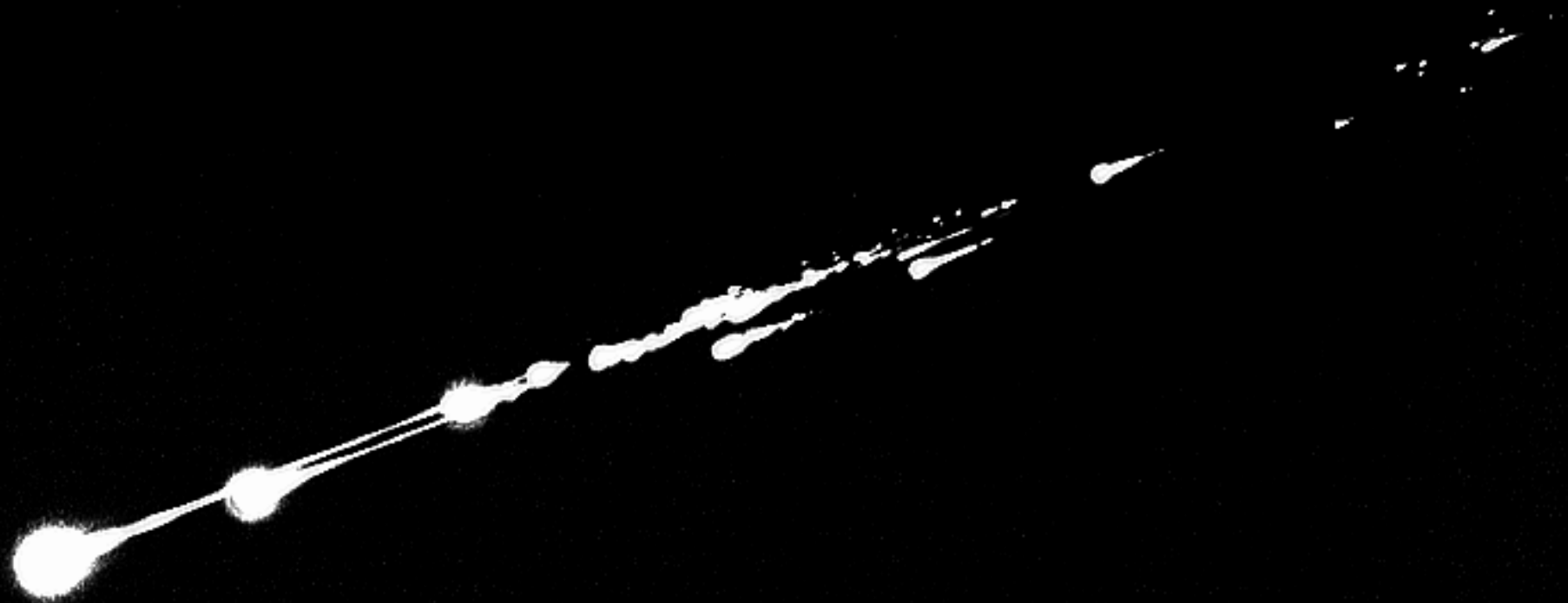


# Les météorites, témoins de la formation des planètes

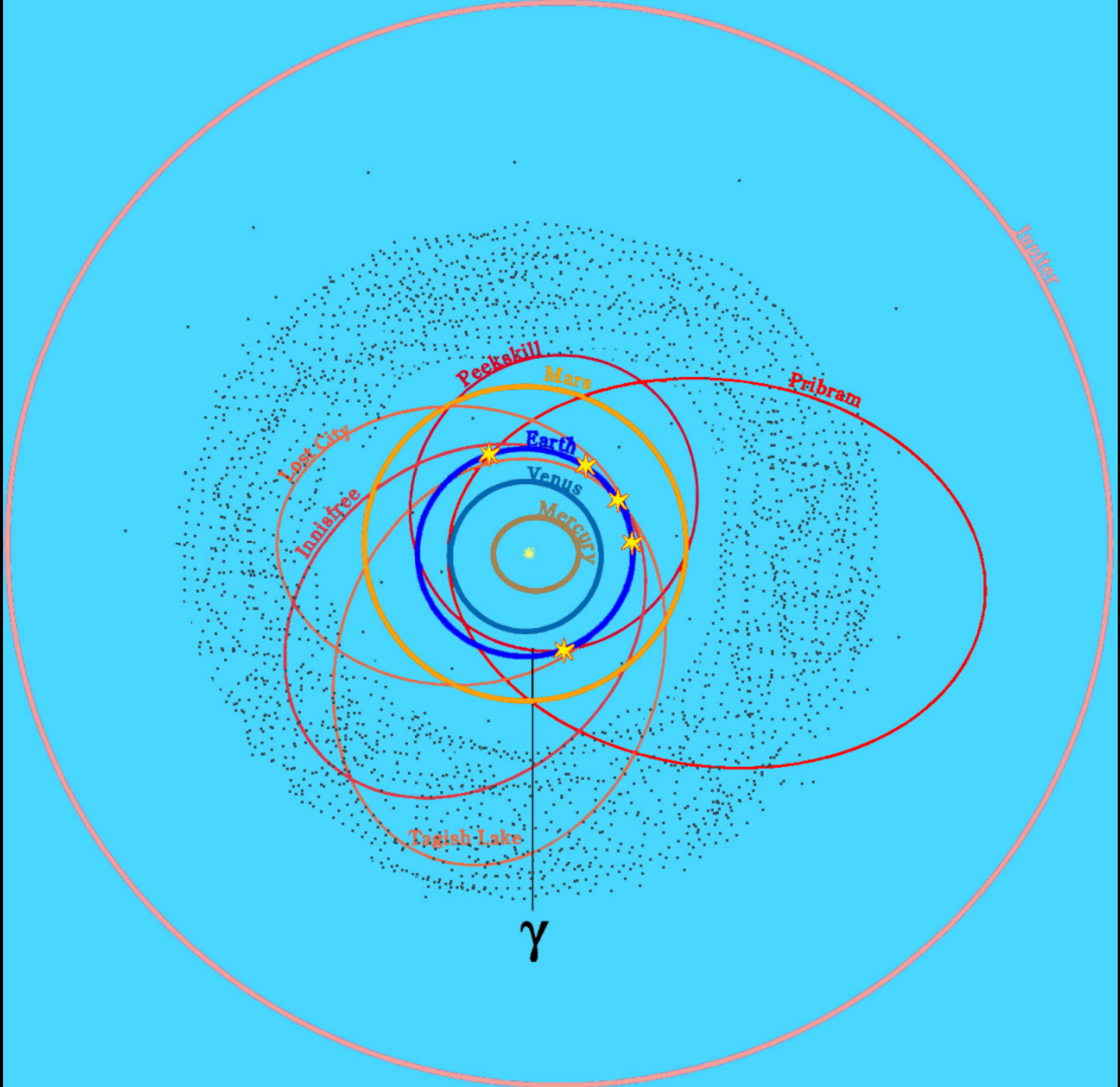
**B. Zanda**

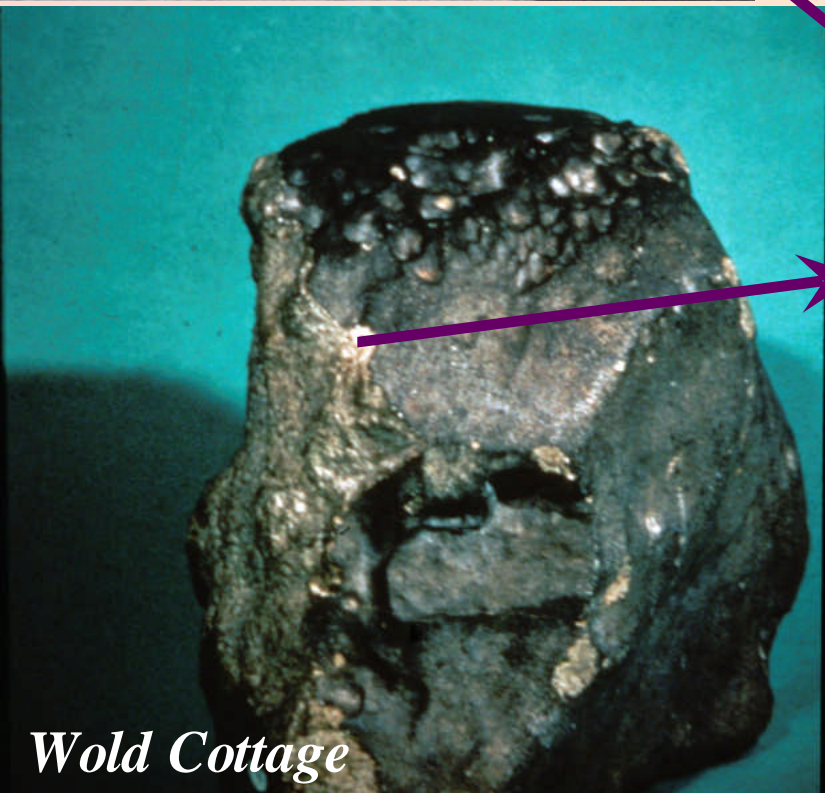
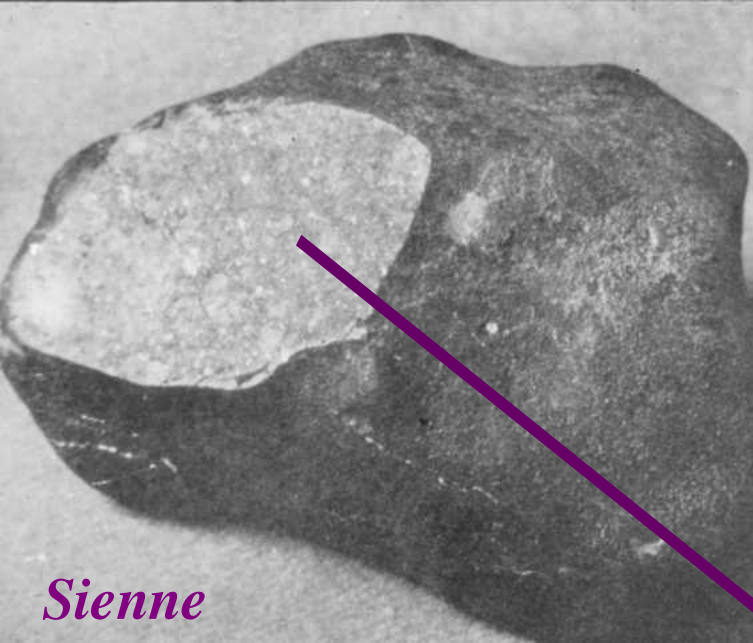
*Laboratoire d'Etude de la Matière extraterrestre*

**Muséum national d'Histoire naturelle**







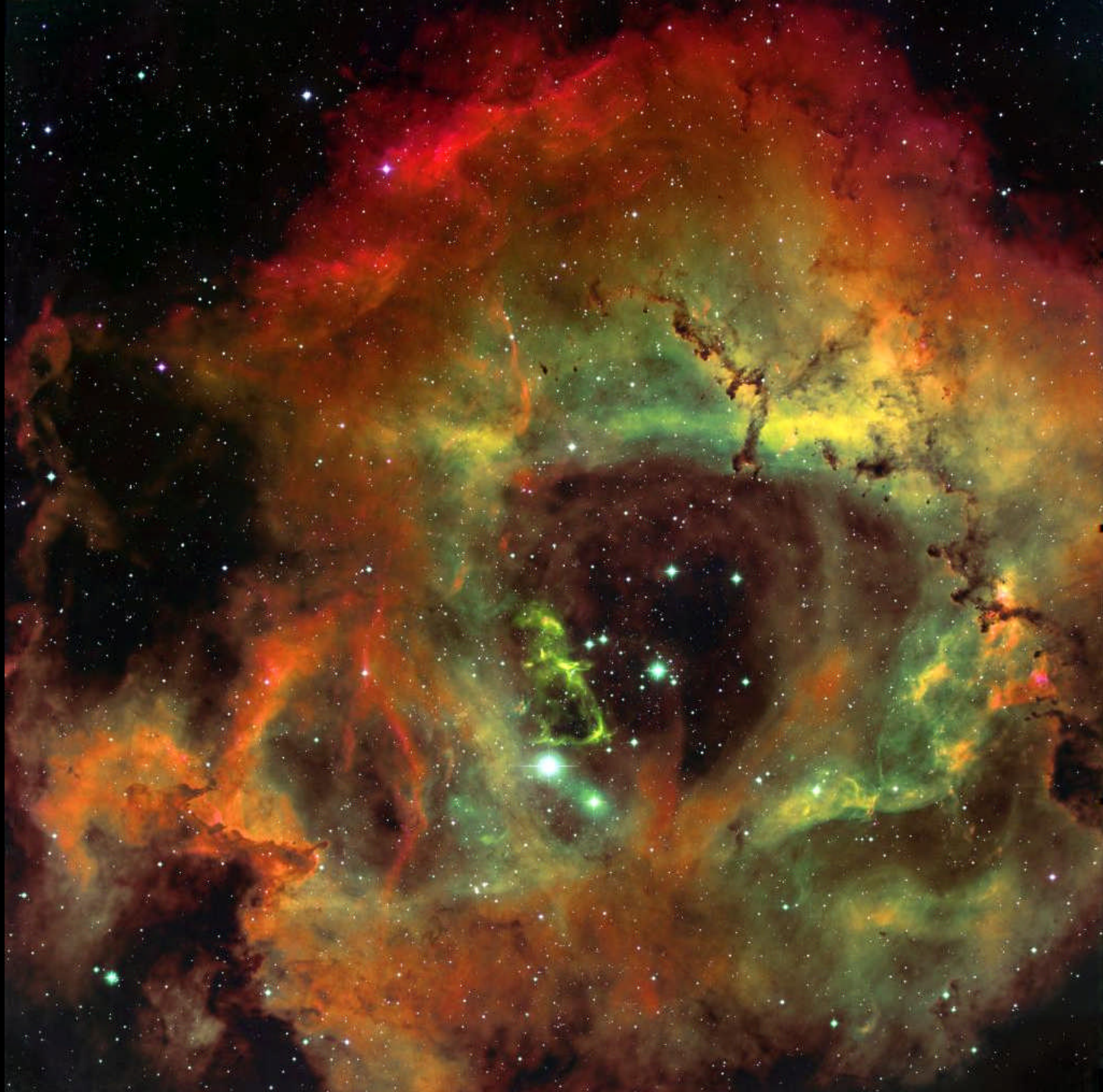


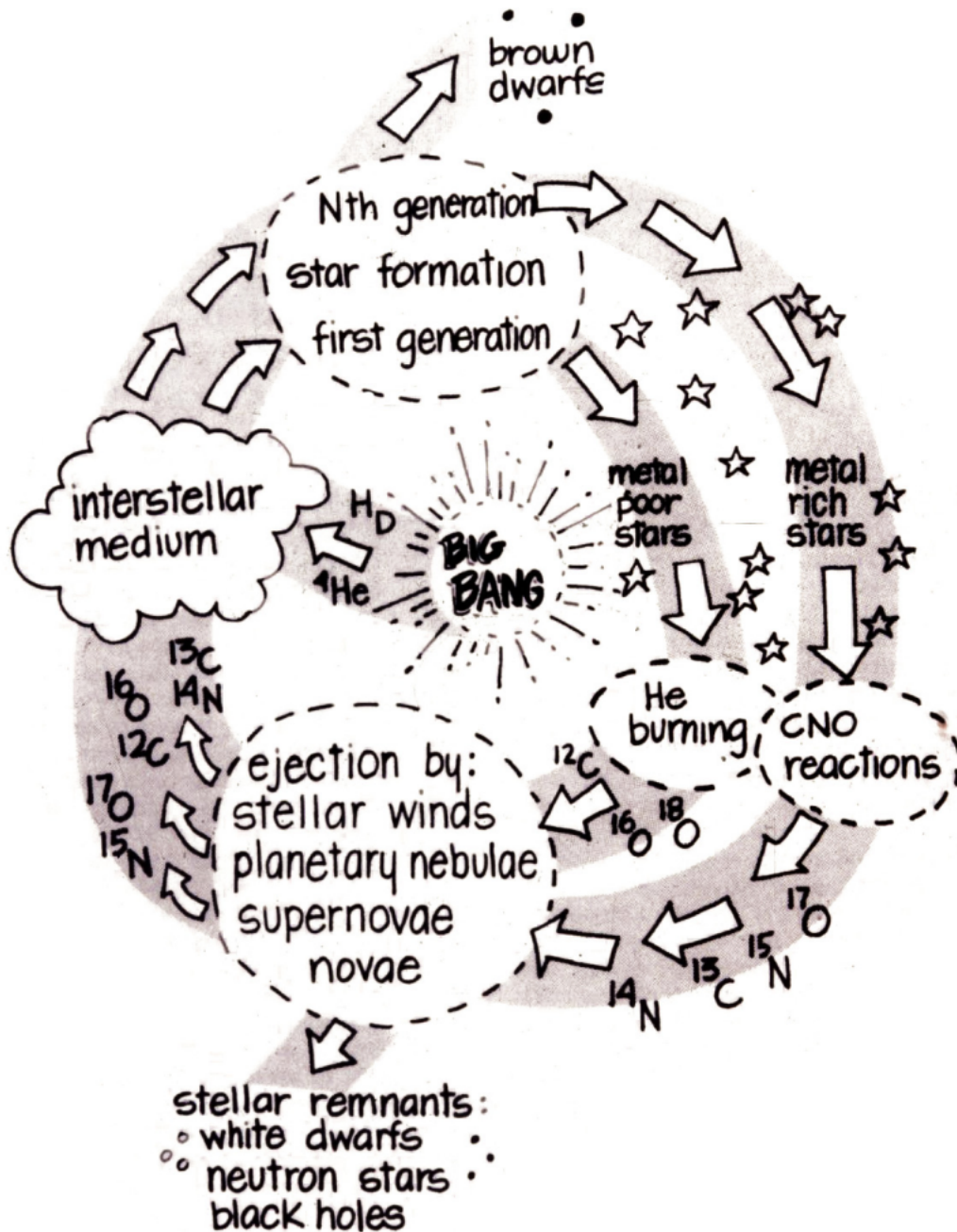
**Fe  
metal  
+ Ni**



# I. Le contexte astrophysique







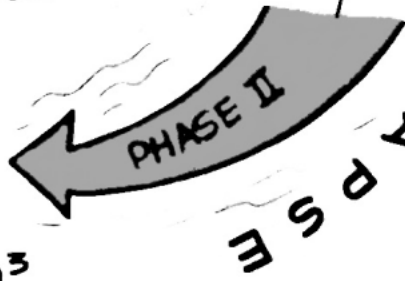


# FRAGMENTATION of an interstellar cloud

Original cloud  
dimension,  
 $\sim 10$  pc  
 $\rho \sim 10^4 \text{ H}_2/\text{cm}^3$   
 $T \sim 10\text{-}50 \text{ K}$



P  
R  
E  
S  
T  
E  
L  
L  
A  
R  
C  
O  
L  
L  
A  
P  
S  
E



Solar  
nebula:

$\sim 10^2$  AU  
 $\sim 10^{20} \text{ H}_2/\text{cm}^3$   
 $\sim 2000 \text{ K}$



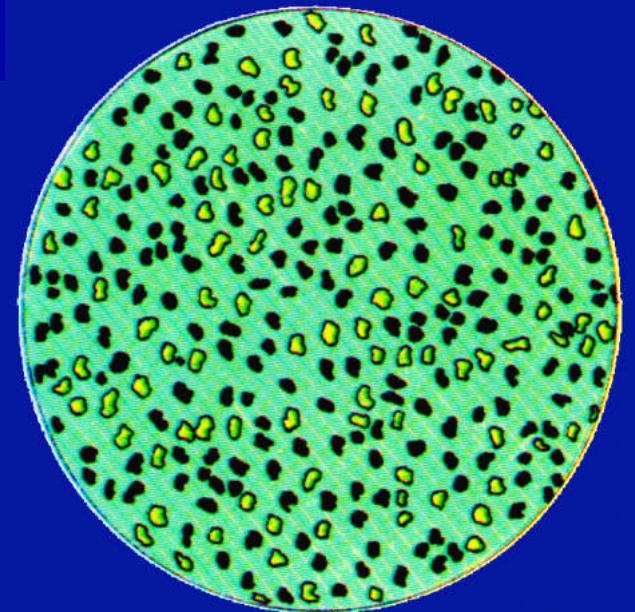




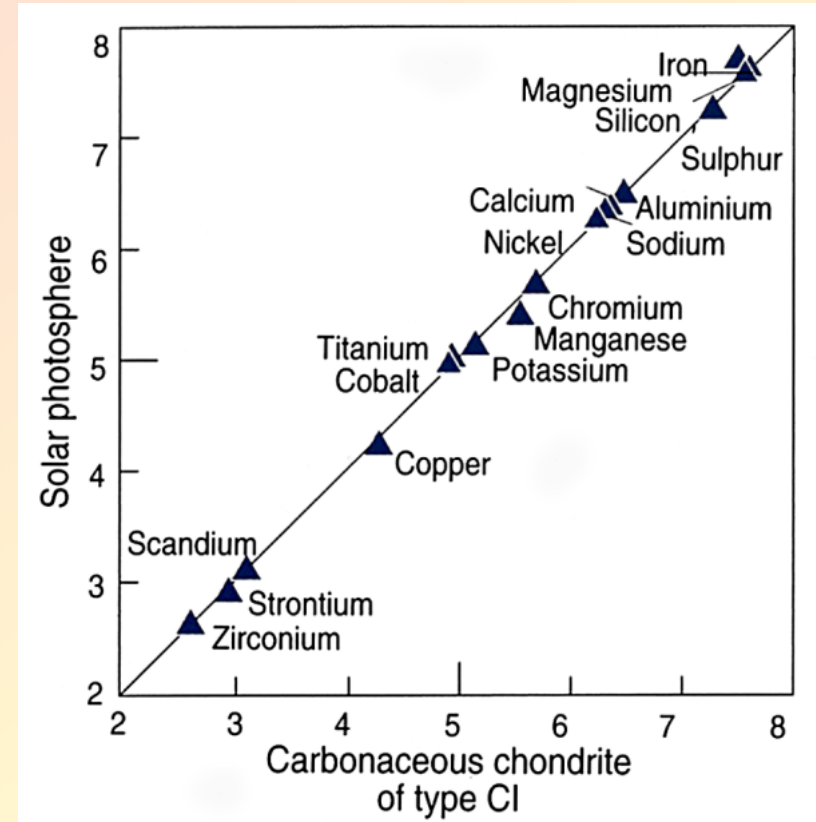
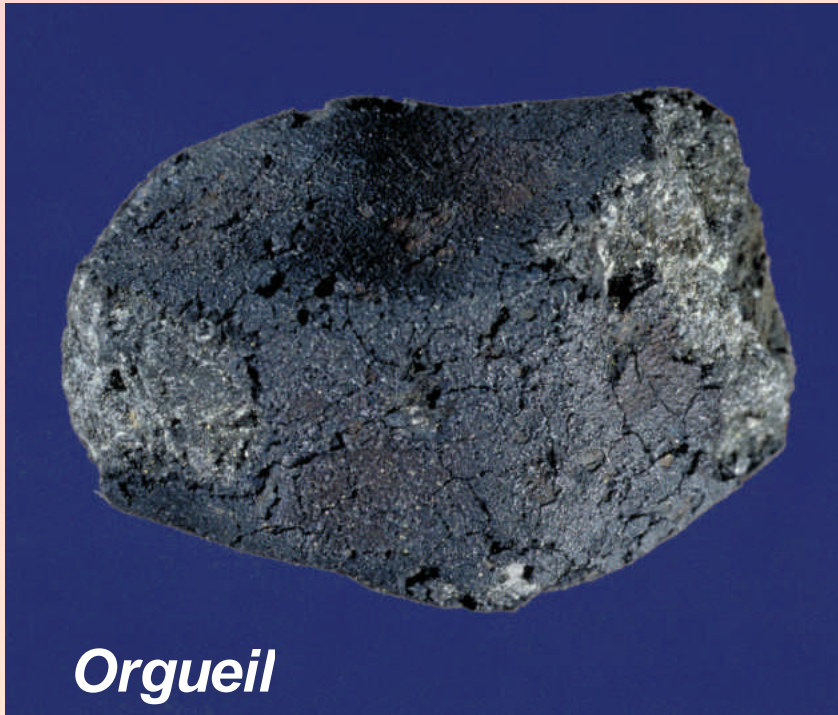
*W.K. Hartmann*



**Les premiers solides formés  
au voisinage du soleil avaient  
la même composition  
chimique que celui-ci...**



Seules les chondrites carbonées CI ont réellement la composition chimique du système solaire...

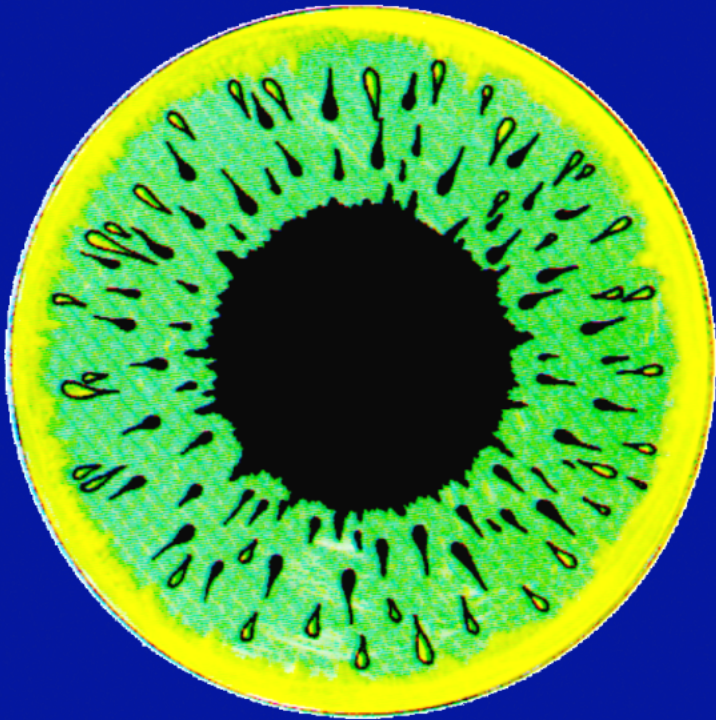


*mais elles n'ont pas de chondres!*  
*...et apparaissent plutôt comme de la « boue » asséchée*

A microscopic view of plant tissue, likely a leaf cross-section, stained with various dyes. The cells are stained in shades of yellow, orange, red, purple, and blue, highlighting different cellular structures and tissues. The overall appearance is a complex, interconnected network of stained cells.

# II. La différenciation

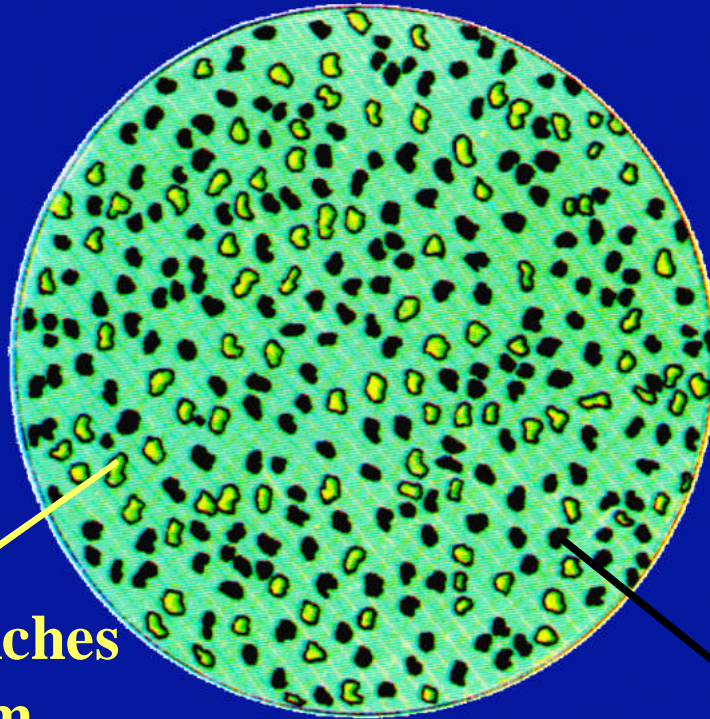
**La chaleur dégagée par la décroissance radioactive des éléments de période courte et aussi par le bombardement intense a fondu la plupart de ces corps:**



**Les minéraux les plus denses ont “coulé” au centre pour former un **noyau**, tandis que les minéraux les moins denses remontaient à la surface pour former une **croûte**. C’est ce qu’on appelle la **différenciation****

**La croûte de la Terre continue à se former: la Terre est une planète « active » avec du volcanisme**

**Mais certaines planètes plus petites ou formées plus tard que les autres (après la décroissance des éléments radioactifs de courte période) n'ont PAS FONDU...**

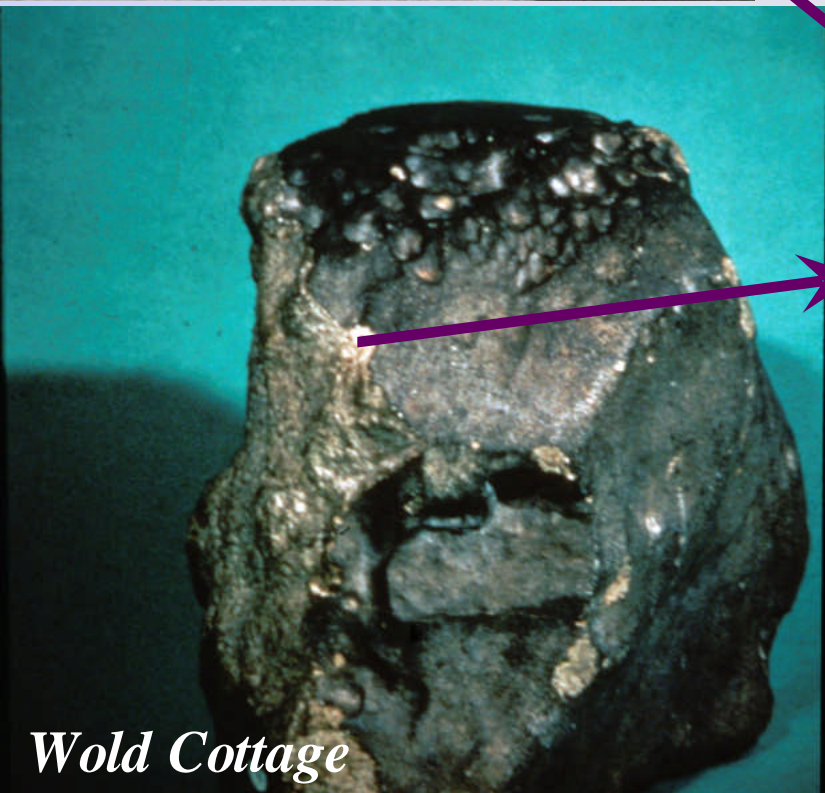
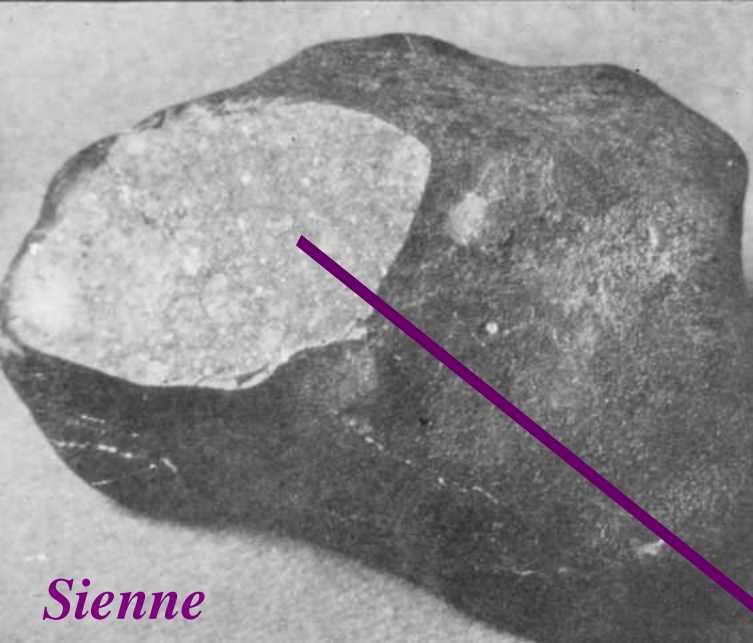


**Minéraux riches  
en calcium,  
aluminium et  
sodium (légers)**

**Minéraux riches  
en fer (denses)**

**Les fragments qui nous  
en proviennent ont  
conservé la composition  
chimique du soleil et de  
la nébuleuse solaire. On  
dit que ces objets sont  
non-différenciés**





**Fe  
metal  
+ Ni**



# Météorites différenciées



Chondrites



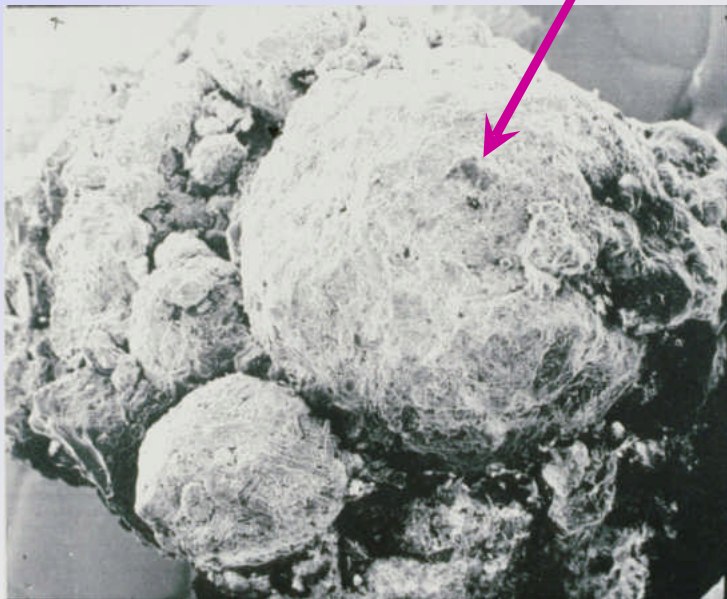
**Métal**



**Croûte de fusion**

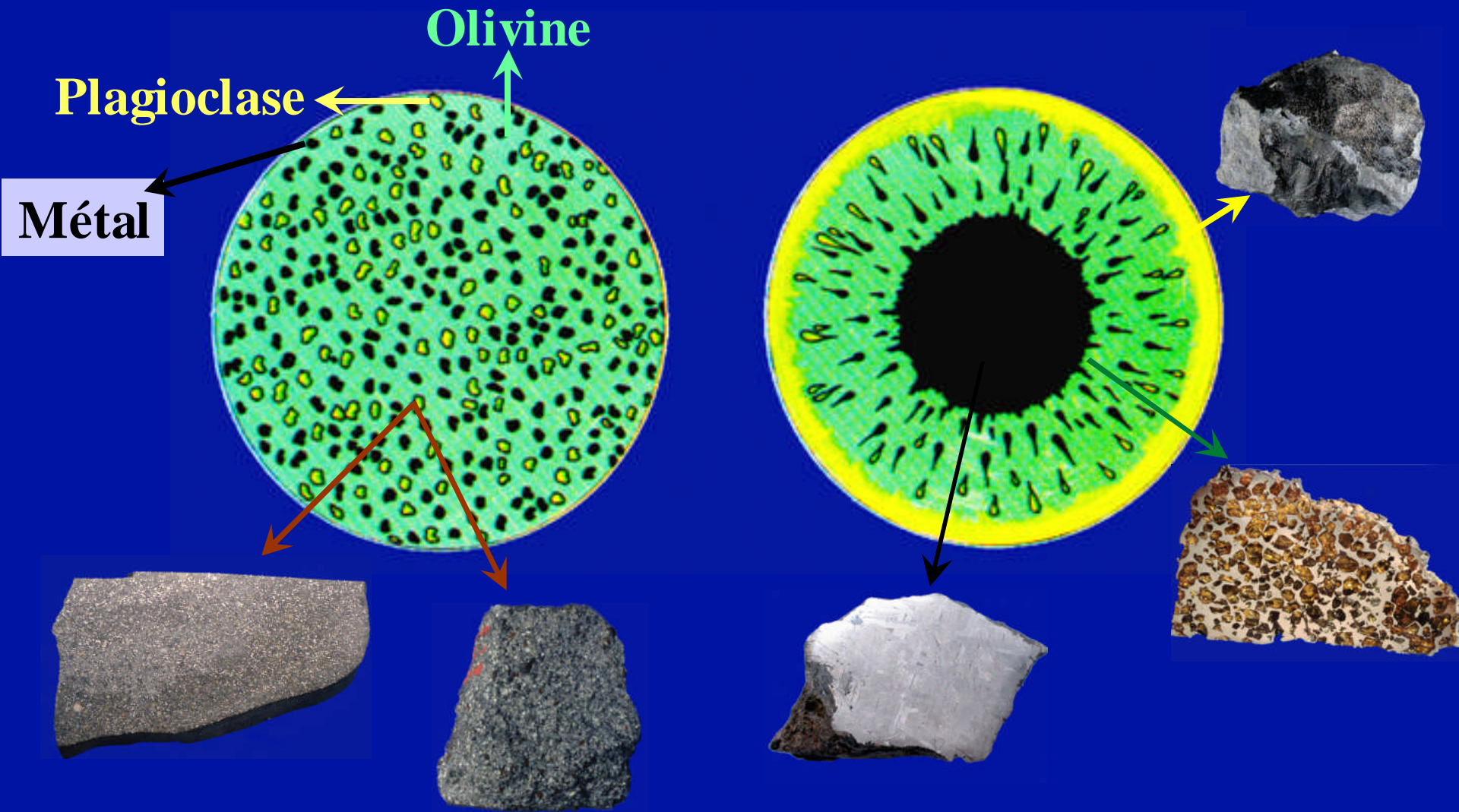
**Chondres**

**Chondrites**

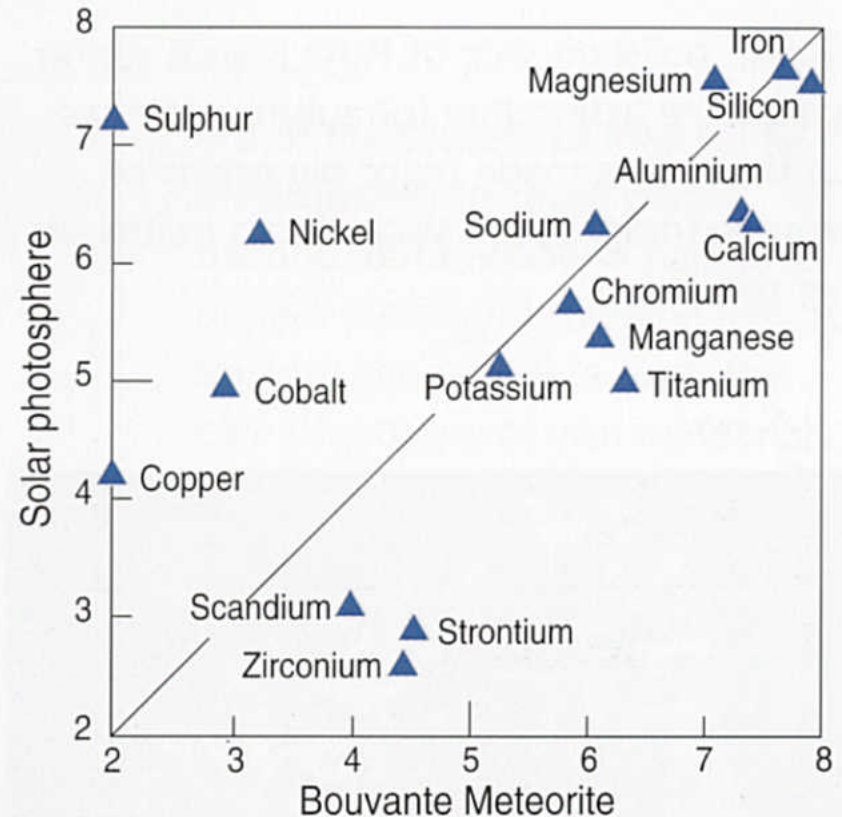
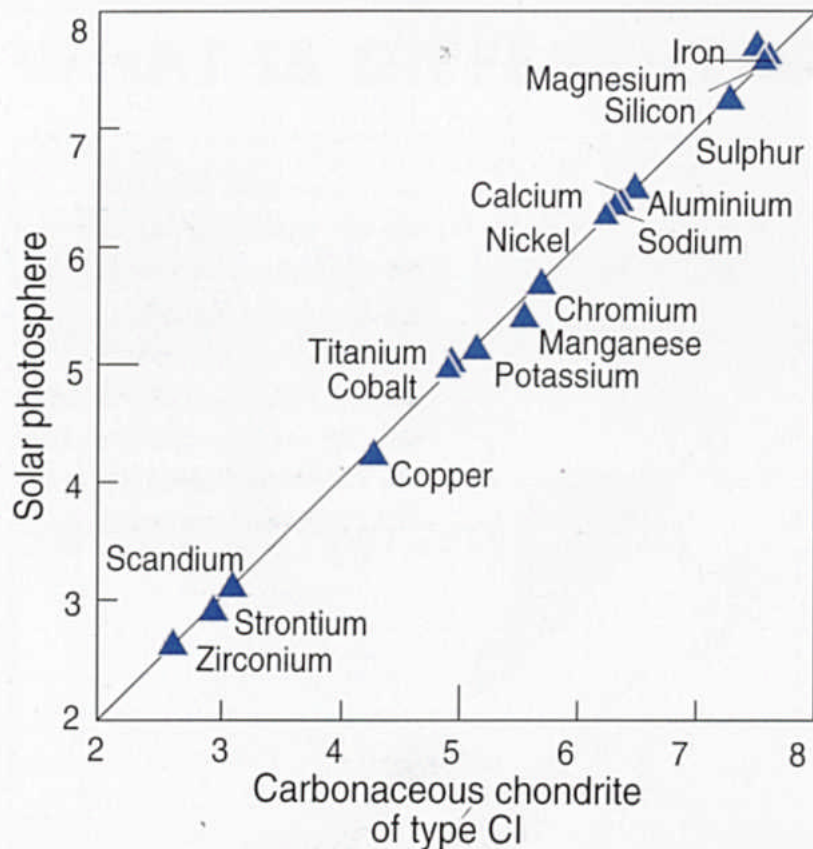


# Chondrites

# Météorites différenciées

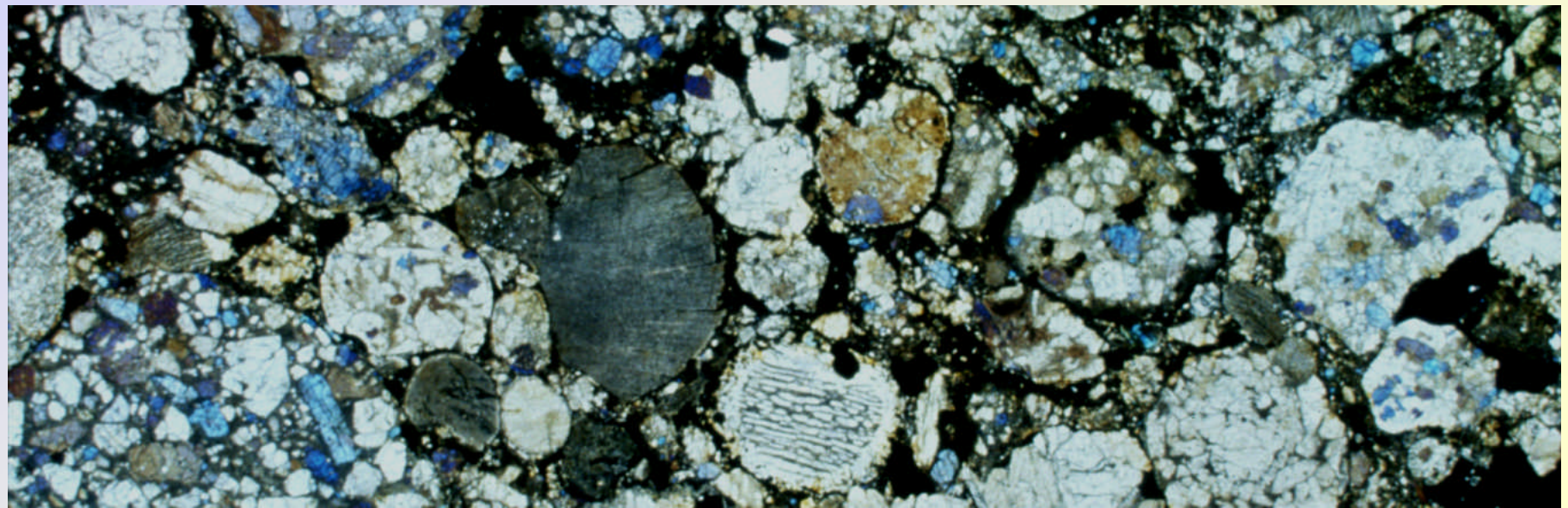


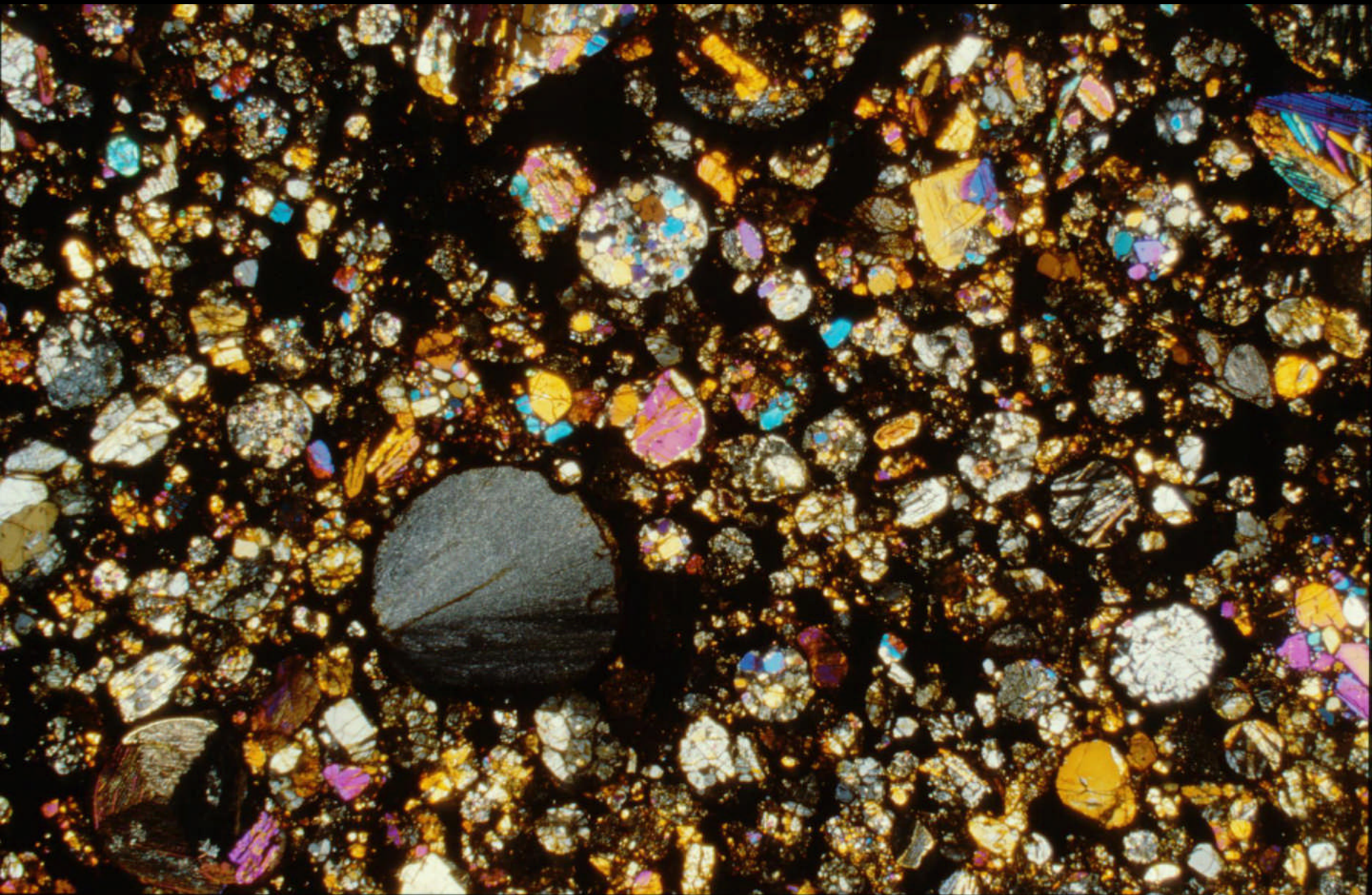
# Composition chimique des **chondrites carbonées CI** et d'une **achondrite** comparées à la photosphère solaire



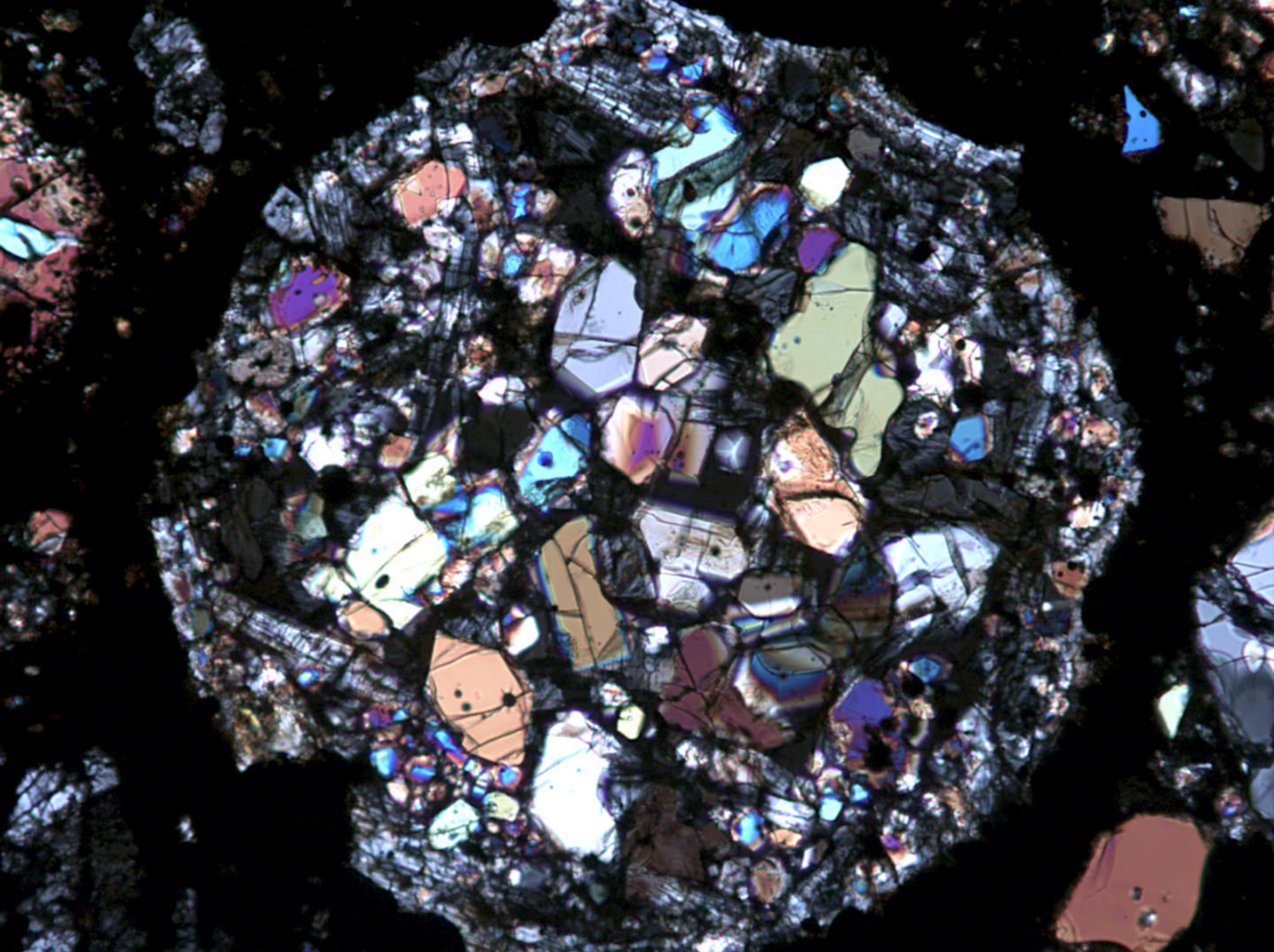


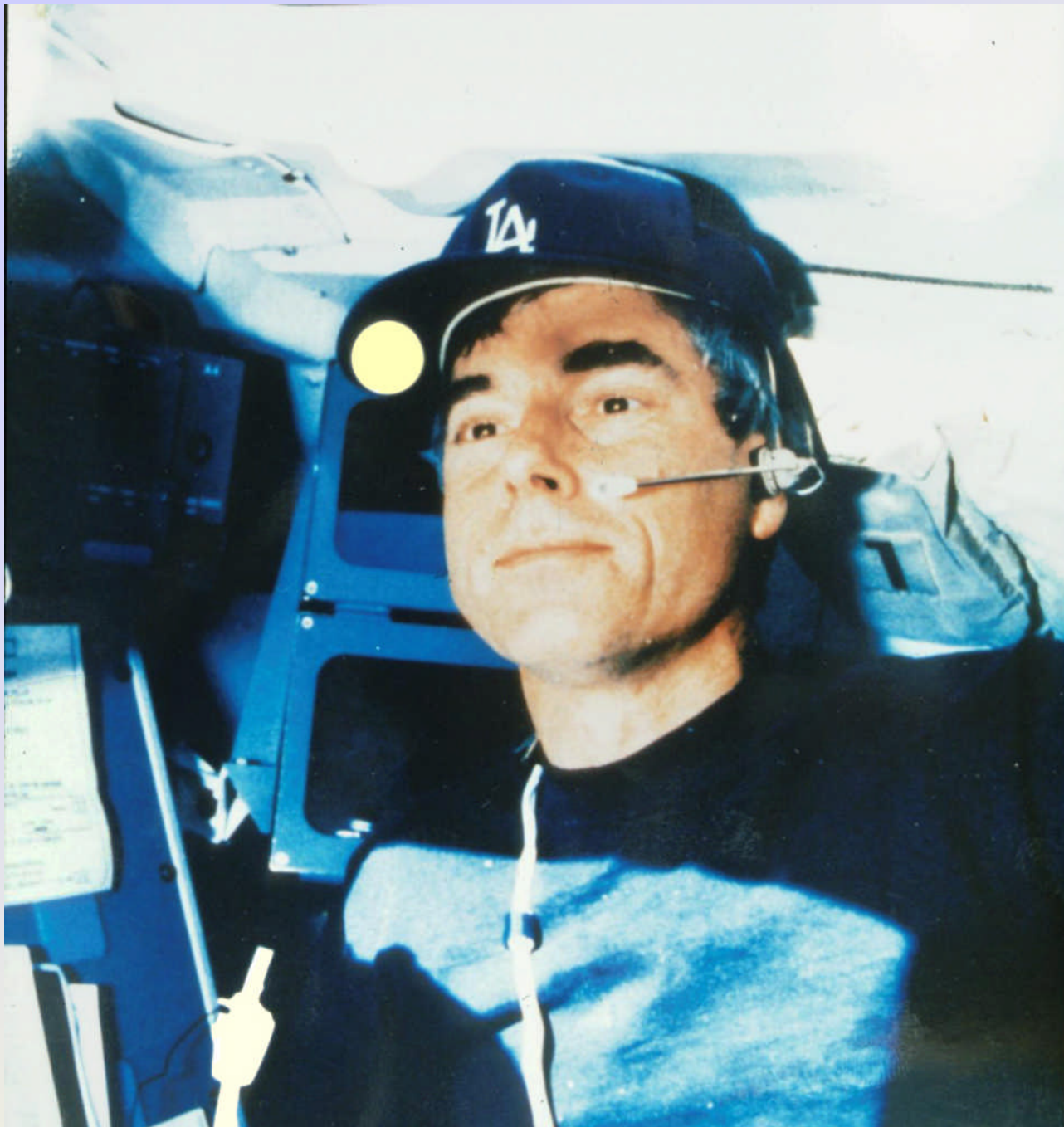
# III. Les chondrites









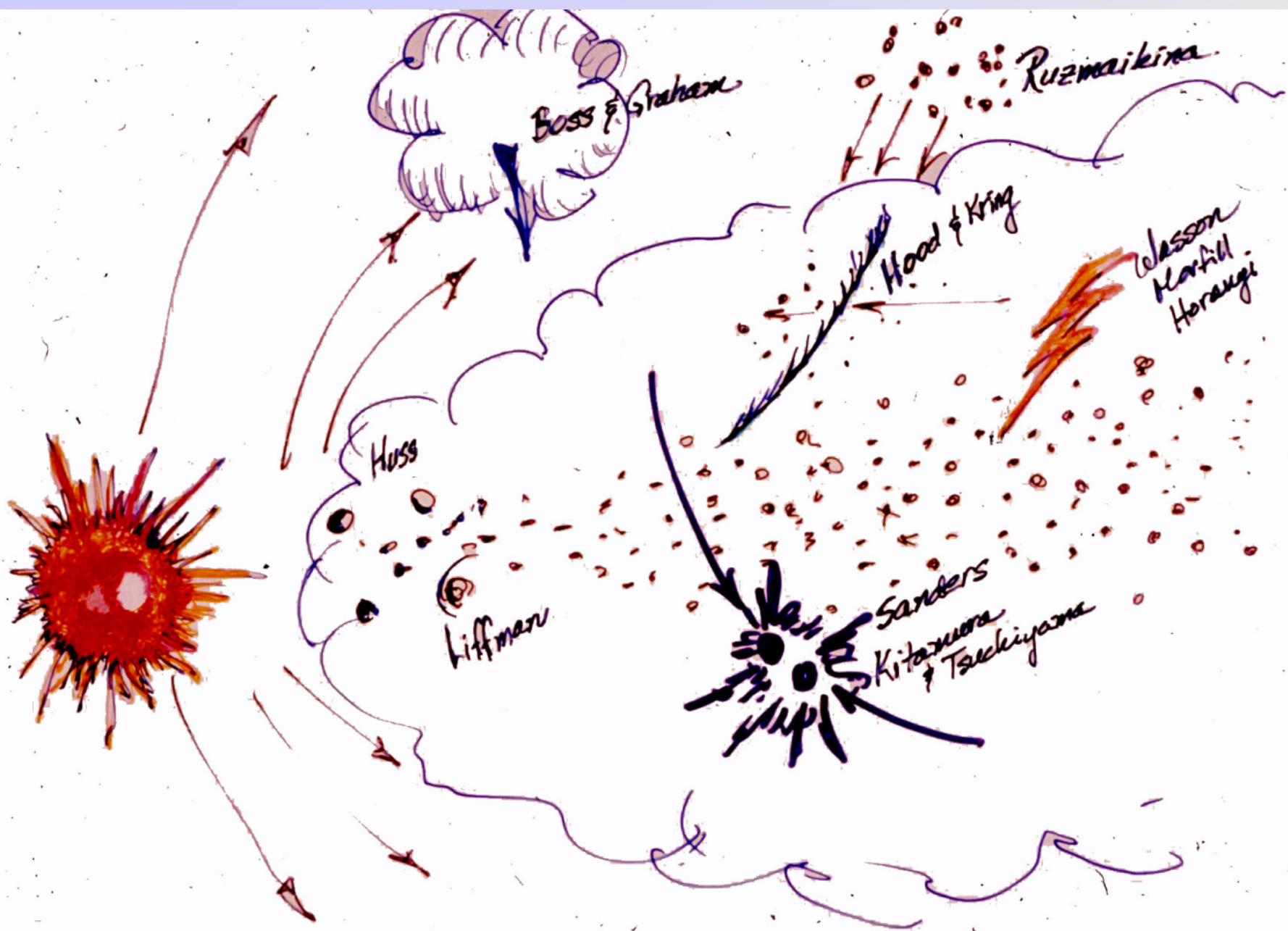


NASA

Tu v-v-vois, mon vieux whisky, toi t-t-tu  
t'es transformé en b-b-boule, mais moi  
je suis d-d-d-devenu un joli petit z-oiseau!...  
Tchip!... Tchip!... Tchip!...



Tintin! Tintin!...  
Où es-tu?...



Boss & Graham

Ruzmaikina

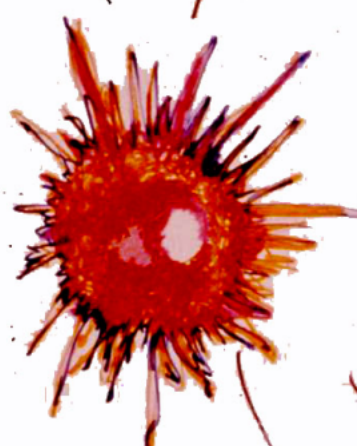
Hood & King

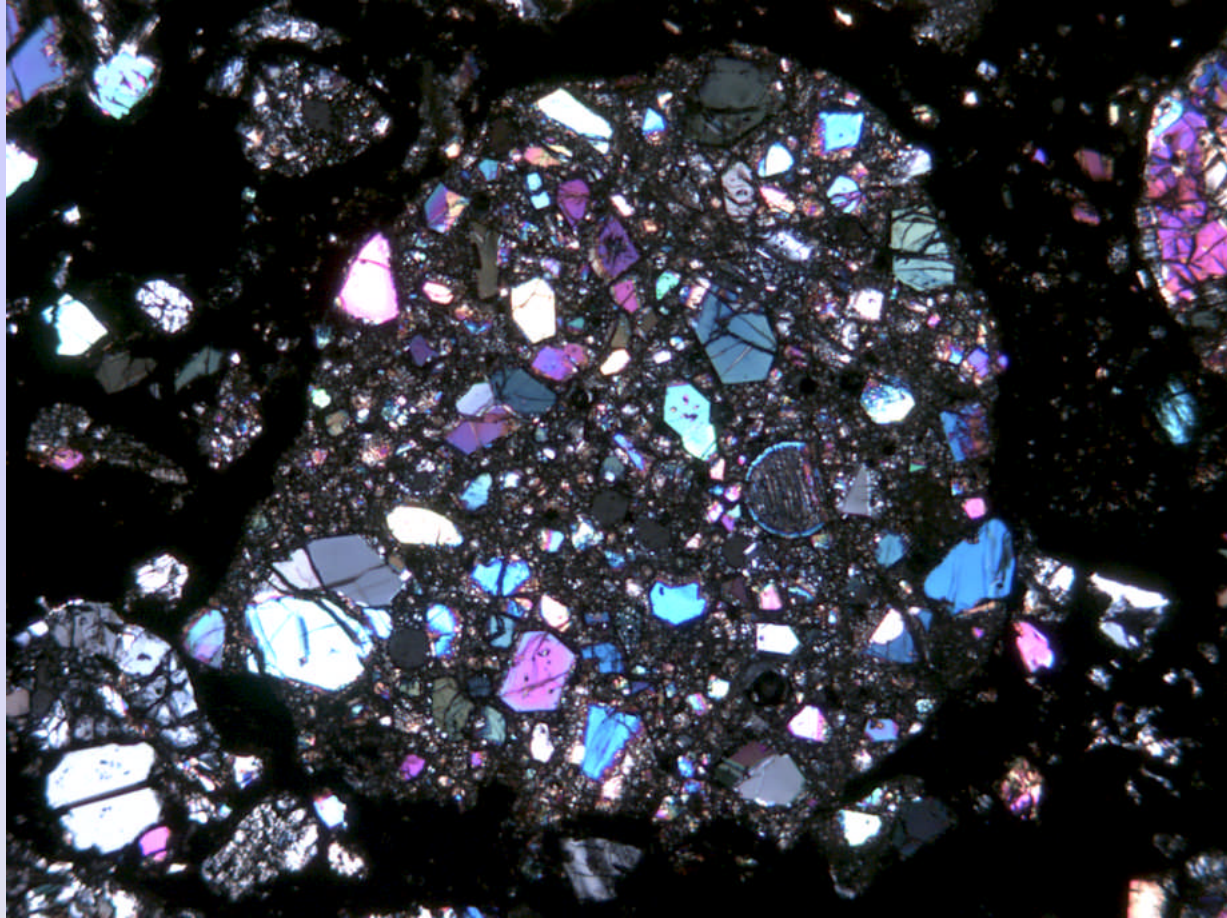
Wesson  
Morfill  
Horangi

Huss

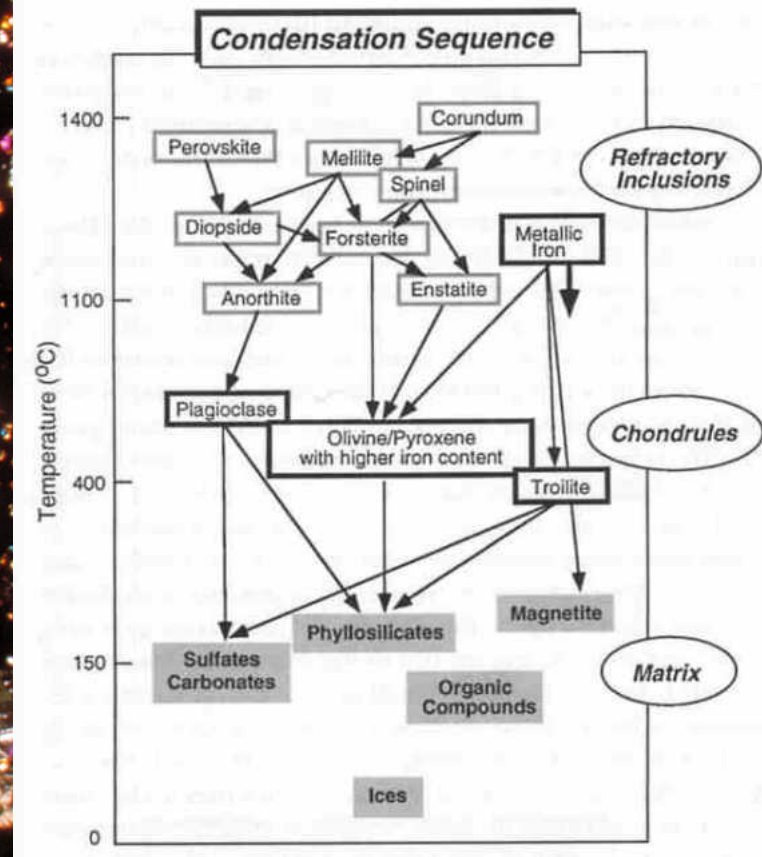
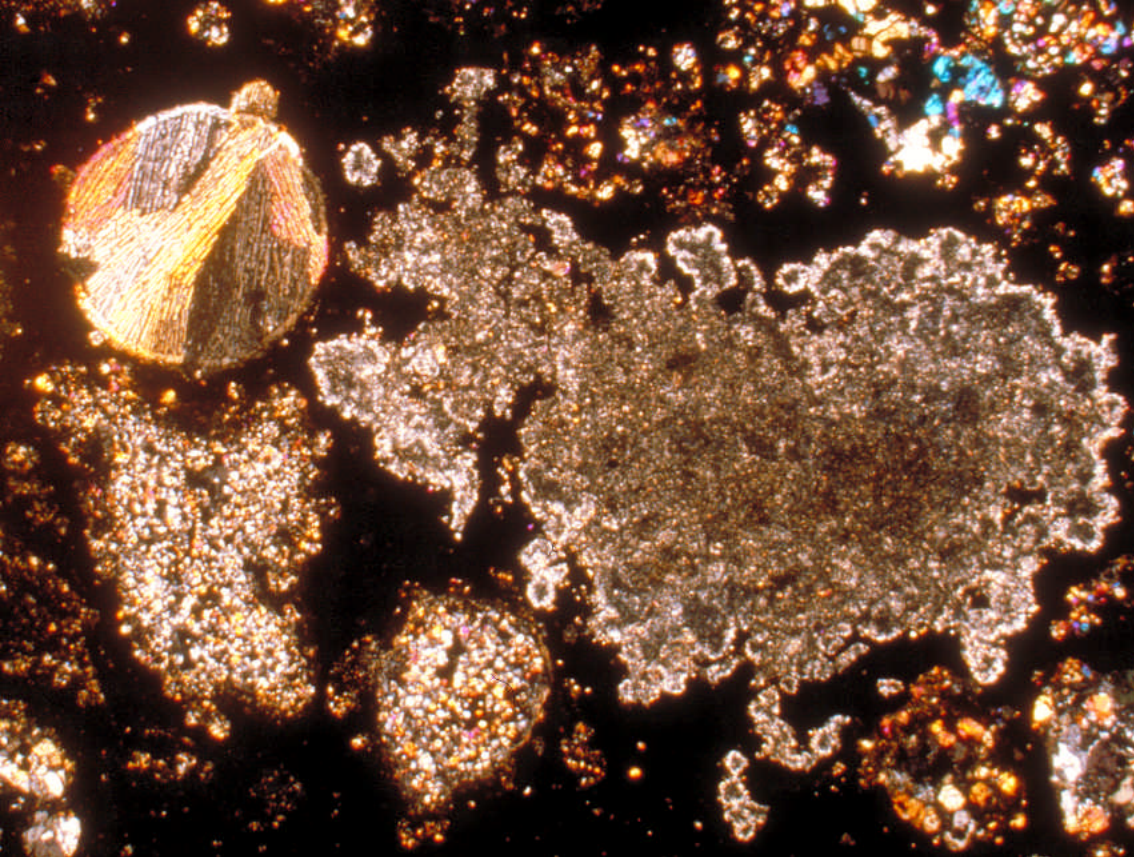
Hoffman

Sanders  
Kitamura  
& Tsuchiyama

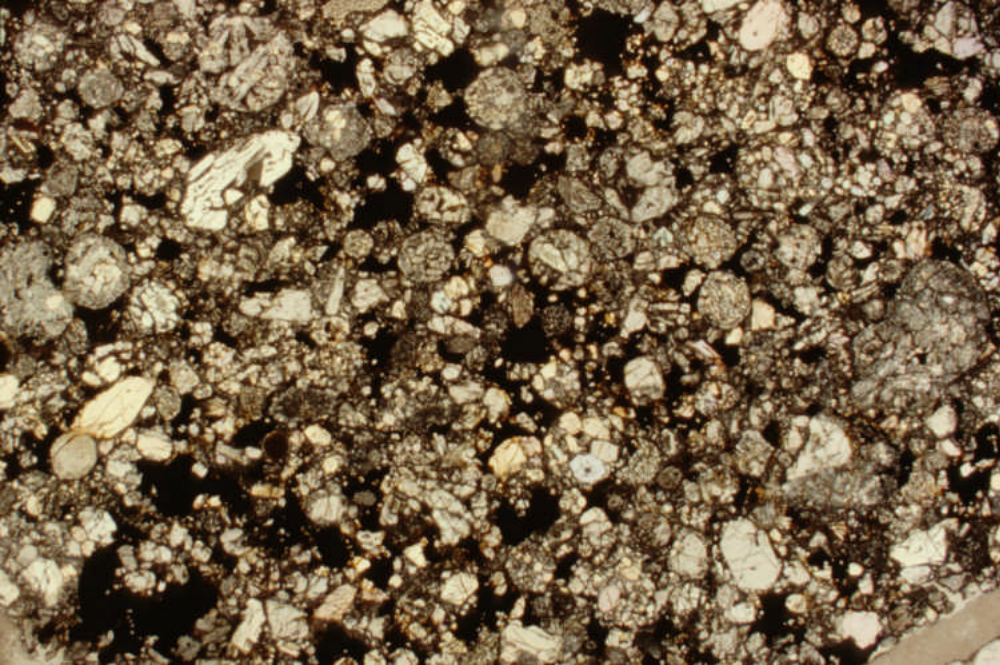




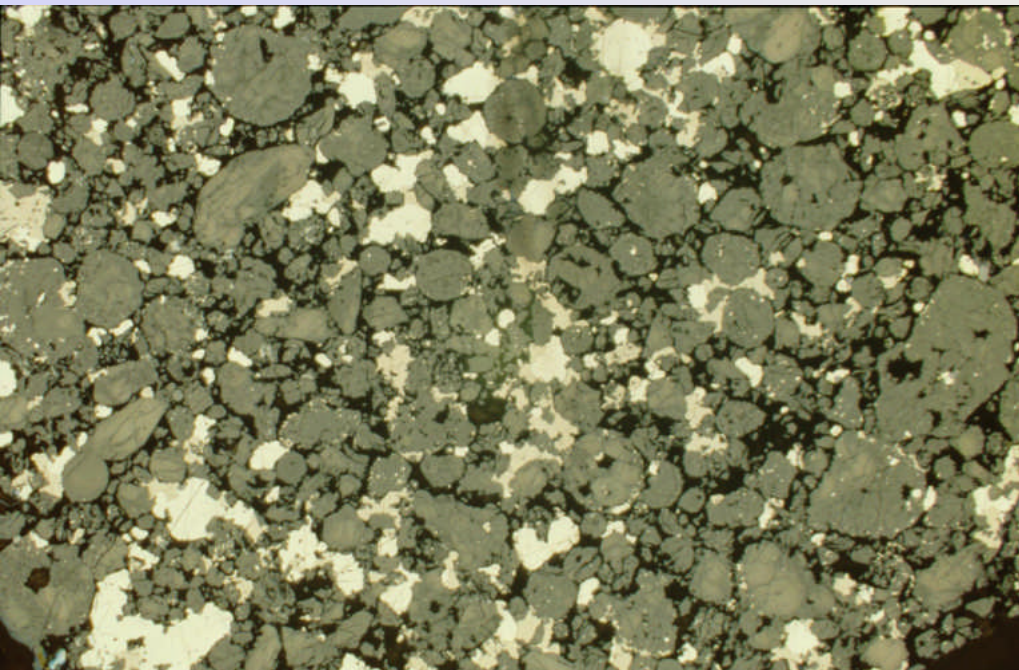
**Formés peu de temps après le soleil, les chondres sont les constituants majeurs de certaines chondrites (jusqu'à 80% du volume dans les chondrites ordinaires) dont ils semblent contrôler la chimie et même la composition isotopique**



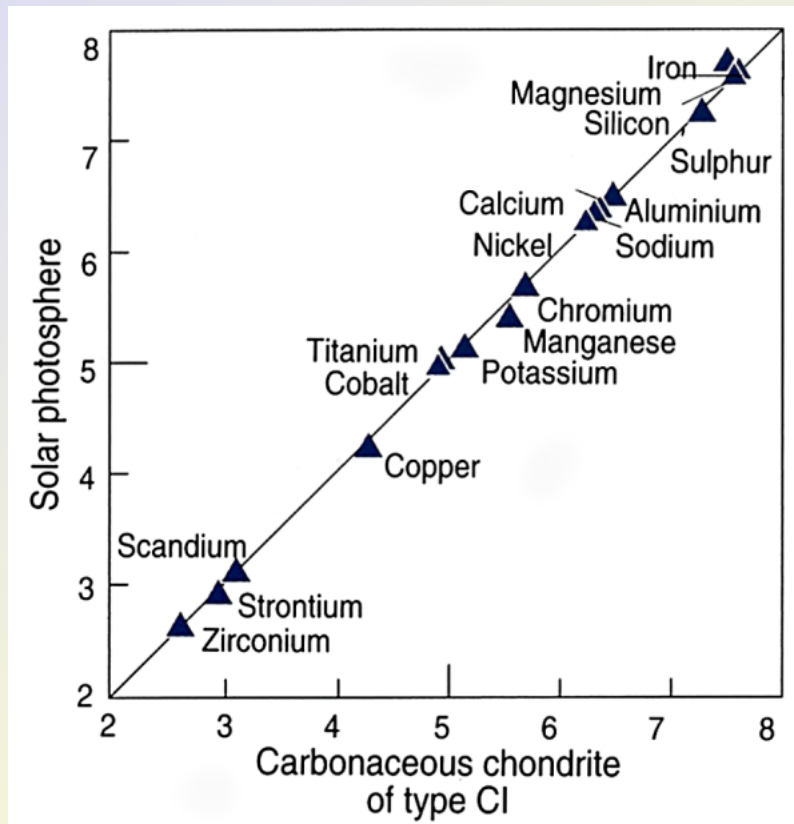
**Formées en même temps que le soleil, les inclusions réfractaires sont les objets les plus vieux du système solaire. Elles semblent contrôler la chimie et la composition isotopique de certaines chondrites carbonées.**



*Ste Marguerite (H4)*



*Lumière transmise*



*Lumière réfléchi*



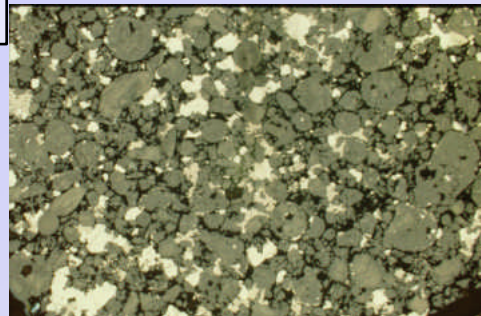
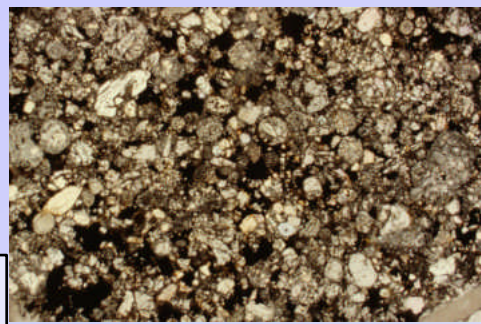
*Renazzo, CR2; Mason and Wiik, 1962*



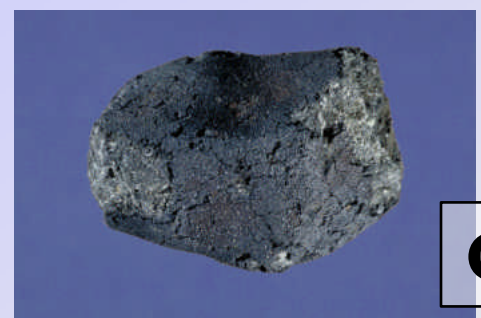
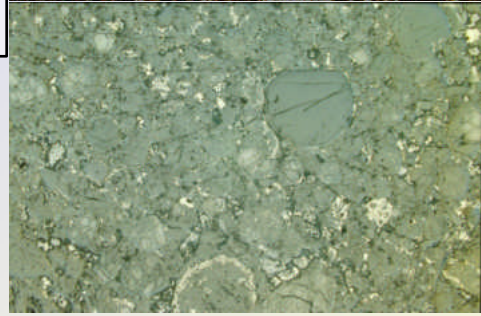
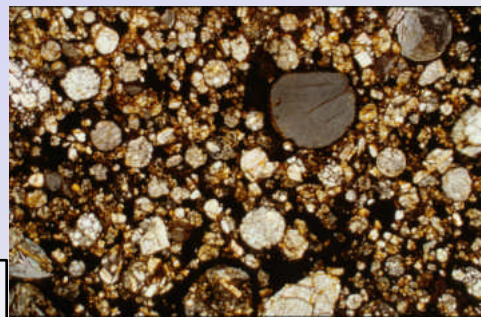
# Chondrites ordinaires

# Chondrites carbonées

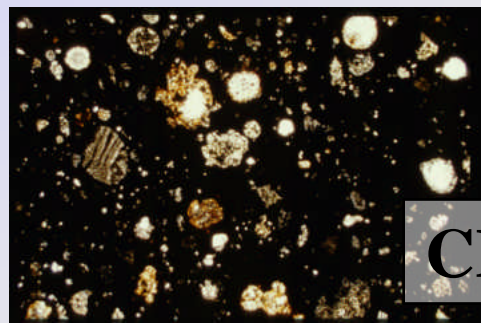
H



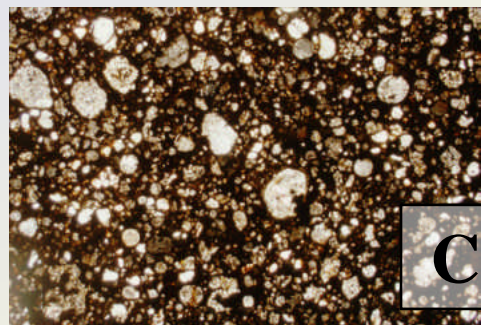
L



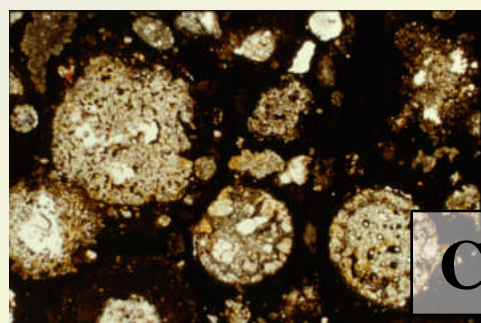
CI



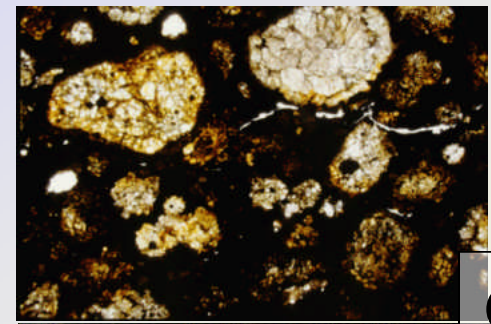
CM



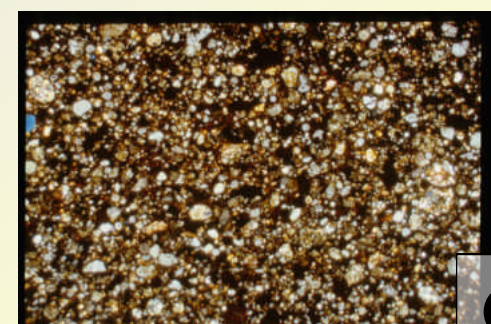
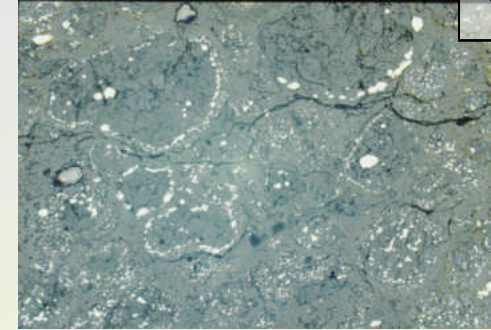
CO



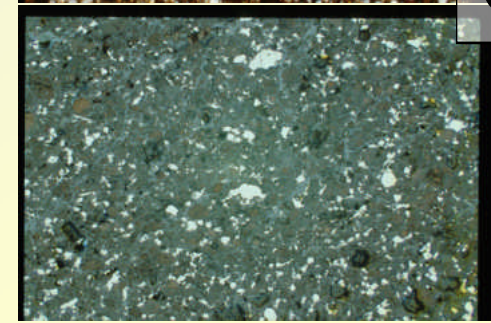
CV



CR



CH



# **IV. – Processus astéroïdaux**

- Chocs et bréchification**
- Altération aqueuse (« basse »T)**
- Métamorphisme thermique**
- Différenciation**



*St Mesmin*

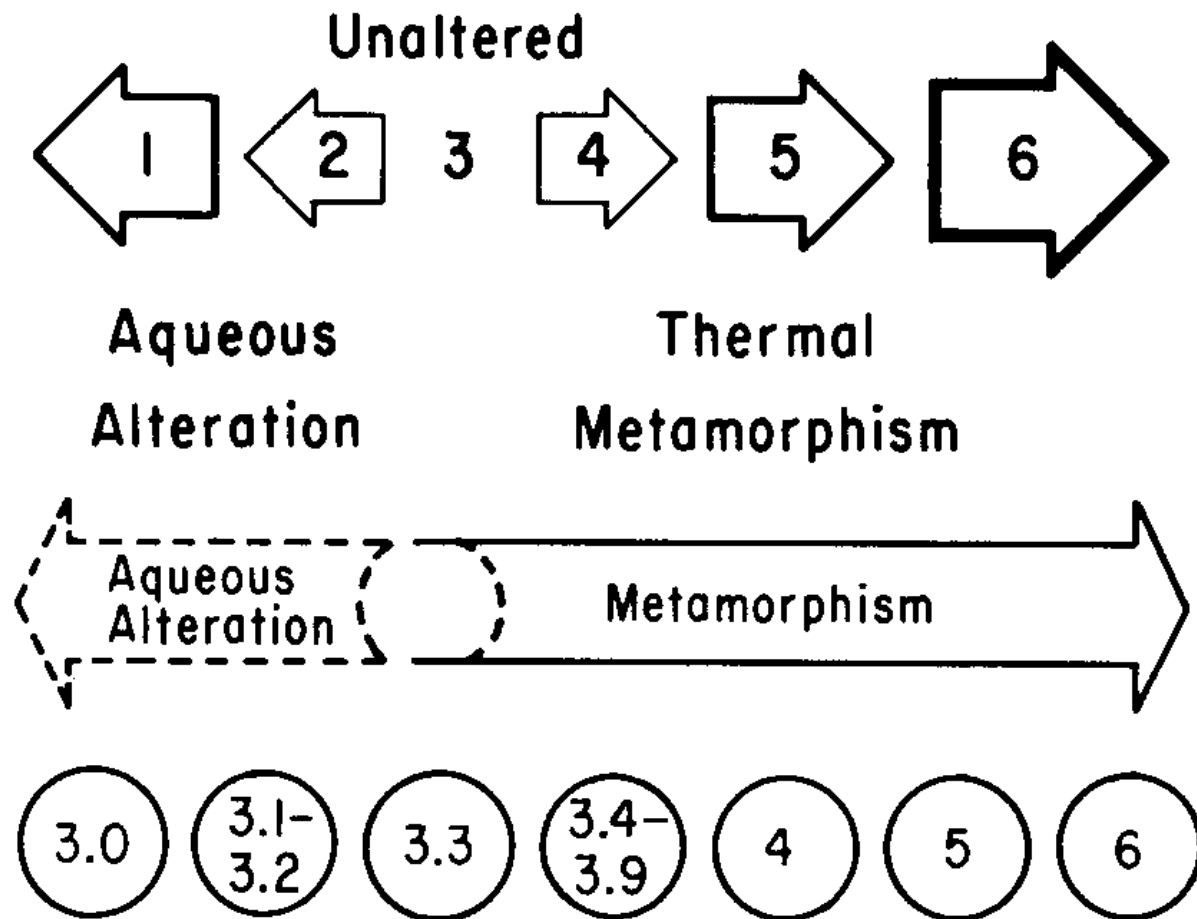
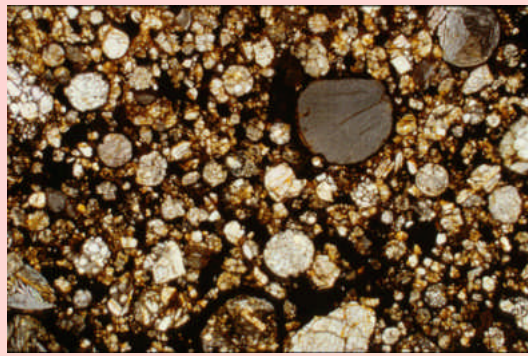


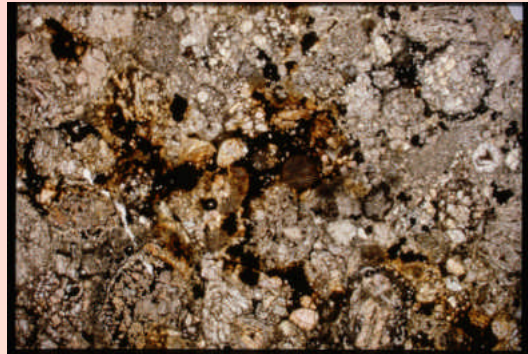
Fig. 1.1.12. Sketches suggesting possible relationships between aqueous alteration, metamorphism and petrographic type for all chondrites (*above*, from McSween [1979]) and for ordinary chondrites (*below*, based on Guimon et al. [1987]). These meteorites have apparently experienced aqueous alteration, but its importance relative to metamorphism is unclear.

# Transformations métamorphiques dans les chondrites

L3



L4



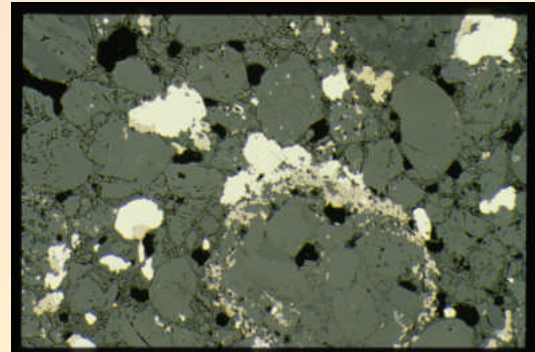
L5



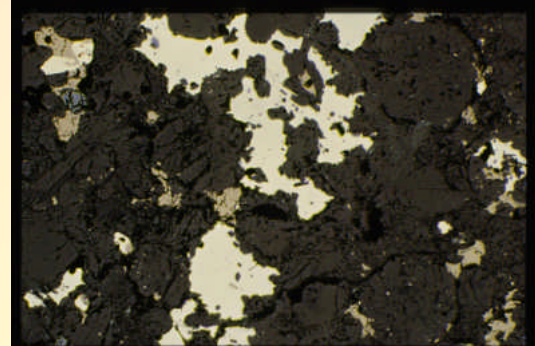
L6



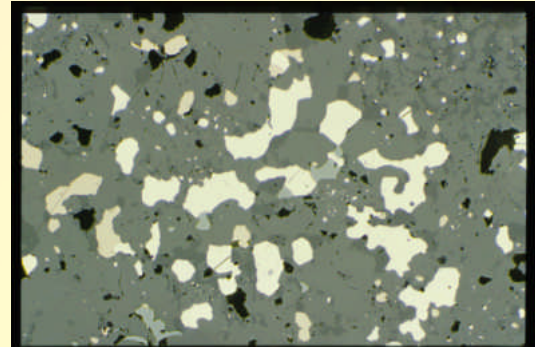
*En lumière  
réfléchiée x50*



H4

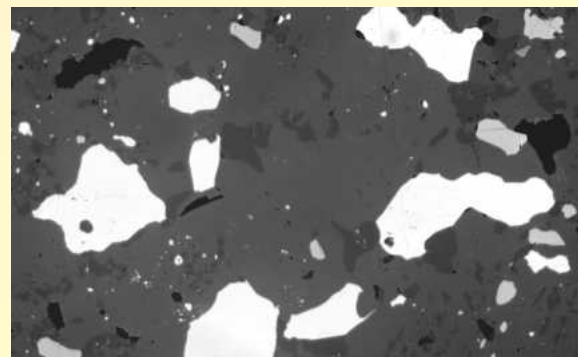
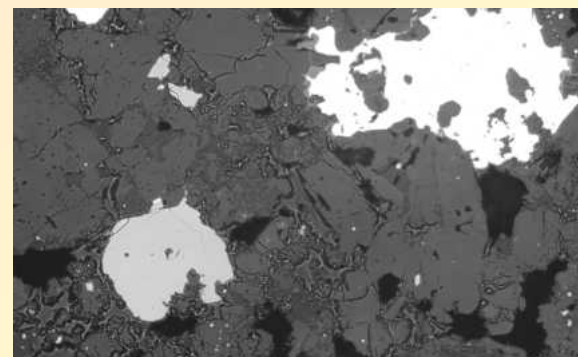
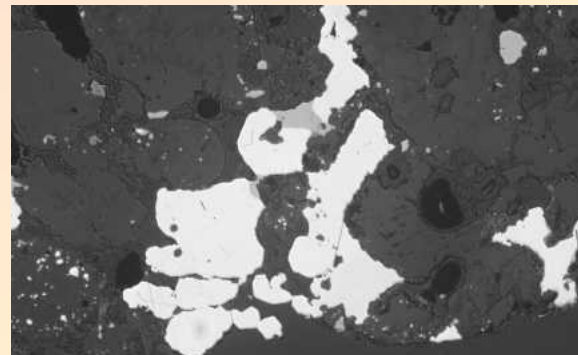
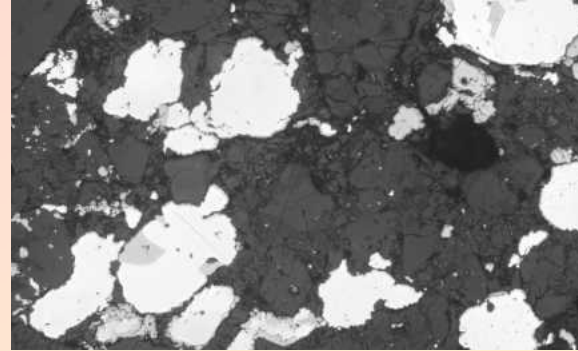
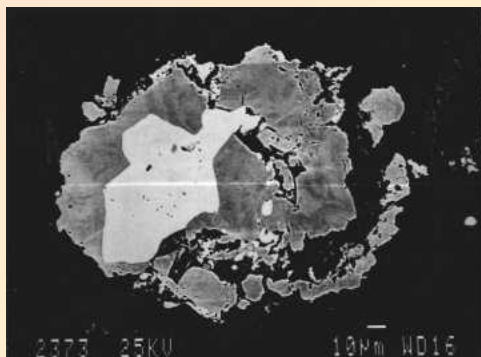
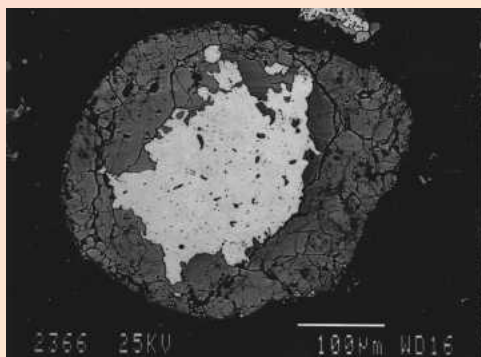
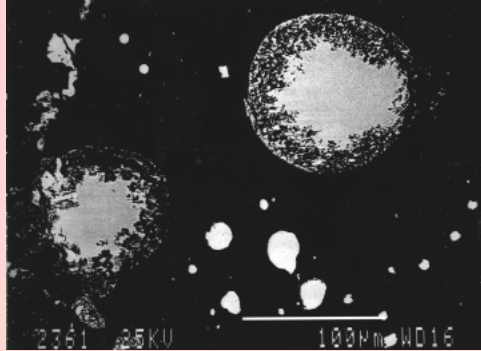


H5



H6

*En lumière  
transmise x15*



## IDENTIFICATION DU TYPE PETROGRAPHIQUE ET DE LA CLASSE SUR LA BASE DES OBSERVATIONS MICROSCOPIQUES ET DONNEES DE MICROSONDE

	1	2	3	4	5	6
HOMOGENEITE DE COMPOSITION DES OLIVINES	-	>5% de variation moyenne OLV équilibrées vers 3.8/3.9: Présence possible de Ca dans l'Olv		<5% de var. moy. PX équil. vers 4-5:	Uniforme: <b>H 16-20% Fa 15-17% Fs</b> <b>L 21-26% Fa 18-22% Fs</b> <b>LL 27-31% Fa 22-30% Fs</b>	
ETAT STRUCTURAL DES PX PAUVRES EN CA	-	Essentiellement monocliniques <i>(en fait proto-px inversés: mâcles lamellaires et fissures de rétractions en angle. Couleurs interférentielles du 1er ordre)</i>		Monocliniques >20%   <20%		Orthorhombiques <i>(pas de mâcles, clivages extinction droite, pléochroïques si riches en Fe [LLs], relief modéré)</i>
DEVELOPPEMENT DES FELDSPATHS SECONDAIRES	-	<u>Pas</u> de feldspaths secondaires <i>(le verre est isotrope)</i>		Taille < 2µm	Taille <50µm	Taille >50µm <i>(Faible relief, mâcles, transparents en LN, Couleurs du 1er ordre)</i>
VERRE	-	Verre primaire, clair et isotrope, abondance variable		Trouble quand il y en a		Absent
TEXTURE GENERALE	Pas de chondres	Chondres très bien définis		Chondres bien définis	Chondres dont les limites s'effacent	Chondres très mal délimités
TEXTURE MATRICE	A grain fin, totalement opaque	Très opaque	Opaque	Microcristalline et transparente	Matrice recristallisée	
MINERAUX OPAQUES	Sulfures essentiellement	Métal et sulfure intimement associés, dans nodules opaques et couronnes autour de chondres	Sulfure et métal se séparent	Les grains de métal ont coalescé, mais on devine encore leurs limites	Gros grains de métal xénomorphes avec occasionnelles inclusions silicatées	Tout a recristallisé, cristaux sont plus petits, plus compacts et bien "propres"

Notes: En LP (nicols croisés), un minéral isotrope (ou un verre) est noir, les couleurs du premier ordre sont : gris-blanc à jaune pâle. Un minéral pléochroïque change légèrement de couleur suivant l'orientation en LN. Les mâcles des feldspaths plagioclases et des orthopyroxènes sont polysynthétiques, c'est à dire en lamelles.

# V. Les météorites différenciées





# Achondrites

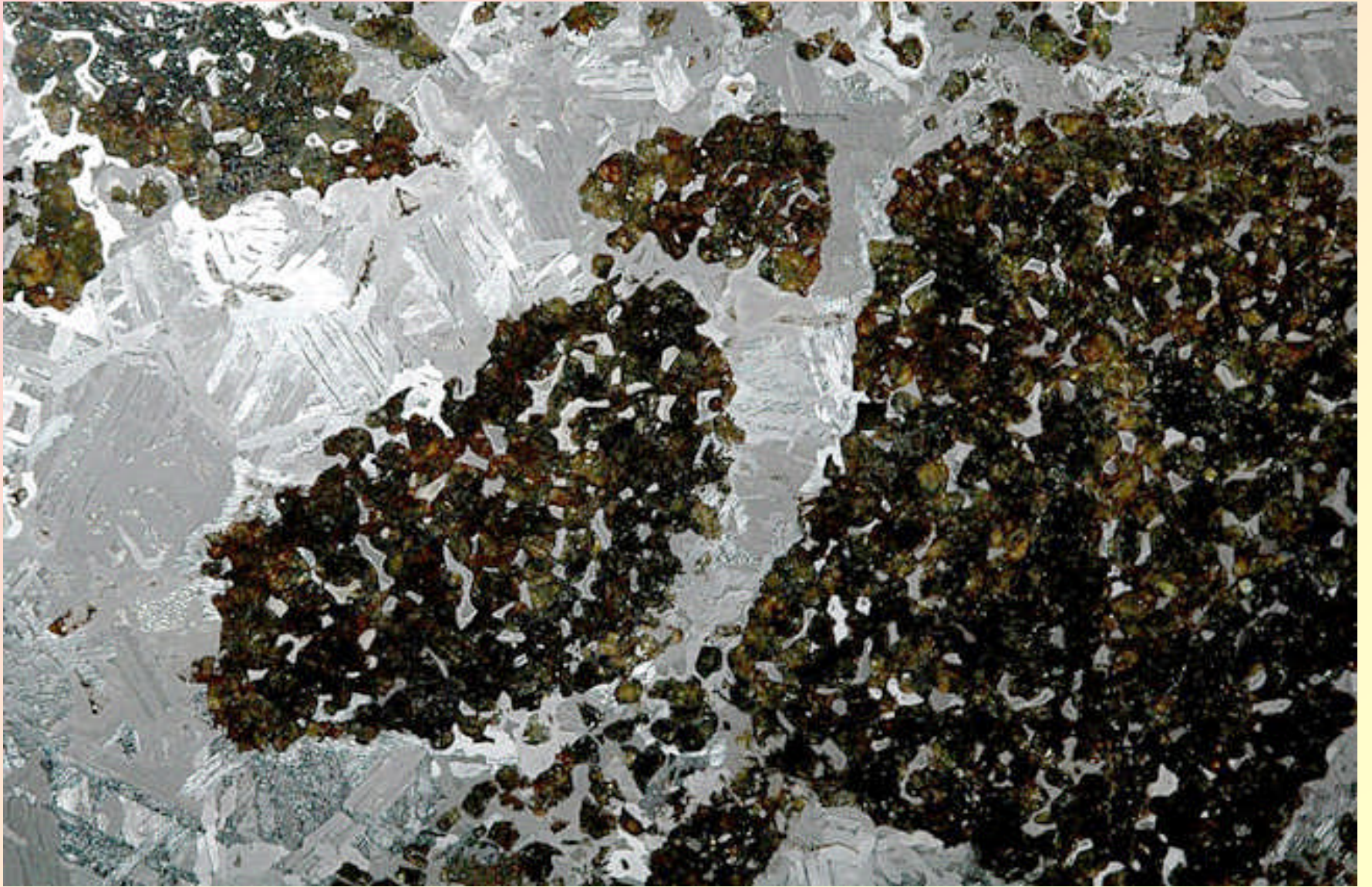


# Mésosidérites



# Pallasites





# Fers



**Textures de Widmannstätten, formées par la démixion de 2 alliages de fer-nickel (taenite et kamacite), que l'on révèle par une attaque acide**



# des fragments de la Lune...



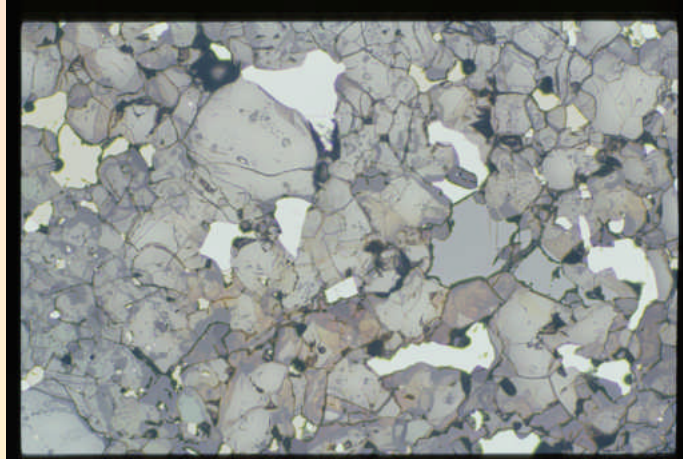
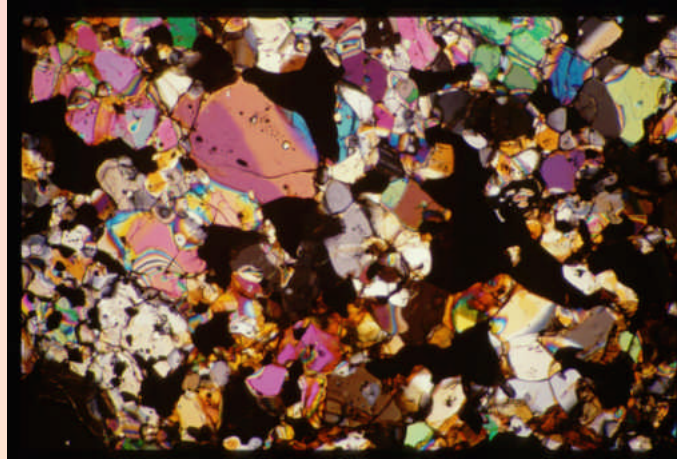
# ... et même de Mars!



# Les premières étapes de la différenciation: les « achondrites primitives »

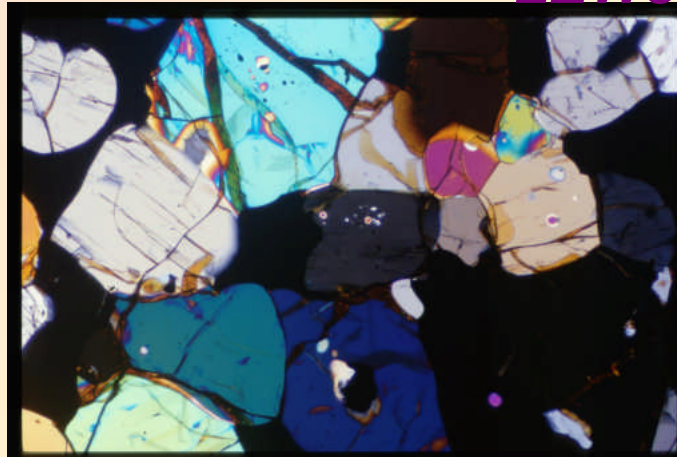
**ALHA81**

Les **acapulcoïtes** ont gardé la composition de chondrites mais en ont perdu la texture



**LEW88280**

Les **lodranites** n'ont plus la composition de chondrites: elles ont perdu du soufre et du fer



*En lumière transmise polarisée*

*En lumière réfléchie*



# Classification des météorites

## METEORITES NON DIFFERENCIEES

### Chondrites carbonées:

CI  
CM  
CO  
CV  
CK  
CR  
CH

### Rumurutites

### Chondrites ordinaires:

LL  
L  
H

### Chondrites à enstatite:

EL  
EH

## METEORITES DIFFERENCIEES

### Météorites de fer, fers à inclusions silicatées

### Pallasites

### Mésosidérites

### Achondrites:

Eucrites, Diogénites,  
Howardites

Angrites

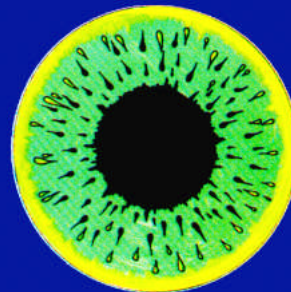
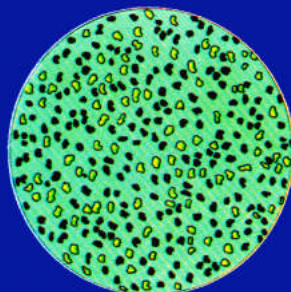
Ureilites

Aubrites

**AL** (Acapulcoites, Lodranites)  
+ Brachinites

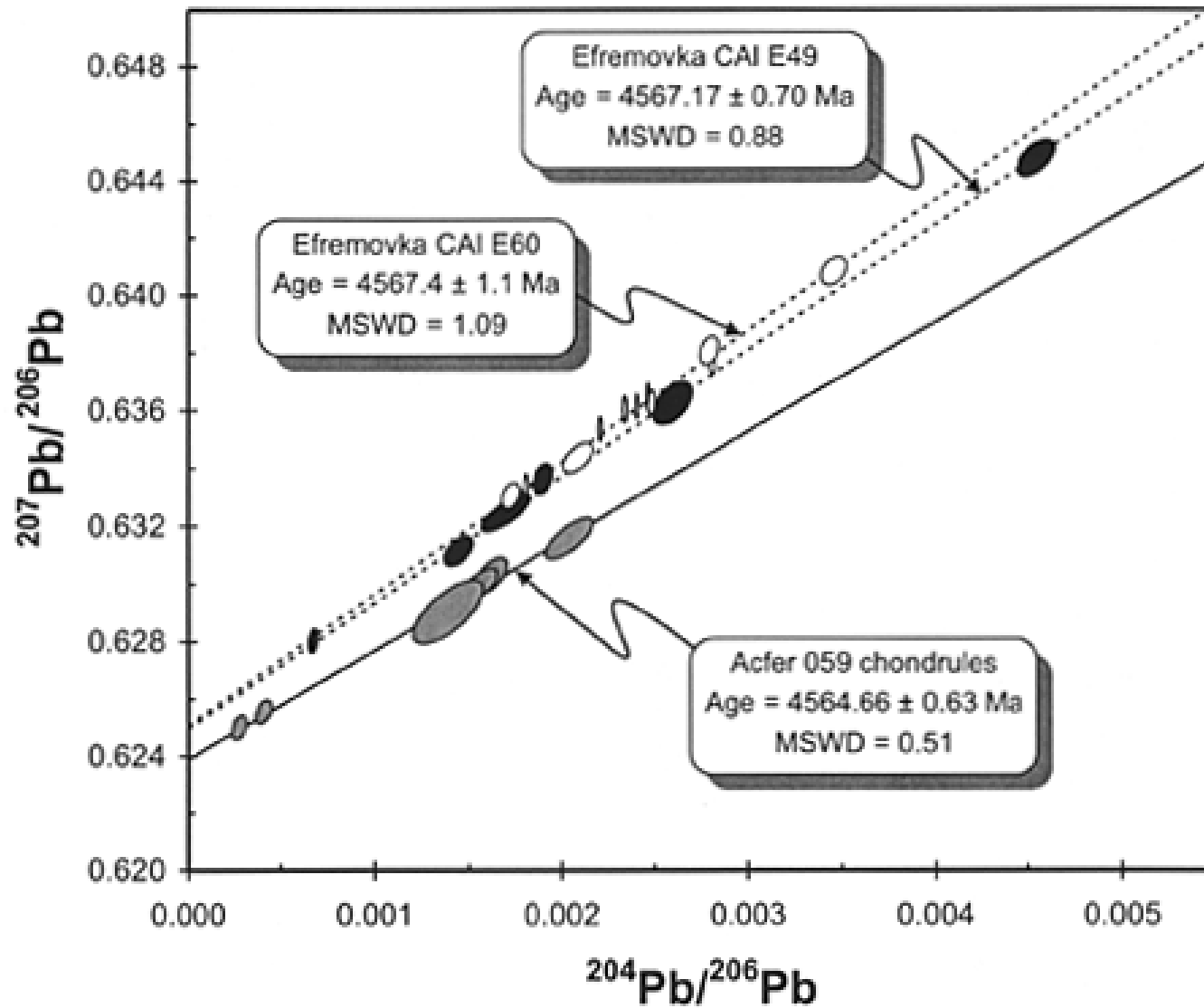
**Basaltes et brèches  
lunaires**

**Achondrites  
martiennes**



# **VI - Tentative de chronologie**

## Pb-Pb isochrons



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

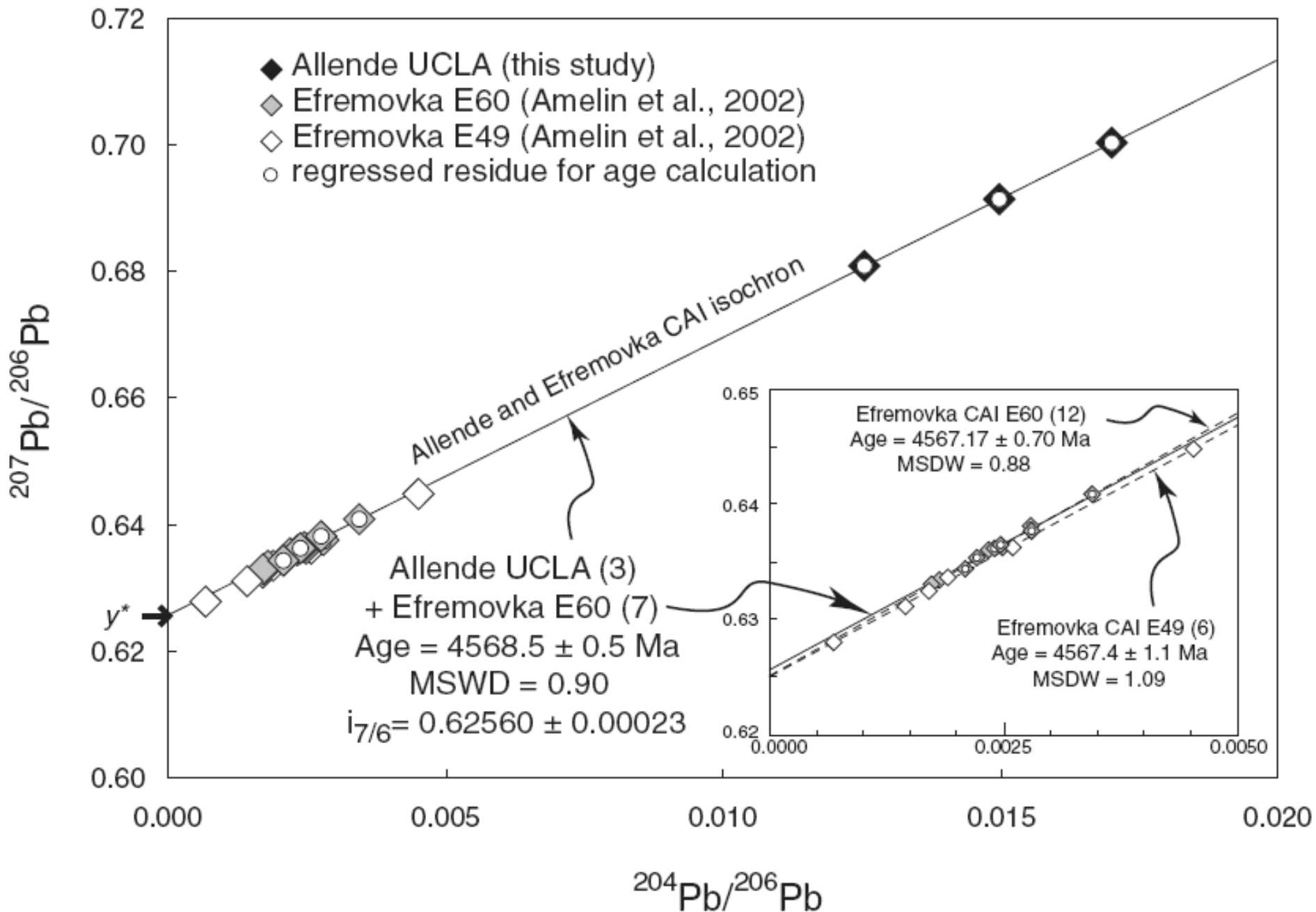


TABLE 1.	Short-lived isotopes initially present in meteorites .				
Radioactive Isotope (R)	T (m.y.)	Daughter Isotope	Stable Isotope (S)	Initial Abundance (R/S)	
<sup>7</sup> Be	52 d	<sup>7</sup> Li	<sup>9</sup> Be	$6 \times 10^{-3}$	
<sup>41</sup> Ca	0.1	<sup>41</sup> K	<sup>40</sup> Ca	$1.5 \times 10^{-8}$	
<sup>36</sup> Cl	0.3	<sup>36</sup> S	<sup>35</sup> Cl	$> 1.1 \times 10^{-5}$	
<sup>26</sup> Al	0.74	<sup>26</sup> Mg	<sup>27</sup> Al	$5 \times 10^{-5}$	
<sup>10</sup> Be	1.5	<sup>10</sup> B	<sup>9</sup> Be	$4-14 \times 10^{-3}$	
<sup>60</sup> Fe	1.5	<sup>60</sup> Ni	<sup>56</sup> Fe	$0.1-1.6 \times 10^{-6}$	
<sup>53</sup> Mn	3.7	<sup>53</sup> Cr	<sup>55</sup> Mn	$1-12 \times 10^{-5}$	
<sup>107</sup> Pd	6.5	<sup>107</sup> Ag	<sup>108</sup> Pd	$>4.5 \times 10^{-5}$	
<sup>182</sup> Hf	9	<sup>182</sup> W	<sup>180</sup> Hf	$>1.0 \times 10^{-4}$	
<sup>129</sup> I	16	<sup>129</sup> Xe	<sup>127</sup> I	$1.0 \times 10^{-4}$	
<sup>92</sup> Nb	36	<sup>92</sup> Zr	<sup>93</sup> Nb	$10^{-5} - 10^{-3}$	
<sup>244</sup> Pu	81	Fission products		<sup>238</sup> U	$4-7 \times 10^{-3}$
<sup>146</sup> Sm	103	<sup>142</sup> Nd	<sup>144</sup> Sm	$7 \times 10^{-3}$	

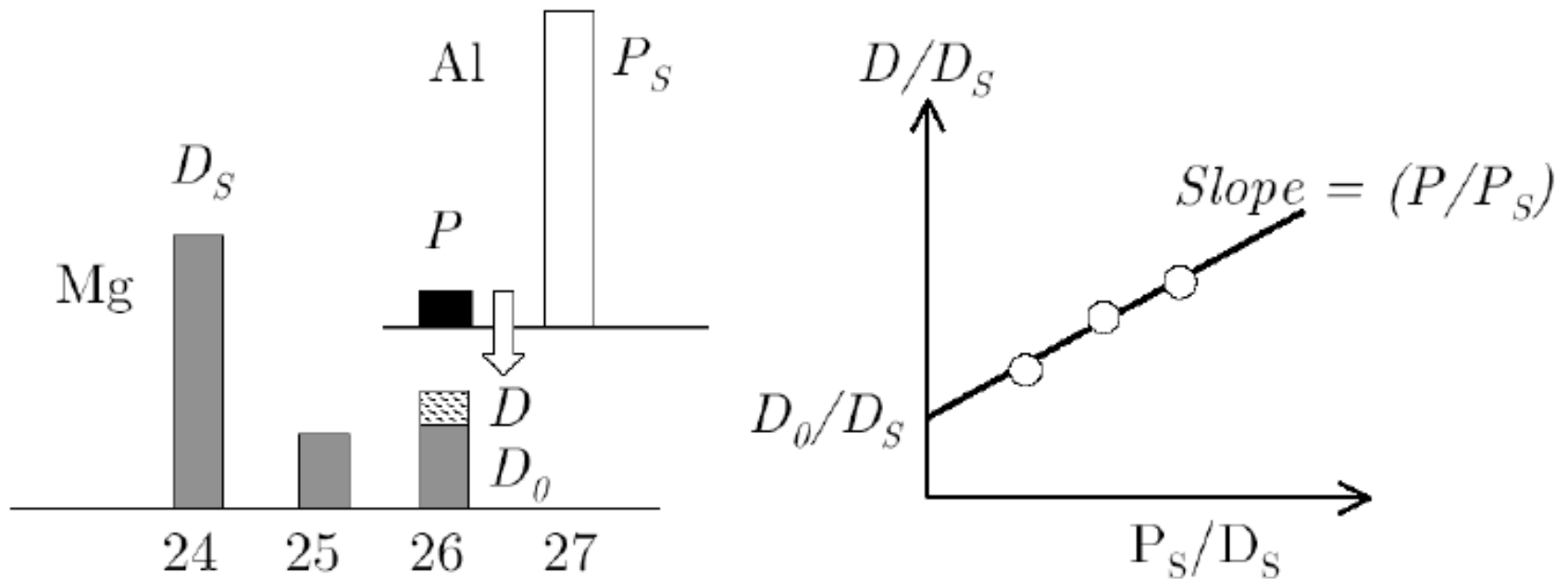
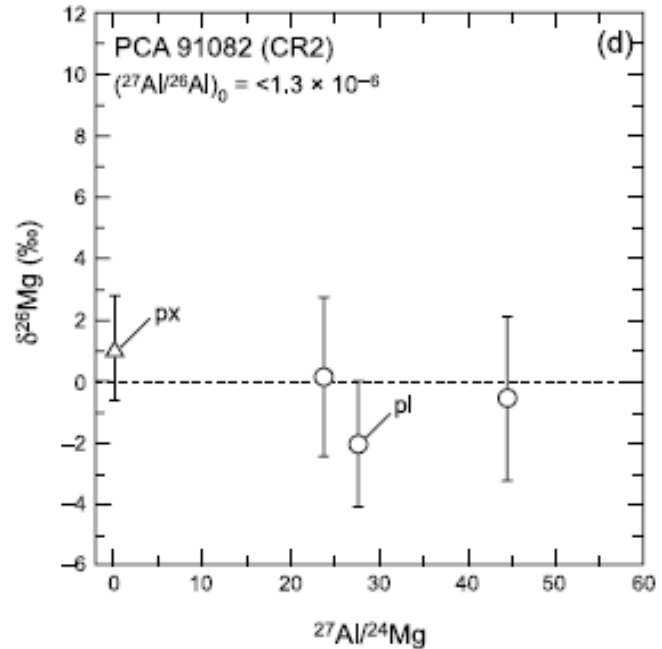
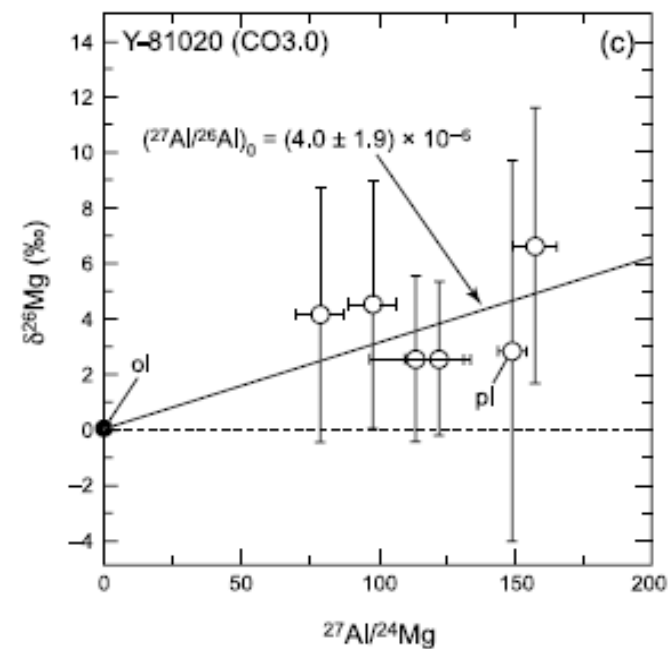
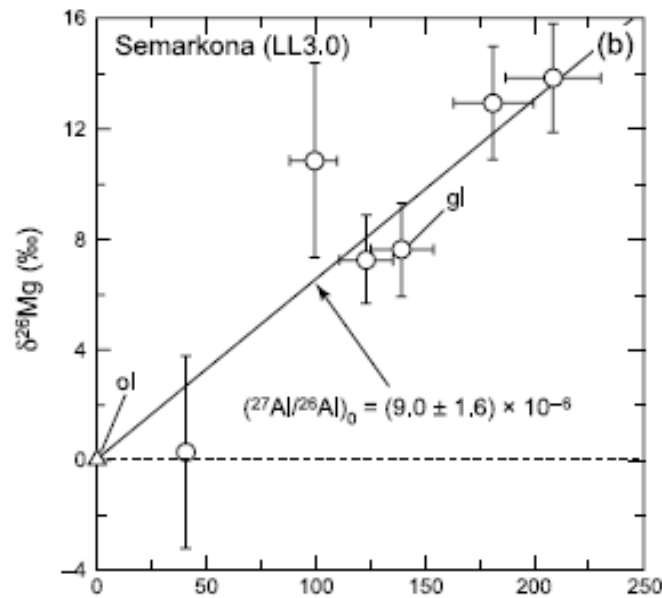
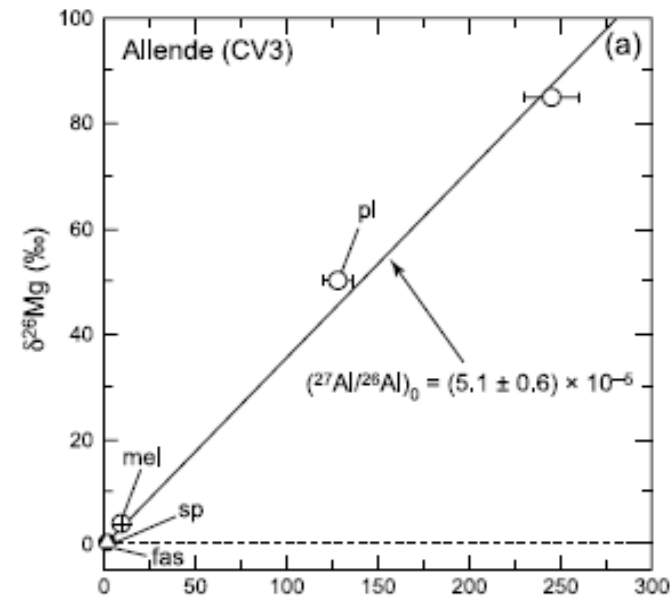


Figure 1. Example of an isochron diagram for  $^{26}\text{Al}$  decay to  $^{26}\text{Mg}$ . The isotopic ratio of the short-lived nuclide to its stable isotope ( $P/P_S$ ) is determined from the best-fit line (called an “isochron”) for a set of data from a single sample that have a range of ( $P_S/D_S$ ) ratios. The slope of the isochron, ( $P/P_S$ ), changes exponentially with time according to Eq. (2) thus defining the sample’s age.



**Fig. 3.** Al-Mg evolutionary diagram for **(a)** an igneous (Type B) CAI from the CV3 chondrite Allende (from Lee *et al.*, 1976), **(b)** a ferromagnesian chondrule from the LL3.0 chondrite Semarkona (from Kita *et al.*, 2000), **(c)** a ferromagnesian chondrule from the CO3.0 chondrite Y-81020 (from Kunihiro *et al.*, 2004), and **(d)** an Al-rich chondrule from the CR2 chondrite PCA 91082 (from Hutcheon *et al.*, 2004). The observed range in the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios, if interpreted chronologically, suggests that chondrule formation lasted for at least 2–3 m.y. after CAI formation. fas = fassaite; gl = glass; ol = olivine; pl = plagioclase; px = pyroxene; sp = spinel.

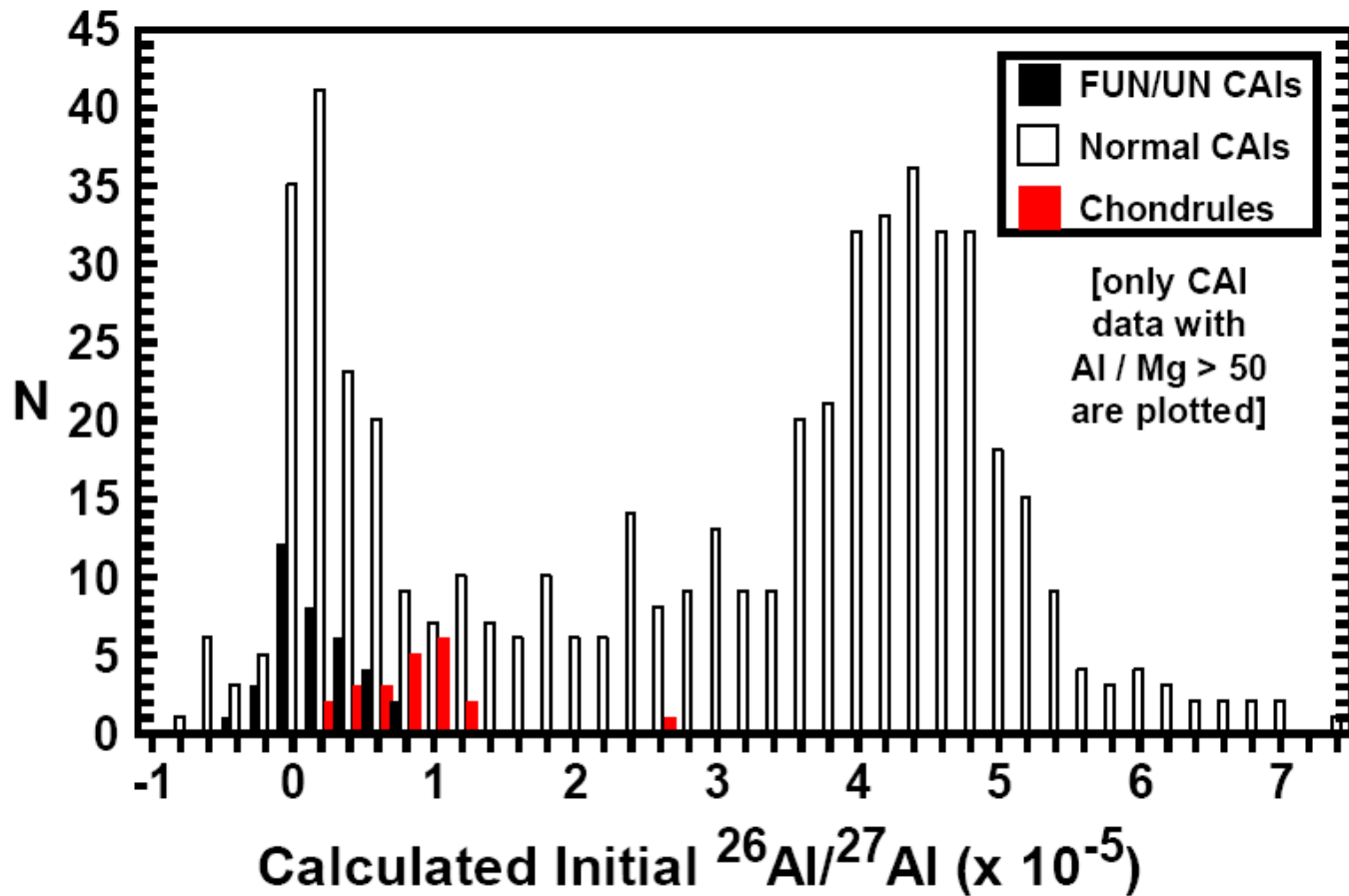


Figure 2. Histogram of calculated initial  $^{26}\text{Al}/^{27}\text{Al}$  ratios in normal CAIs, FUN/UN CAIs, and chondrules.



**Bulk analyses: Time of Al and Mg closure to external environment**

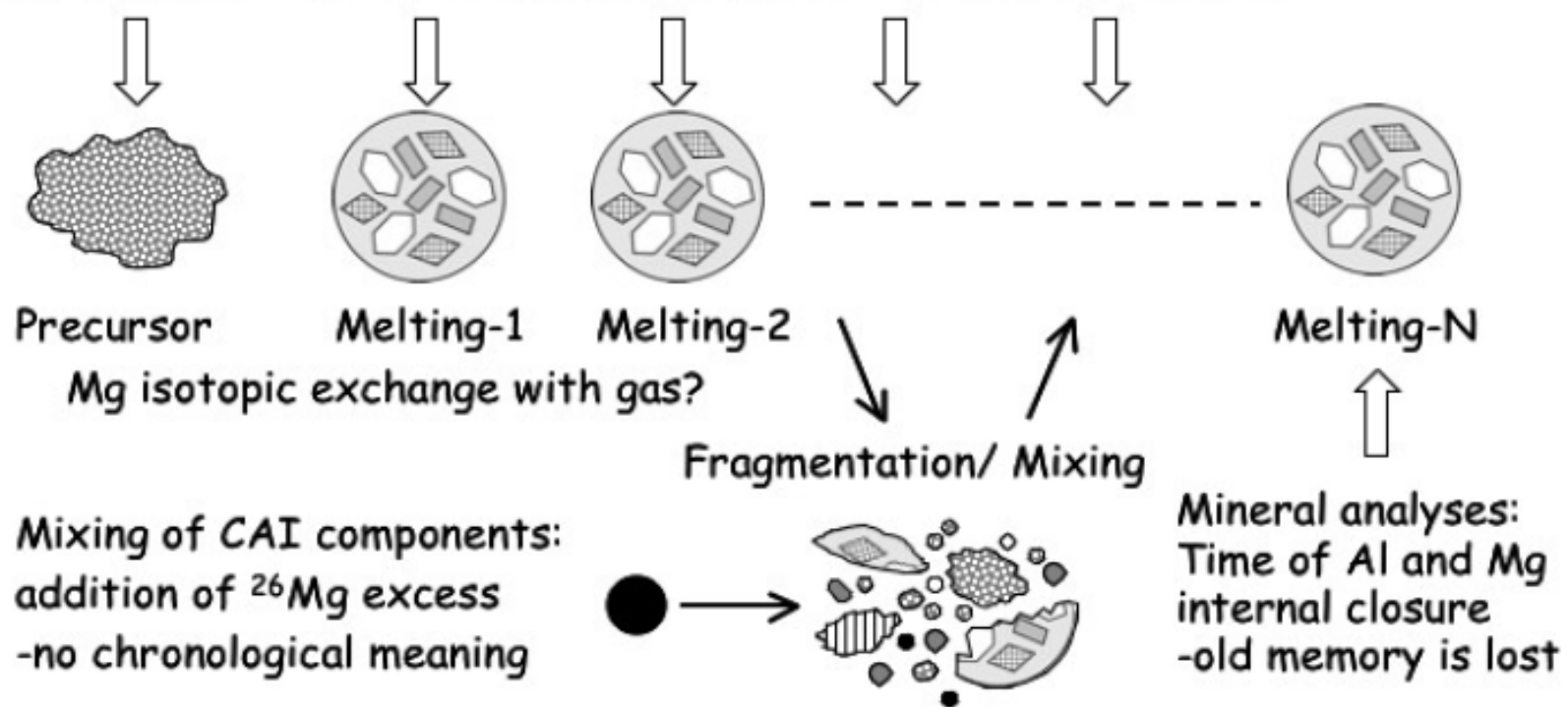
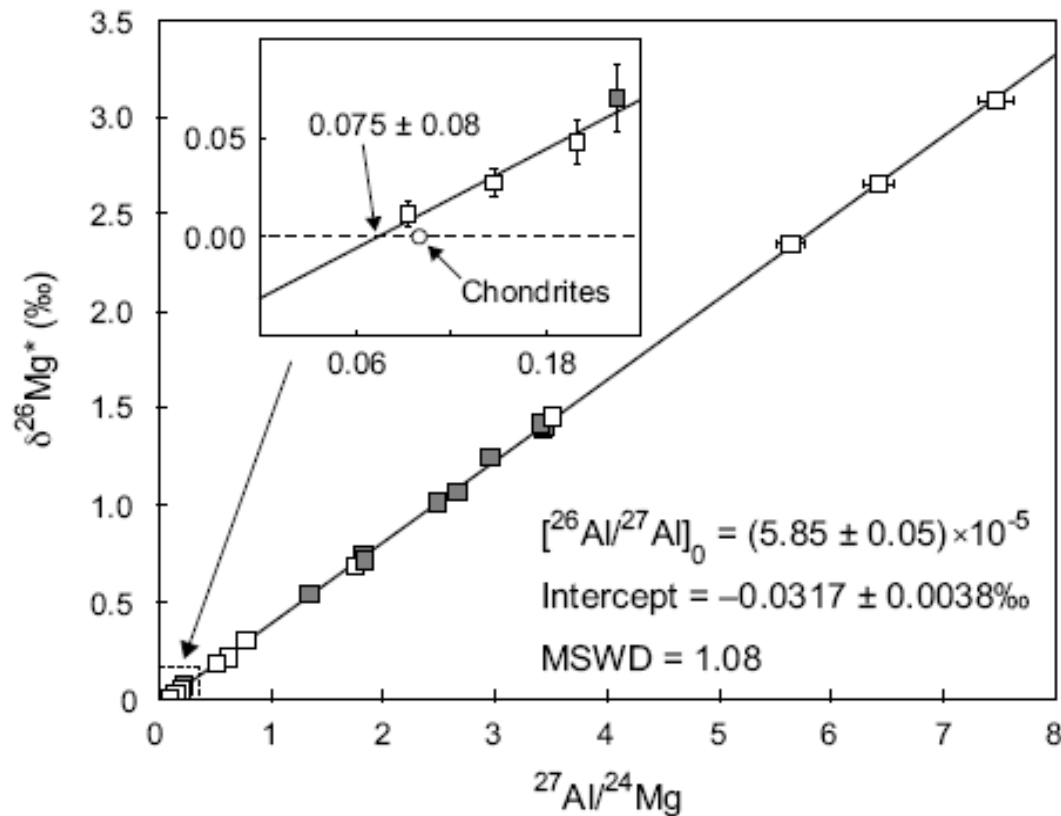
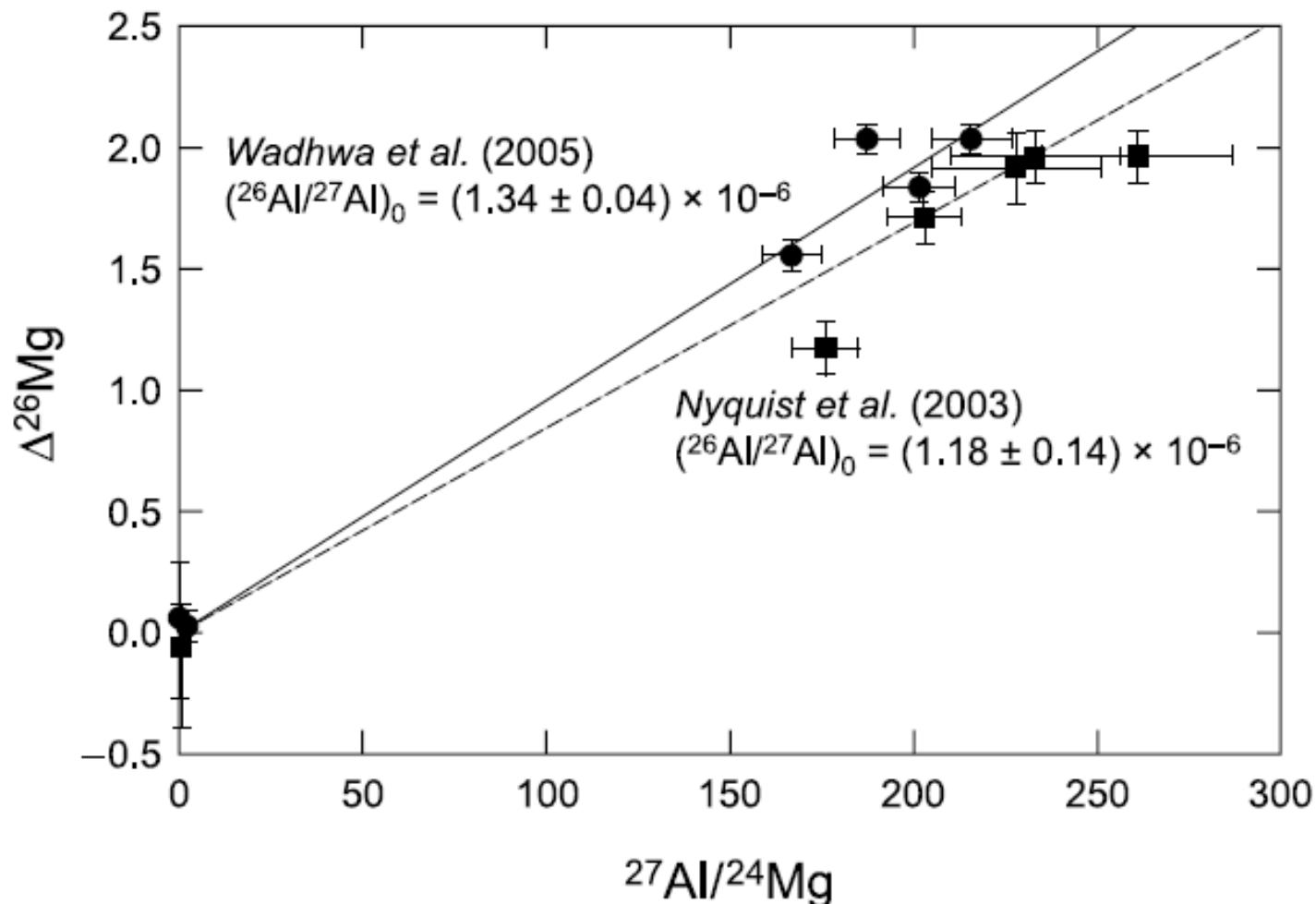


Fig. 5



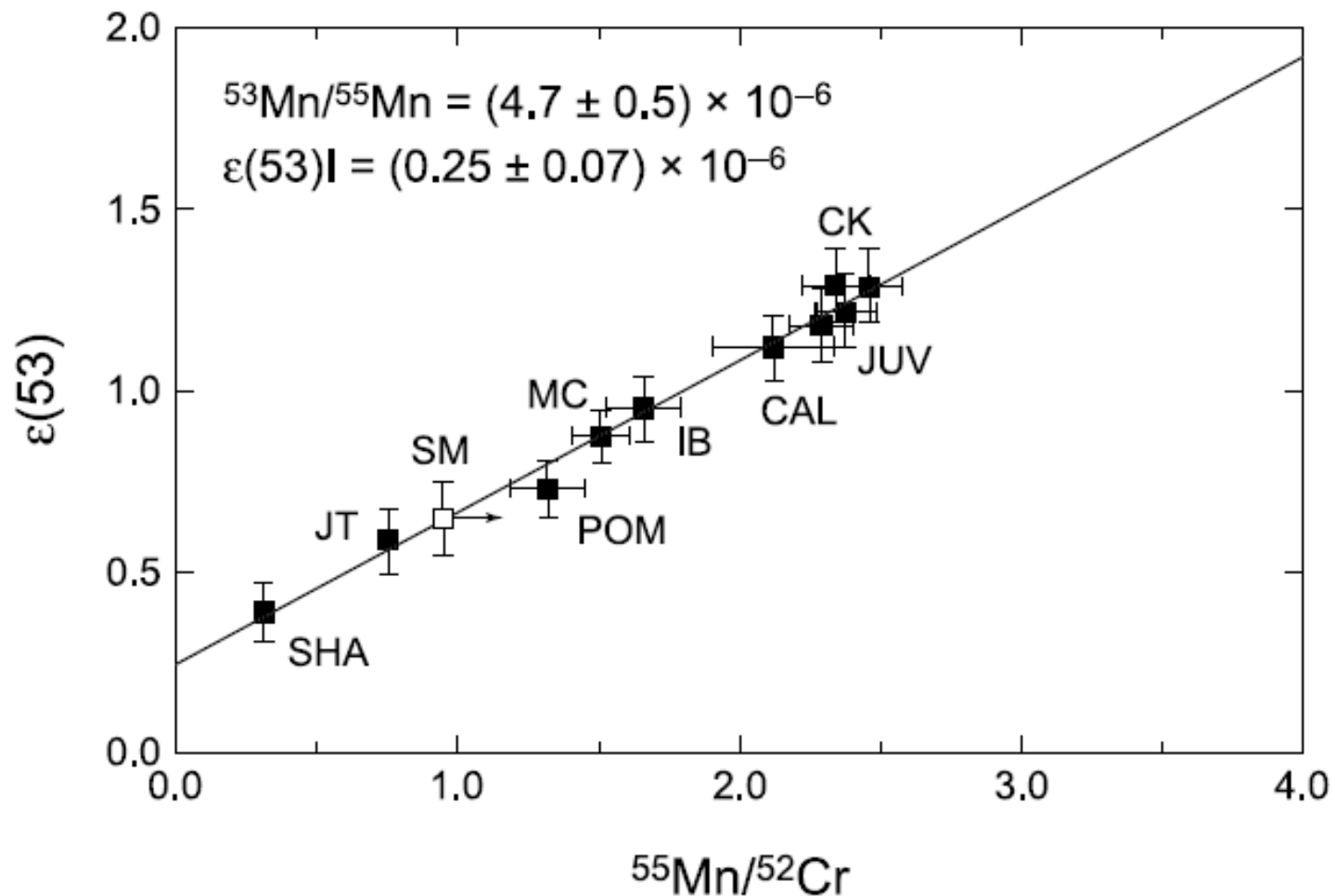
Thrane, Bizzarro &  
Baker 2006

High precision Mg isotope measurements of **Allende CAIs** [1] define an isochron corresponding to an initial  $^{26}\text{Al}/^{27}\text{Al}$  of  $(5.85 \pm 0.05) \times 10^{-5}$  and intercept of  $-0.0317 \pm 0.0038$ ‰ (Fig. 1). The CAI regression intercepts the present day inner Solar System  $^{26}\text{Mg}$  abundance at a  $^{27}\text{Al}/^{24}\text{Mg}$  ratio of  $0.0752 \pm 0.0082$  (Fig. 1, inset) that is significantly lower (25%) than current estimates of the solar  $^{27}\text{Al}/^{24}\text{Mg}$  ratio ( $0.101 \pm 0.004$ ; [4]). We infer that the **bulk CAI isochron records the original Al/Mg fractionation leading to the CAI forming event(s)**, in contrast to internal mineral isochrons of individual CAIs, which in most cases record secondary events such as thermal reprocessing and melting [12]. As such, the bulk CAI isochron dates the timing of primary formation of CAI material (and/or CAI precursor material) from the early solar nebula, and this may have occurred in a **time interval as short as 20,000 yr**, as this corresponds to the analytical uncertainty of the isochron.

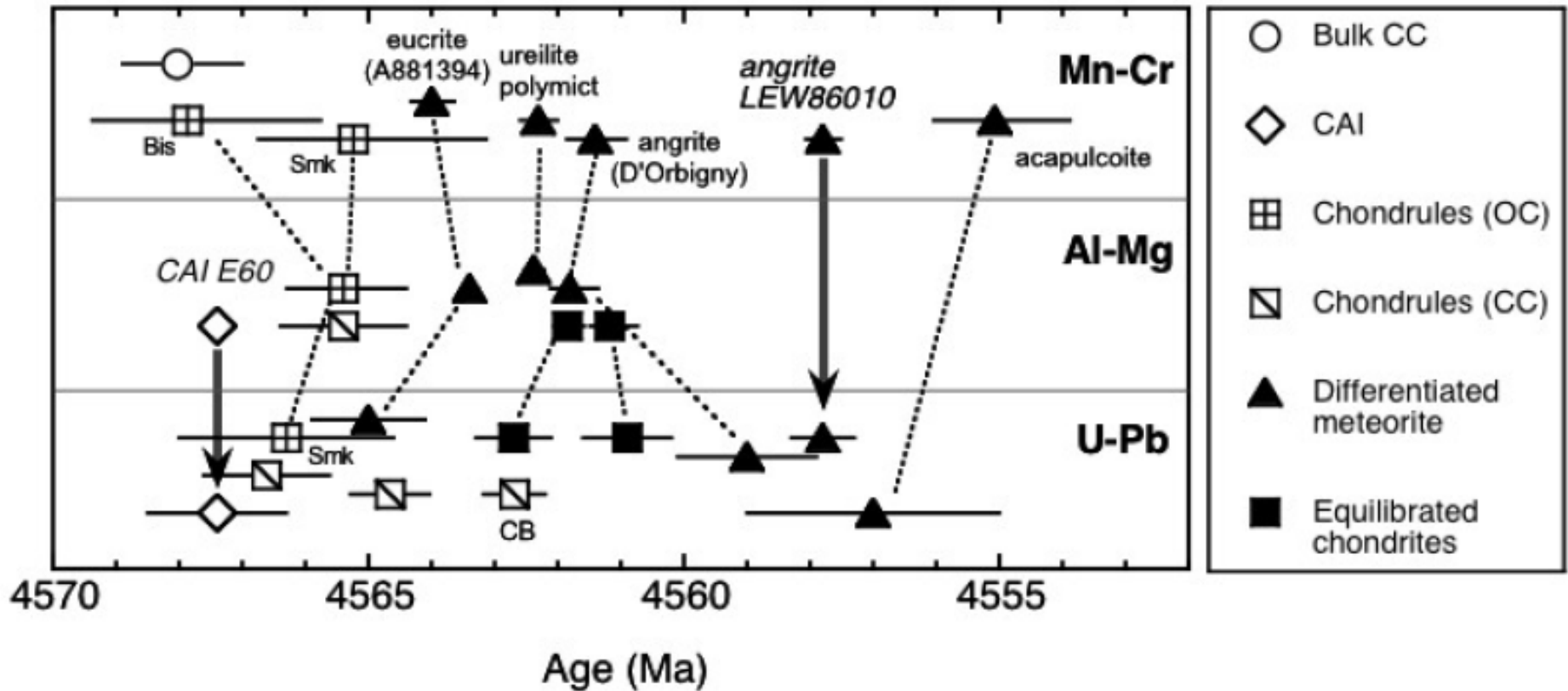


**Fig. 3. Live  $^{26}\text{Al}$ .** Excesses in the  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio in per mil, in the Asuka 881394 eucrite; low Al/Mg data points near the origin are for pyroxene and whole rock, and high Al/Mg data points are for plagioclase. Al-Mg age  $4563.5 \pm 0.9$  Ma

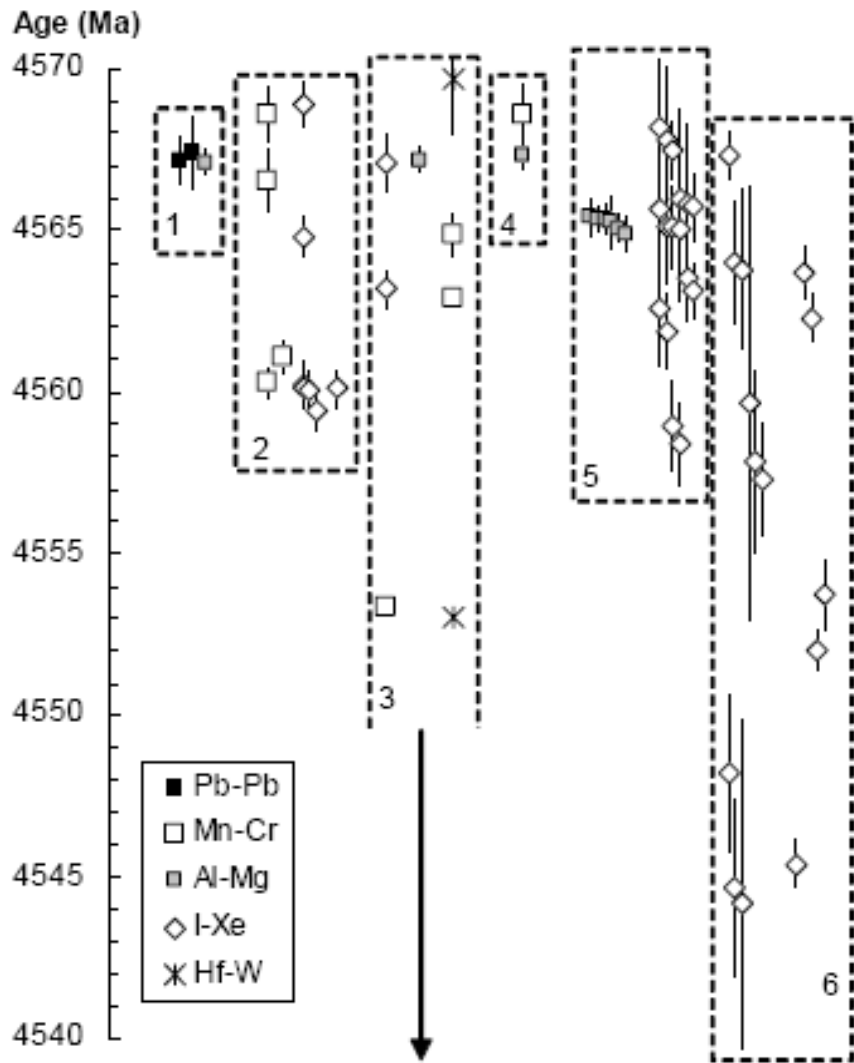
**Pb-Pb mineral isochron** for the Asuka 881394 eucrite yielded  $4566.5 \pm 0.9$  Ma **only  $0.7 \pm 1.1$  m.y. younger than CAI** ( $4567.2 \pm 0.6$  Ma) and indicates that crust formation on differentiated planetesimals occurred within  $\sim 2$  m.y. of the formation of CAI.



**Fig. 4.  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  systematics in the HED parent body.** Data points are whole rocks of noncumulate eucrites and SM = Serra de Magé, and diogenites (JT = Johnstown; SHA = Shalka). The slope of the HED whole rock isochron corresponds to a  $^{53}\text{Mn}/^{55}\text{Mn}$  ratio of  $(4.7 \pm 0.5) \times 10^{-6}$ . Comparison with the LEW angrite gives a Mn-Cr age of  $4564.8 \pm 0.9$  Ma for **global silicate fractionation on the HED parent body,  $2.4 \pm 1.1$  m.y. after CAIs**



**Kita** Figure 9. Comparison of three chronometers. The relative Al-Mg and Mn-Cr ages are converted to absolute ages using Pb-Pb ages obtained for CAI E60 ( $4567.2 \pm 0.6$  Ma; Amelin et al. 2002) and LEW86010 angrite ( $4557.8 \pm 0.5$  Ma; Lugmair & Galer 1989), respectively. Dashed lines connect the data obtained from the same meteorites. “Smk” and “Bis” indicate chondrules from Semarkona and Bishunpur meteorites, respectively.



**Hutchison CPD** Figure 2. A schematic timescale for early Solar System events, calibrated to a Shallowater I-Xe age of  $4563.2 \pm 0.6$  Ma (see Gilmour et al. 2005 for cross-calibration and references).

1. CAI origin.
2. Aqueous alteration (CI, CM, CR carbonates; Mokoia fayalite; Allende dark inclusions; CI magnetite; secondary minerals in CAIs; Monahans halite).
3. Igneous rocks and differentiation (Semarkona CC-1 by Al-Mg; H chondrite clast, Barwell, L6; Serra de Magé; Mars core formation (Hf-W isotope dating, Kleine et al. 2002); Magmatic iron meteorite formation (Hf-W isotope dating; earliest age plotted; Kleine et al. 2005); LEW 86010; Shallowater pyroxene).
4. Chondrule model ages.
5. Chondrule I-Xe isochrons, Semarkona (LL3.0).
6. Chondrule I-Xe isochrons, Chainpur (LL3.4).

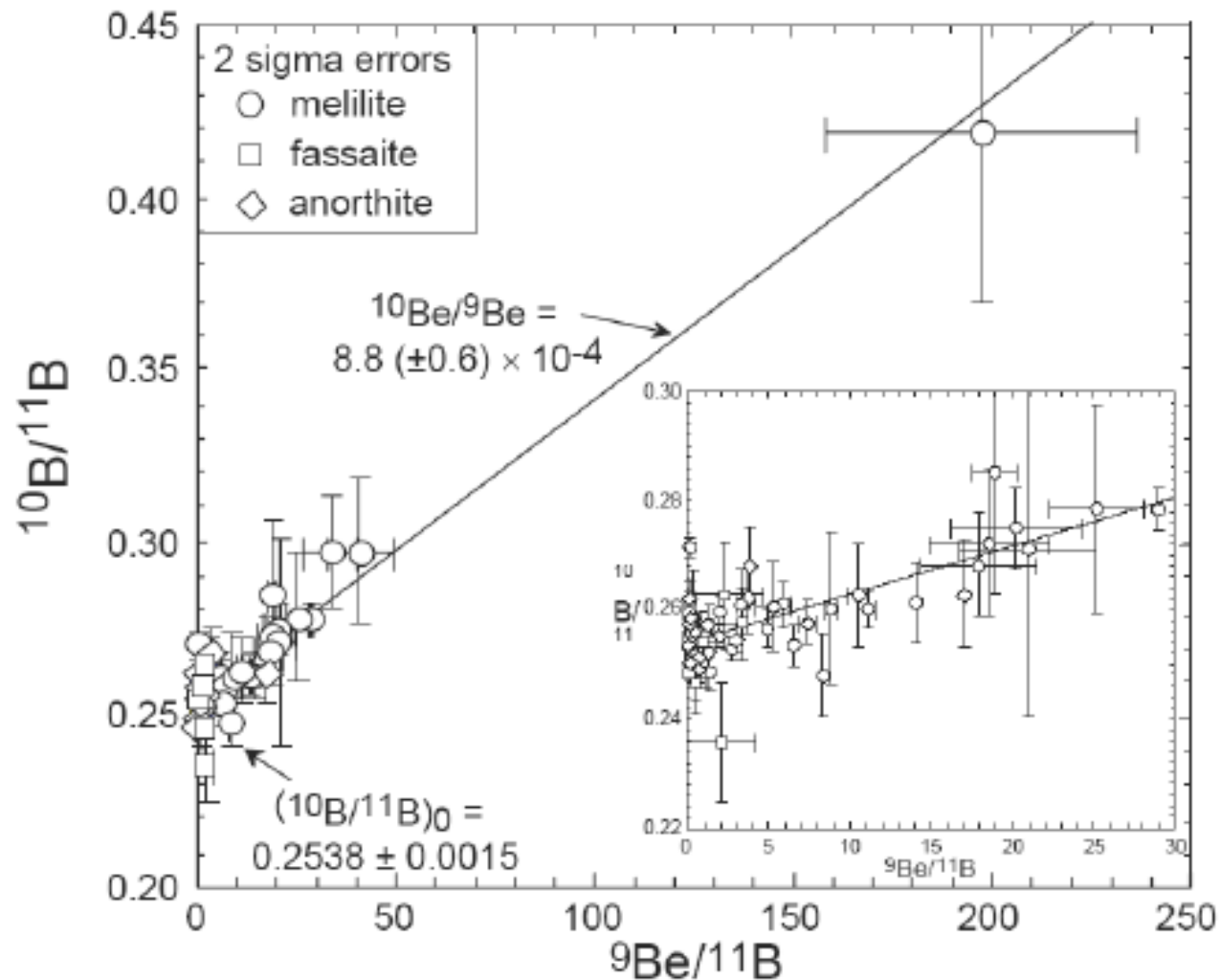
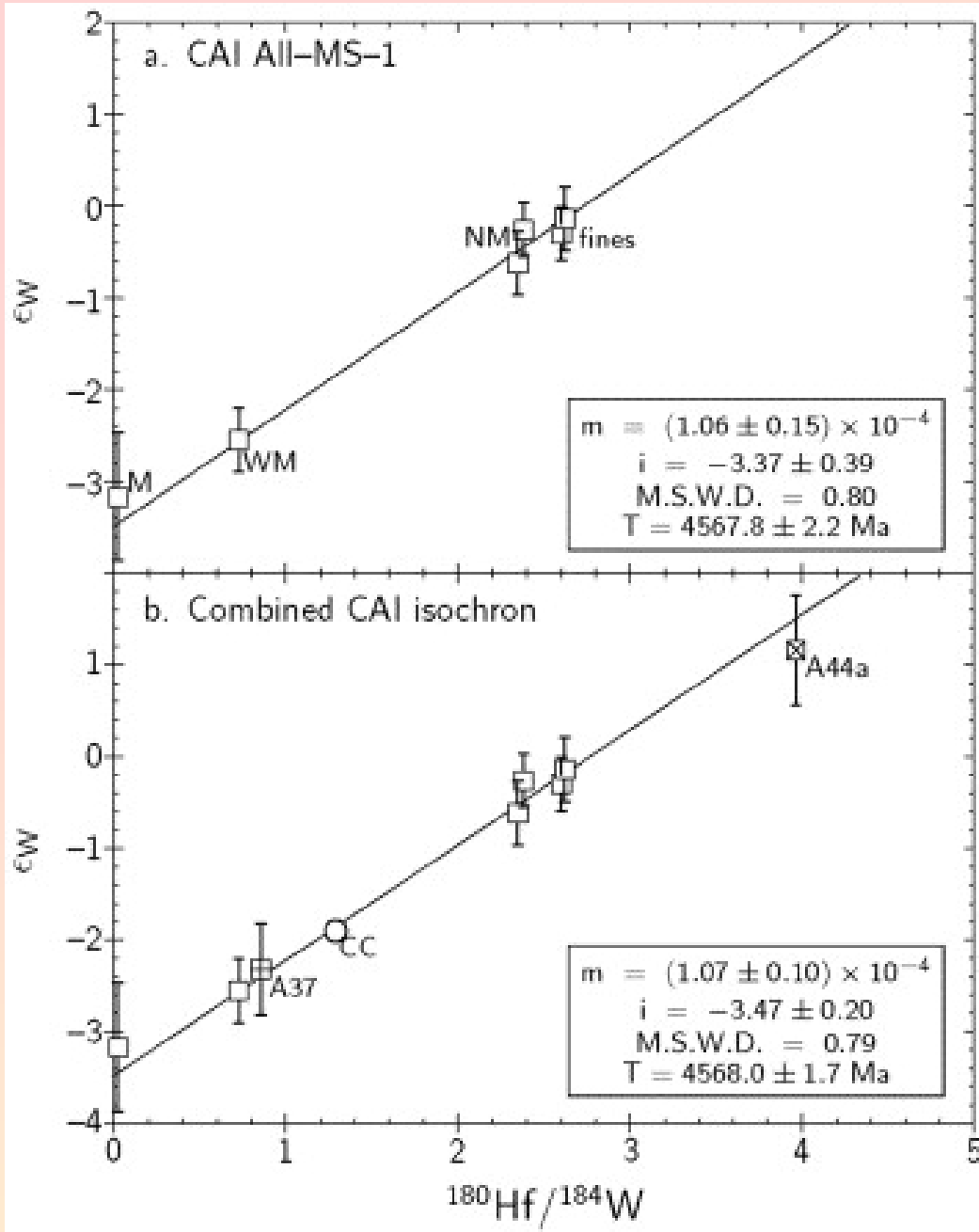


Figure 4. Boron isotopic ratios,  $^{10}\text{B}/^{11}\text{B}$ , measured in various mineral phases in CAIs from the Allende meteorite, plotted as a function of their  $^9\text{Be}/^{11}\text{B}$  ratios. The correlation of  $^{10}\text{B}/^{11}\text{B}$  with Be/B ratio is evident and indicates the presence of  $^{10}\text{Be}$  at the time of formation of these refractory phases. The inferred initial  $^{10}\text{Be}/^9\text{Be}$  ratio is also shown (data from Chaussidon et al. 2004).



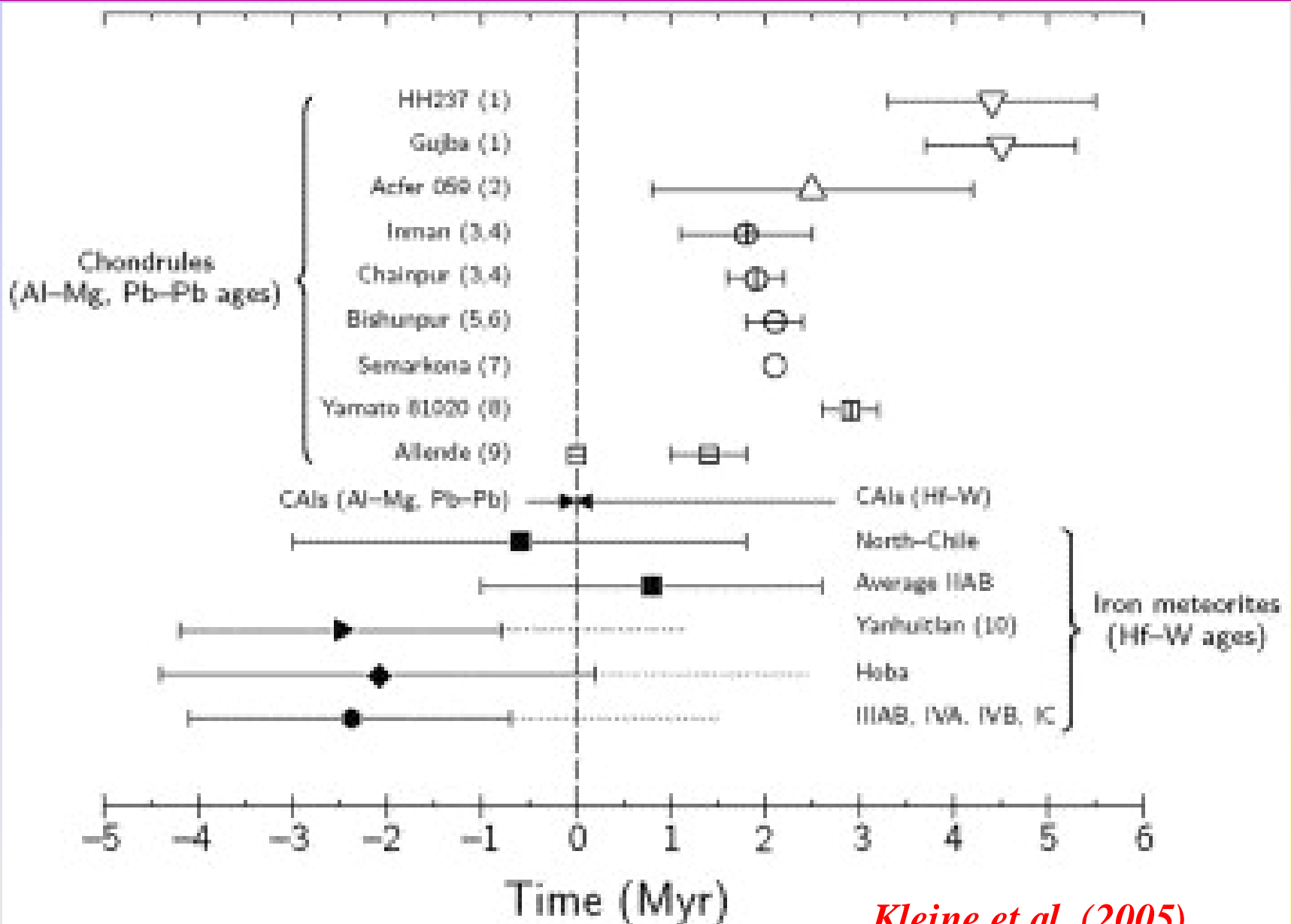
**Kleine et al. (2005)**

Hf-W isochrons for CAIs. Error bars represent  $2\sigma$  uncertainties,  $m$  = initial  $^{182}\text{Hf}/^{180}\text{Hf}$ ,  $i$  = initial  $\epsilon_W$ . The absolute ages ( **$\sim 4568\text{myr}$** ) are calculated from their initial  $^{182}\text{Hf}/^{180}\text{Hf}$  ratios relative to the well-dated H chondrite Ste. Marguerite



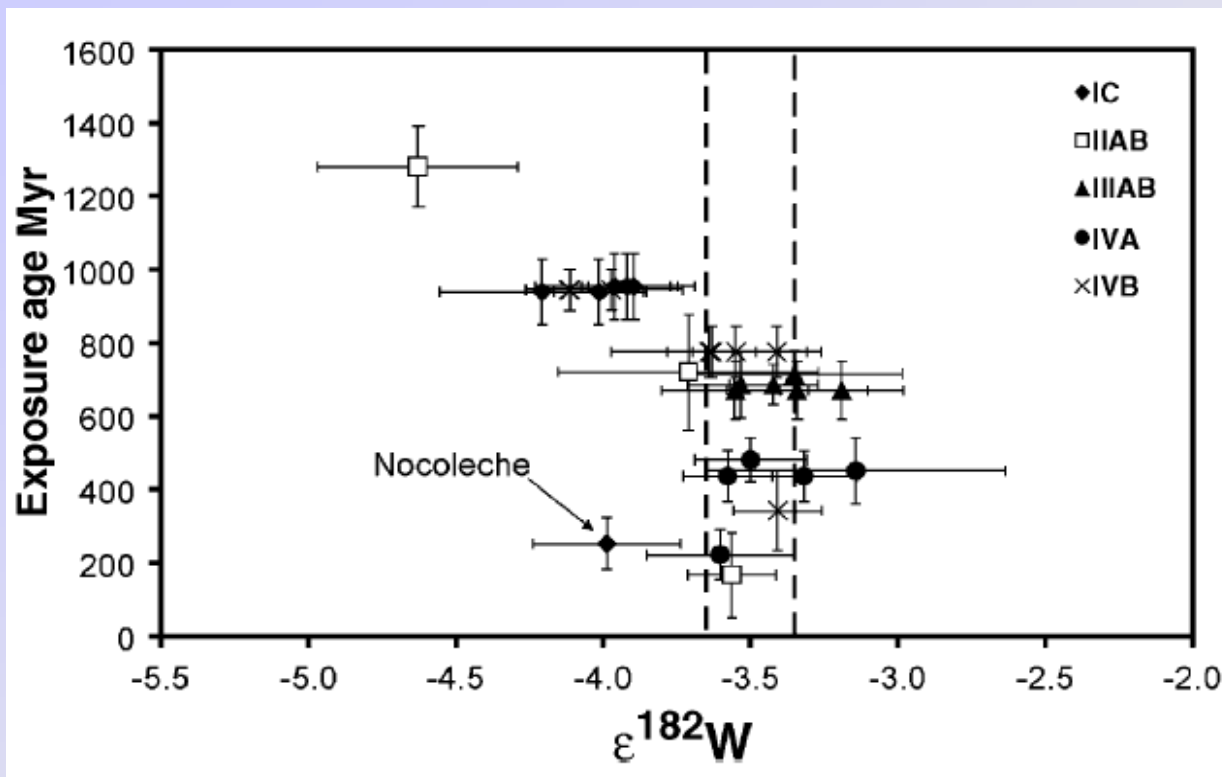
Hf lithophile, W siderophile.

$^{182}\text{Hf} \rightarrow ^{182}\text{W}$ ,  $T=9$  Ma



*Kleine et al. (2005)*

Chondrules formed after irons

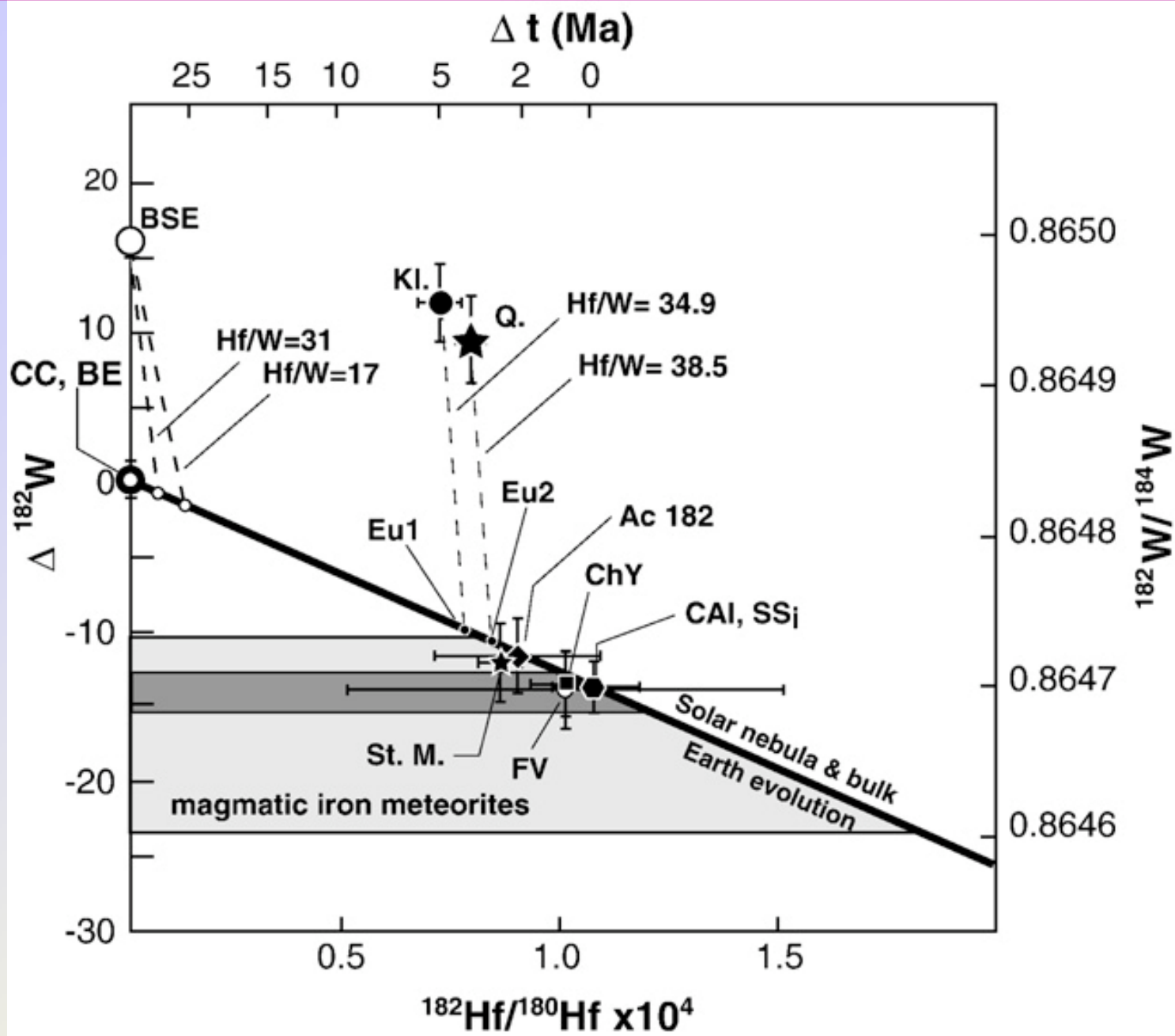


**Schersteín (2006)** Hf–W model ages for magmatic iron meteorites show a limited range of isotopic compositions, ranging between  $\epsilon^{182}\text{W} \sim -4.6$  to  $-3.5$ . **Values significantly less radiogenic than our  $\epsilon^{182}\text{W}_{\text{SSI}}$ -estimate of  $3.51 \pm 0.10/0.19$  are ascribed to spallation during the long exposure** of these meteorites, which is corroborated by our spallation modelling that predicts potentially significant depletions in  $\epsilon^{182}\text{W}$  due to W, Re and Os neutron capture and burnout.

The model ages for unspalled magmatic iron meteorites are indistinguishable between groups, strongly suggesting a **short formation time interval of  $\sim 1.5$  Myr of CAI condensation**. Significantly, the homogeneity of the groups and the lack of distinctly younger (i.e.  $> 1.5$  Myr after CAI) magmatic iron meteorites strongly suggest that the principal melting and iron segregation cause was the decay of short-lived isotopes, especially  $^{26}\text{Al}$ . Furthermore, planetary accretion and differentiation are synchronous with chondrule formation, which thus must have formed in the presence of planetesimals.

Hf lithophile, W siderophile.

$^{182}\text{Hf} \rightarrow ^{182}\text{W}$ ,  $T=9 \text{ Ma}$



***Fig. 1.*** W isotopic evolution of the solar nebula, bulk Earth (BE) and bulk silicate Earth (BSE). The  $^{182}\text{W}/^{184}\text{W}$  ratio and the absolute deviation  $\Delta^{182}\text{W}$  relative to the  $^{182}\text{W}/^{184}\text{W}$  ratio of carbonaceous chondrites (CC) (definition of  $\Delta^{182}\text{W}$  given in Section 2) are plotted versus the  $^{182}\text{Hf}/^{180}\text{Hf}$  ratio. The logarithmic  $^{182}\text{Hf}$  time scale of the upper x-axis is defined in respect to the initial Hf–W features of the solar system SSI ( $^{182}\text{Hf}/^{180}\text{Hf}=1.07\cdot 10^{-4}$ ,  $\Delta^{182}\text{W}_{\text{SSI}}=-13.7\pm 1.7$ ) derived from the Allende isochron (Kleine et al., 2005). The W isotopic evolution of the solar nebula and the bulk Earth is represented by the same line that also connects the SSI and CC data points. The slope of this line corresponds to  $^{180}\text{Hf}/^{184}\text{W}=1.28$ . Sainte Marguerite (St. M.) (Kleine et al., 2002), Forest Vale (FV) (Kleine et al., 2002), Acfer 182 (Ac182) (Kleine et al., 2005), mixed chondrites (ChY) (Yin et al., 2002) indicate the end of the W isotopic equilibration between metal and silicate in these chondrites: the time interval relative to SSI corresponds to  $3.0\pm 0.7$  Ma,  $0.9\pm 5.2$  Ma and  $2.4\pm 2.5$  Ma and  $2.4\pm 2.5$  Ma, respectively. Eu1 and Eu2 represent the metal/silicate differentiation of the eucrite parent body based on Hf–W isochrons obtained on eucrites (Q: (Quitté et al., 2000) and Kl: (Kleine et al. 2004a)): the corresponding time intervals in respect to SSI are 3.1 Ma and 4.1 Ma. The W compositions determined in magmatic iron meteorites (Horan et al., 1998; Kleine et al. 2004a; Lee and Halliday, 1996; Markowski et al., 2006; Schoenberg et al., 2002; Sherstén et al., 2006) yield model ages ranging from  $-9$  Ma to  $+3.4$  Ma relative to SSI (intersection of the gray band with the solar nebula evolution line). The W compositions lower than SSI are interpreted as being due to neutron reactions induced by long exposure to cosmic ray. When these samples are excluded, the remaining data indicate that the magmatic iron meteorites are indistinguishable from each other (Sherstén et al., 2006) and define a time interval of  $\Delta t=0.1 +1.0/-1.4$  Ma relative to CAIs (intersection of the darker band with the solar nebula evolution line). The two-stage model age of the Earth's core is defined by the intersection of the BSE terrestrial evolution line (corresponding to a slope of  $(^{180}\text{Hf}/^{184}\text{W})_{\text{BSE}}=21.3 +7.1/-5.5$  with the BE evolution line: the apparent Hf–W age of the Earth's core is  $33\pm 4$  Ma relative to SSI, assuming an instantaneous and complete metal/silicate re-equilibration). (*legend for previous diagram, from Allegre & al., EPSL 2008*)