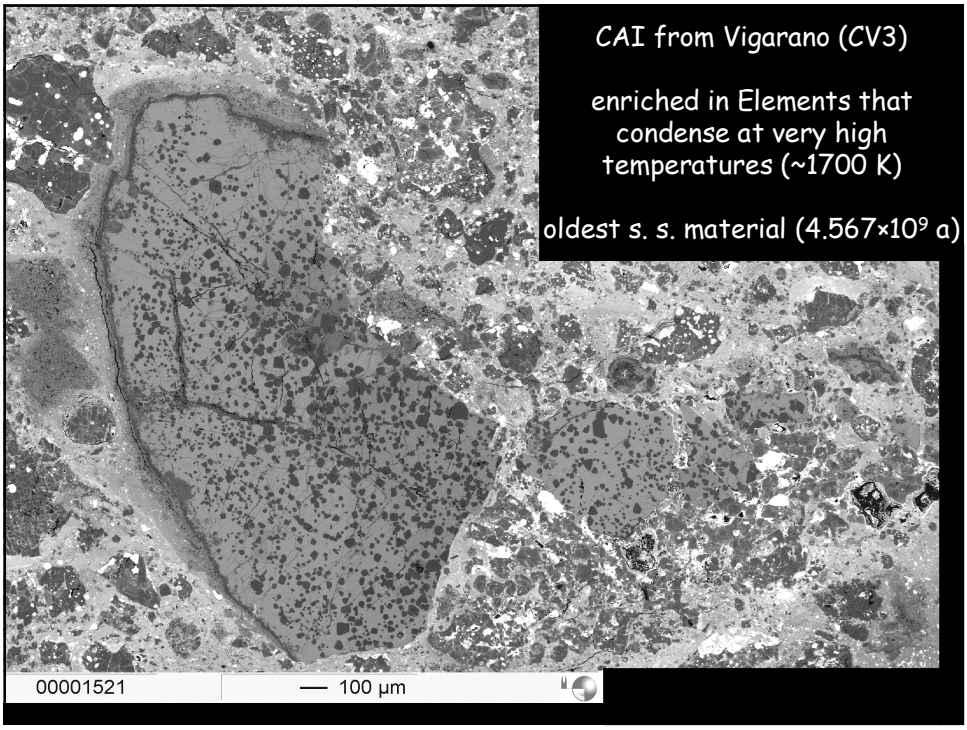
Chondrite major components (I)

- Ca,Al-rich inclusions (CAIs)
- chondrules
- fine grained matrix material

CAIs

- CAIs are rich in refractory elements (Ca, Al, Ti,...)
- formed by high-T fractional condensation (~1550 K) from the nebula
- CAIs are the oldest material from the solar system
  - 4.567×10^9 a old
  - therefore: contain traces of extinct nuclides (e. g. ^{26}Al, ^{53}Mn)



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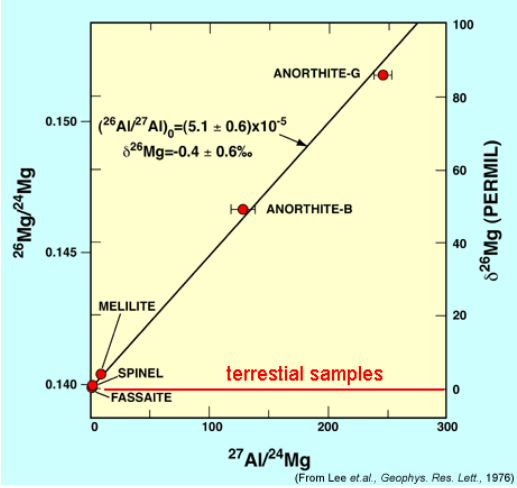
Extinct nuclides in CAIs (^{26}Al)

- ^{26}Al → ^{26}Mg, $t_{1/2}$ = 730000 a



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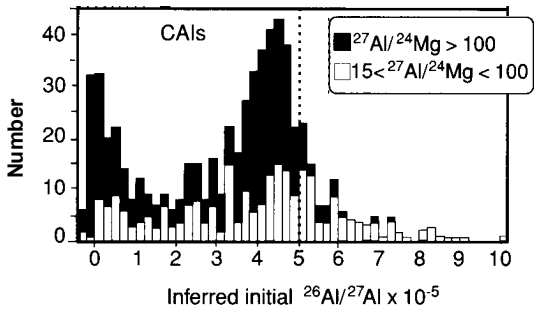
Extinct nuclides in CAIs (^{26}Al)

- initial ^{26}Al/^{27}Al ratio at the beginnig of the solar system (4.567×10^9 a) was 4-5×10^{-5}



- ^{26}Al: Heat source of planetesimales

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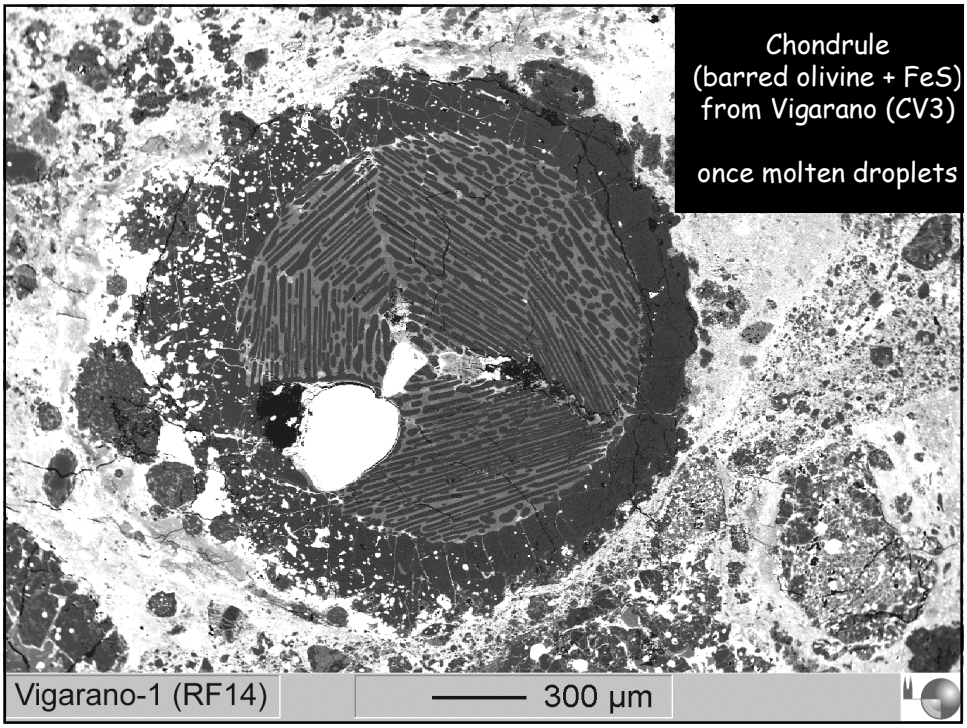
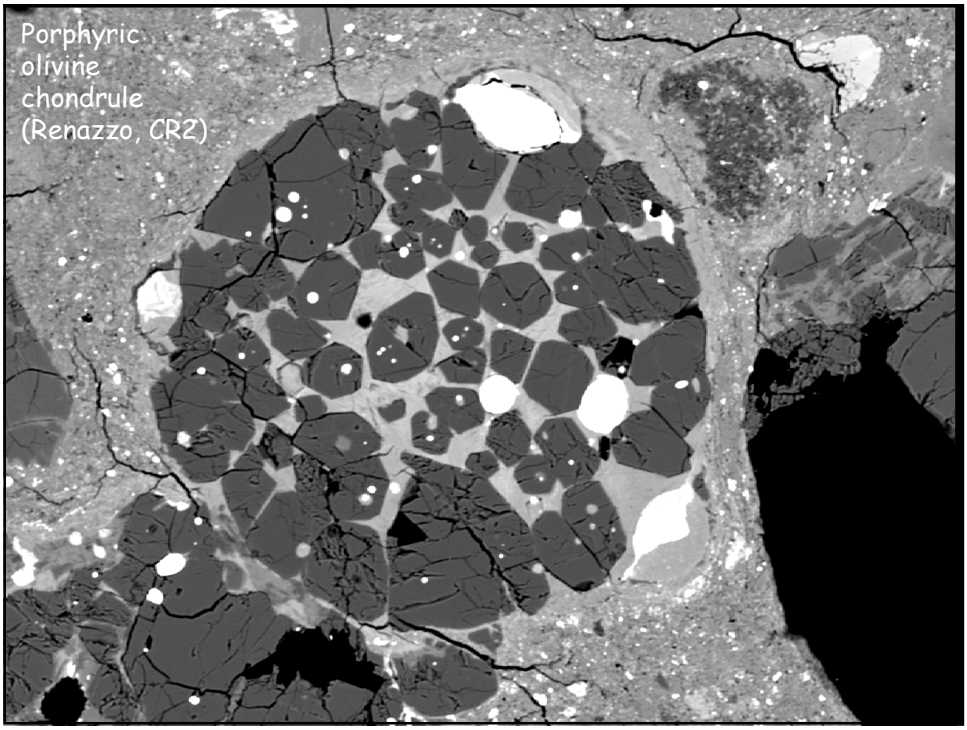
Chondrite major components (II)

- Ca,Al-rich inclusions (CAIs)
- chondrules
- fine grained matrix material

Chondrules ("fiery rain", H. L. Sorby, 1877)

- chondrules are once molten droplets of silicate melt
- formed by a very short heating event (T_{max} ~2200 K) in a cool environment
- chondrules are ~2-4 Ma younger than CAIs





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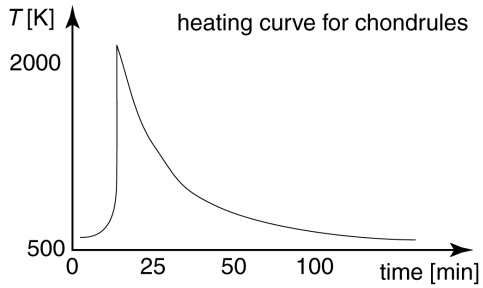
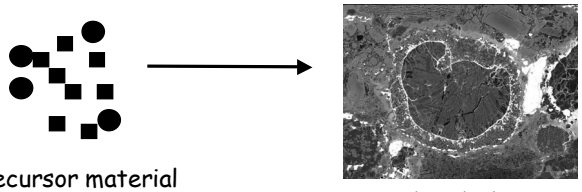
Chondrule formation by flash heating of dust balls





precursor material
(dust)

chondrule

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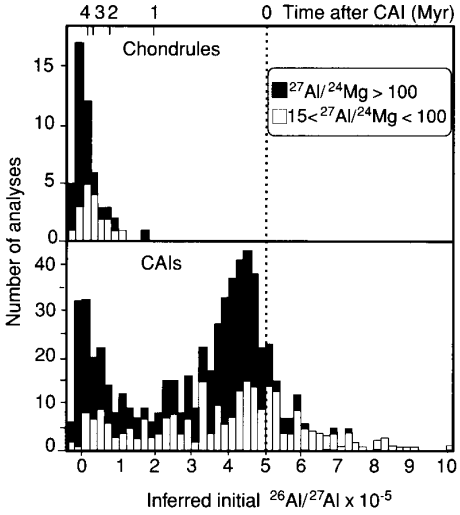
Chondrules are apparently ~2-4×10^6 a younger than CAIs



Assumption: ^{26}Al was uniform in early solar system

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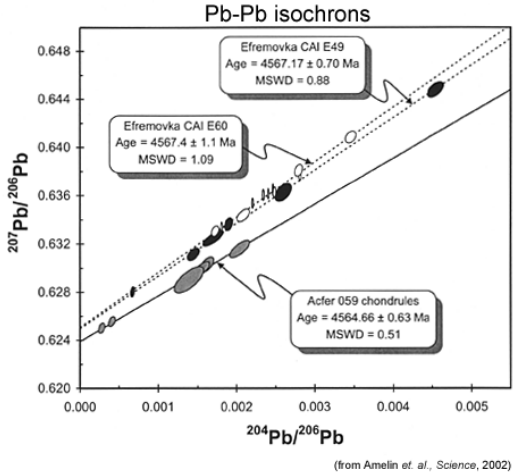
- ^{26}Al data consistent with Pb-Pb absolute age data
- inner solar system had uniform ^{26}Al distribution
- ^{26}Al did not form close to the Sun ("X-point") by irradiation



(from Amelin *et. al., Science*, 2002)

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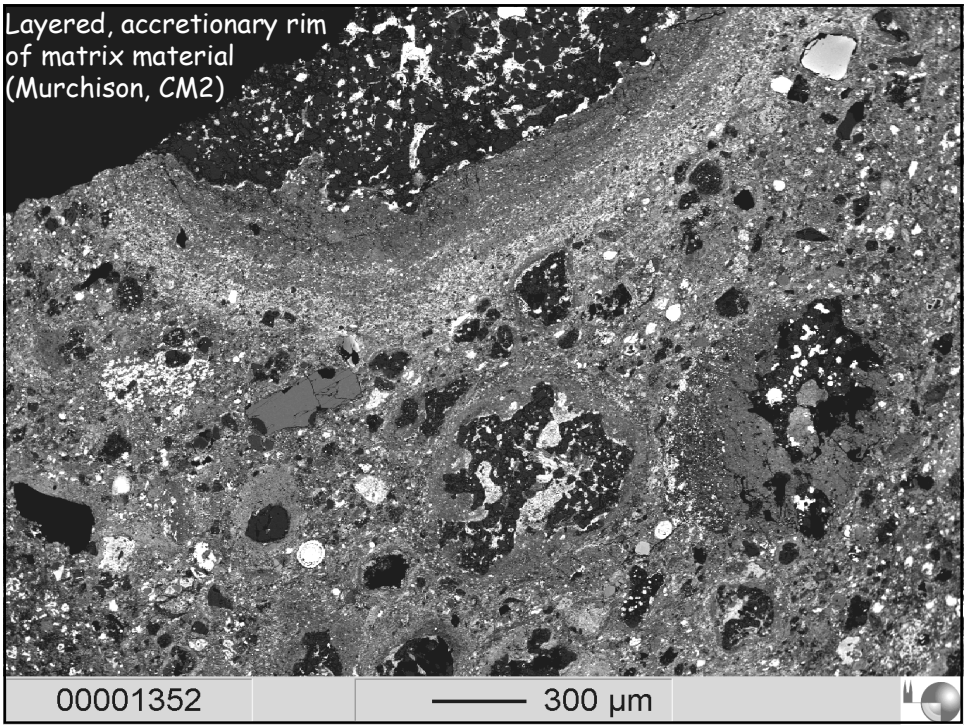
Chondrite major components (III)

- Ca,Al-rich inclusions (CAIs)
- chondrules
- fine grained matrix material

Chondrite matrix

- very fine grained material (<1-5 μm)
- most susceptible to aqueous alteration on the parent body
- represents the low-T fraction of chondrites



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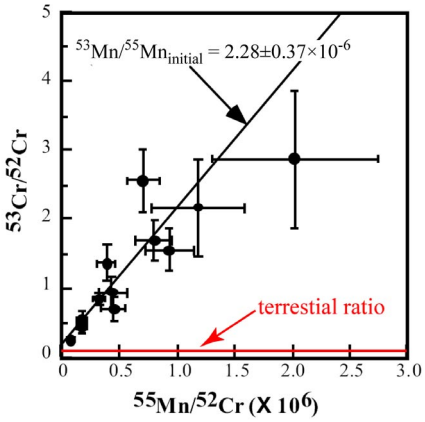
Age dating of matrix material

- $^{53}Mn \rightarrow {}^{53}Cr$, $t_{1/2} = 3.7\times10^{6}$ a, $^{53}Mn/^{55}Mn_{initial} = 1.4\times10^{-5}$

- matrix material (Kaba, CV3) is ~9×10^{6} a younger than± CAIs
- dates the alteration on the meteorite parent body
- $^{53}Mn/^{55}Mn$ ratio was uniform in the early solar system



Hua et al. (2001) LPSC XXXIII

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Are there unprocessed mineral condensates?

- Fe,Ni-Metall ($Fe_{93}Ni_{7}$)
- forsteritic olivine (Mg_2SiO_4)

What were the conditions in the early solar system?

- metal/silicate equilibria can be used to quantify
  - condensation temperature
    - pressure (density) of the nebular gas
  - oxygen fugacity (O/H-ratio)

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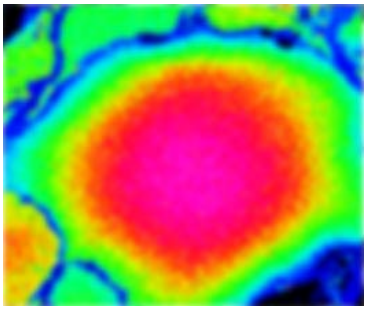
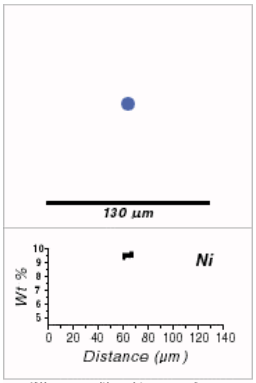
Yes, there are!

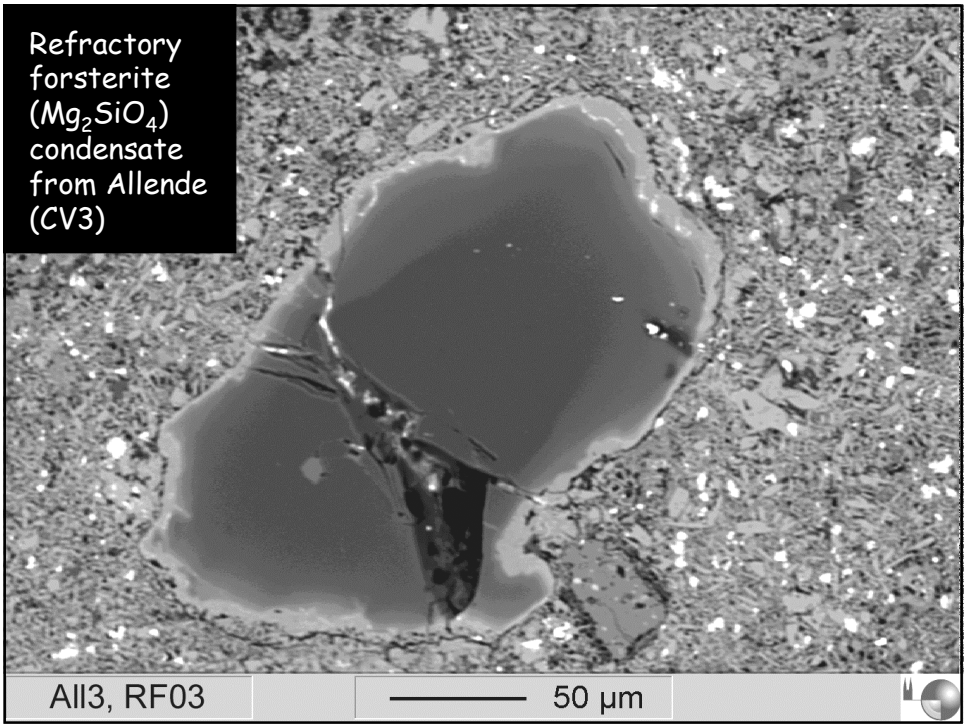
- condensed Fe,Ni-metal grains
- zoning in Ni, Co, Cr, P and Si indicative for formation by gas/solid condensation



false color image of a zoned metal grain (width ~ 200 µm, Schönbeck, 2003)



(Ni compositional traverse from Meibom, *et al.*, 1999.)



Andreas Pack

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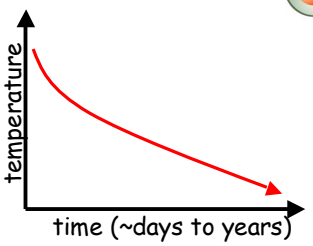
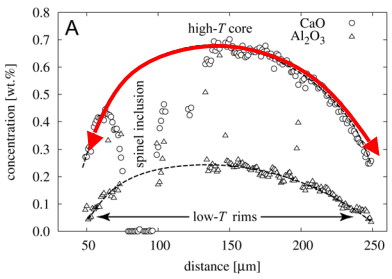
Condensation signatures in single mineral grains from type-3 chondrites

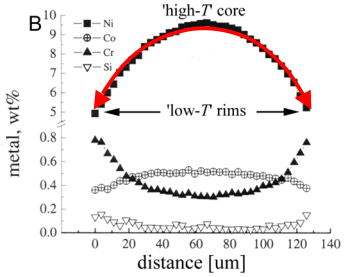
- refractory forsterite
- extremely high contents of Ca, Al, Ti



zoned refractory forsterite*



zoned metal grain



*from Pack et al., MAPS, submitted

Andreas Pack

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Ongoing project on forsterite condensates*

- quantification of temperatures, pressures and O/H-ratios in the early solar system
- forsterite condensates (unlike metal condensates) present in all types of chondrites (carbonaceous, ordinary, R-chondrites)
- T, p, f_{O_2} map of the early solar system (FU-Orionis/T-Tauri phase)
- distribution of ^{16}O in the solar system

*collaboration with H. Palme (Köln), H. St. C. O'Neill (Canberra), H. Yurimoto (Tokyo) and E. Deloule (Nancy)

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iron meteorite with shiny fusion crust (width ca. 25 cm)