Igneous differentiation of asteroids: What do we know we don't know?

Tim McCoy

Smithsonian Institution

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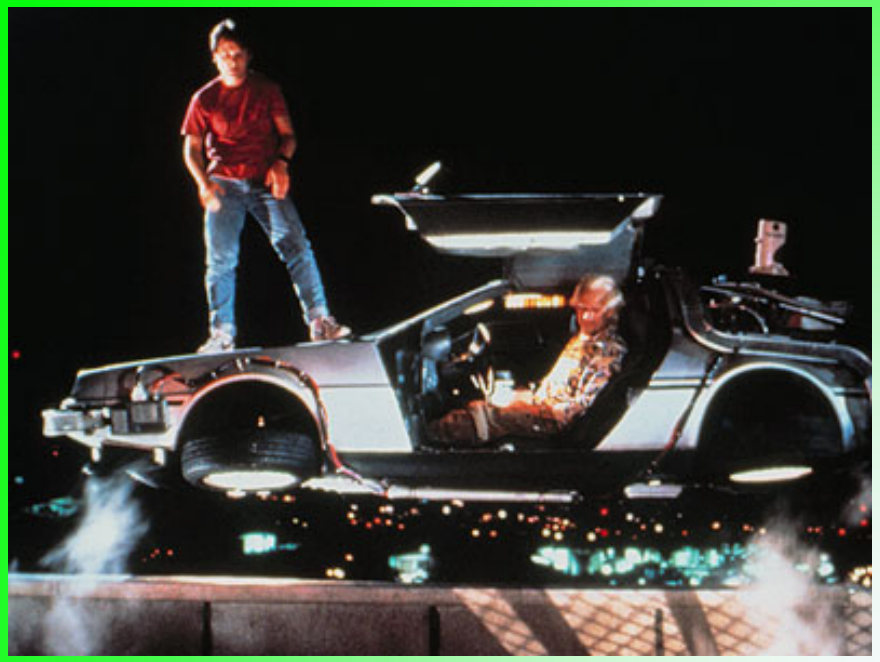
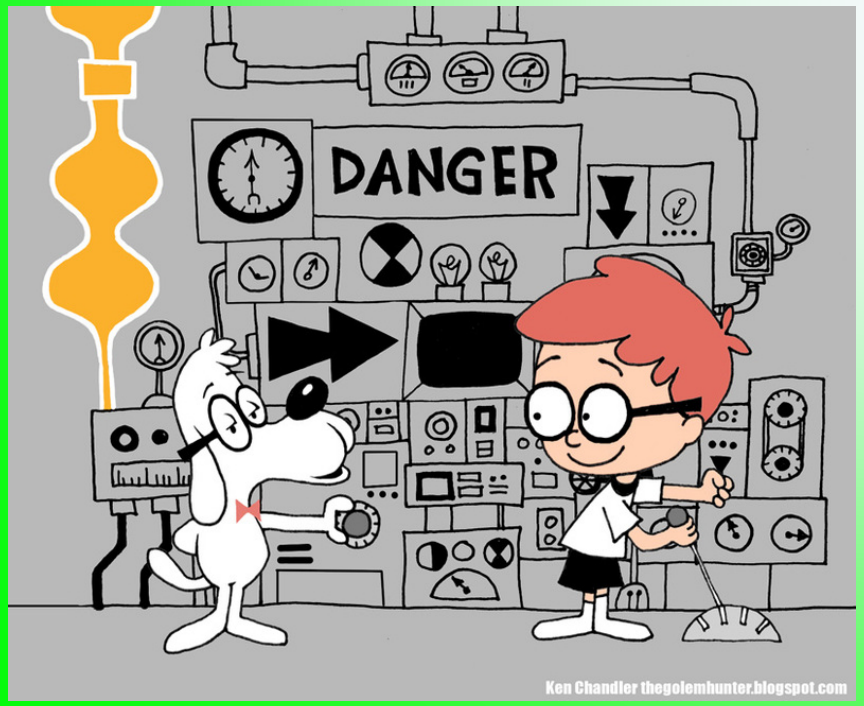
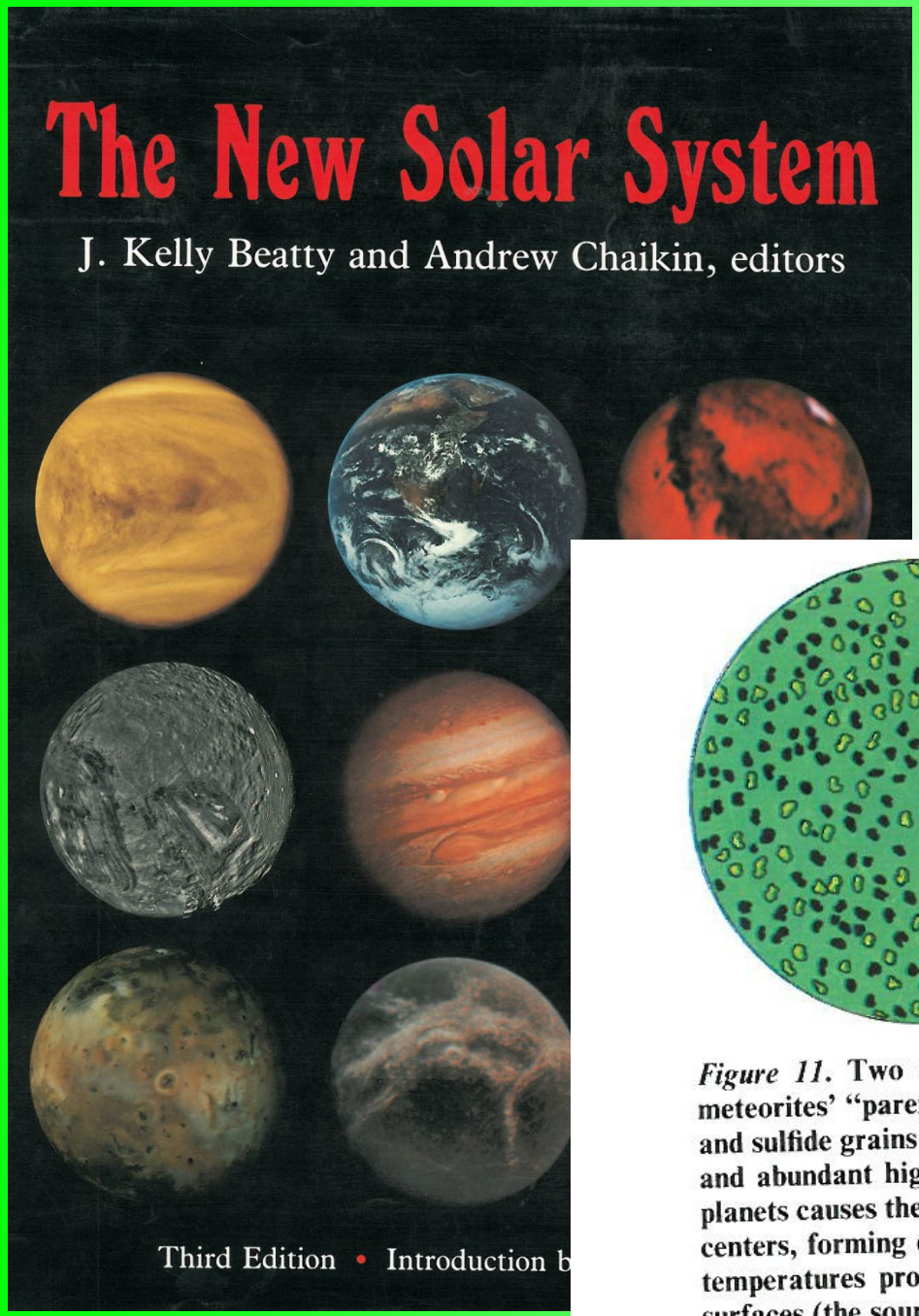



DANGER
Ken Chandler thegolemhunter.blogspot.com



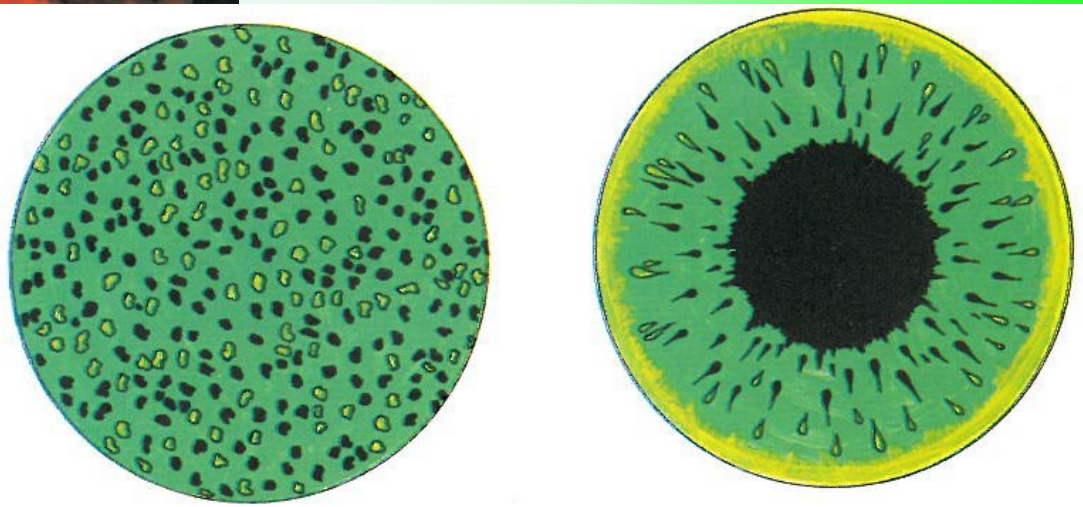


Figure 11. Two schematic cross-sections suggest the evolution of interiors of meteorites' "parent" planets. These accrete (left) as chondritic mixtures of metal and sulfide grains (black), minerals of relatively low melting temperature (yellow), and abundant high-melting Mg and Fe silicates (green). Internal heating of the planets causes them to melt partially (right). Molten metal and sulfide drain to the centers, forming cores (the source of iron meteorites?). Silicates that melt at low temperatures produce a low-density magma, which tends to erupt to planetary surfaces (the source of Ca-rich achondrites?).

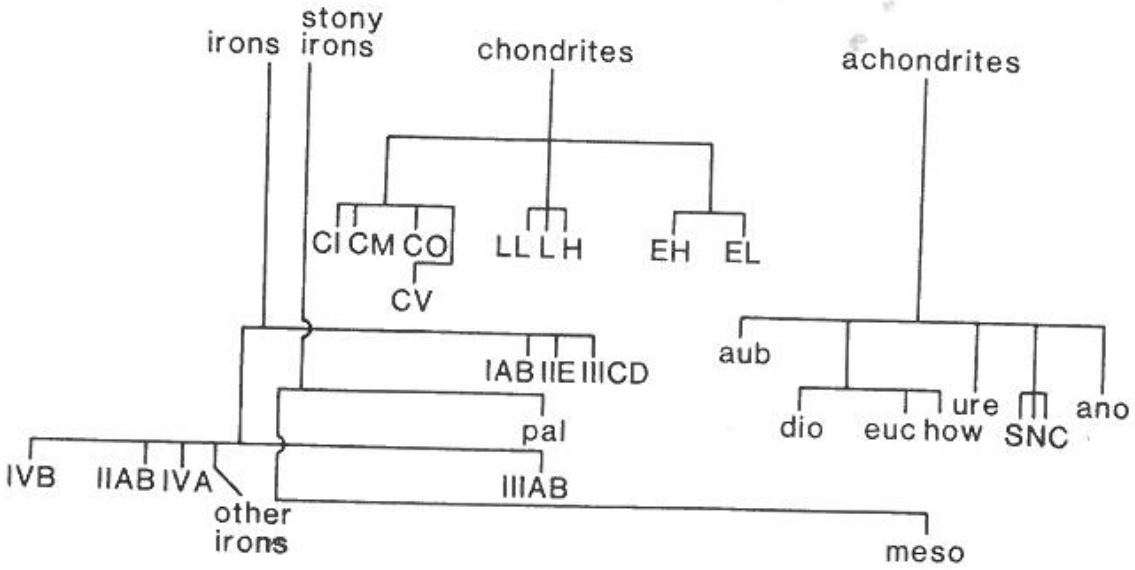


Fig. 1.1.5. A "family tree" of meteorite classes and an indication of possible interclass relationships; for example, the IAB, IIE and IIIAB iron meteorites and the pallasites (pal) may be related to the ordinary chondrites, although it is clear that the relationship is closest for the IAB and IIE irons (which contain silicates of approximately chondritic composition); the mesosiderites (meso) may be related to the howardite and eucrite achondrites, and the aubrites have been related to the enstatite chondrites. Abbreviations for the achondrites are as follows: aubrites, aub; diogenites, dio; eucrites, euc; howardites, how; ureilites, ure; shergottites, nahklites and chassignítes, SNC; the anorthositic breccias, ano.

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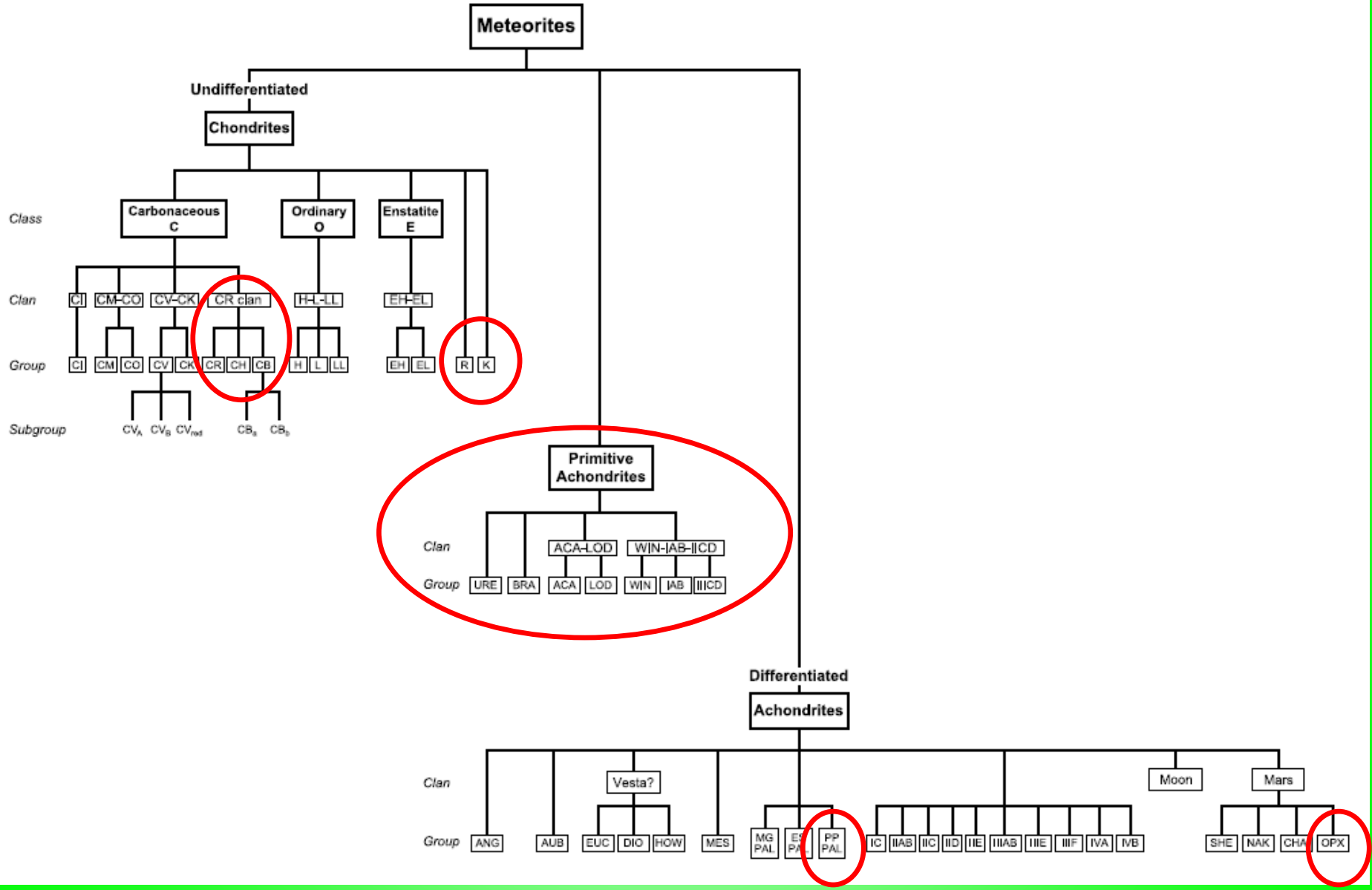
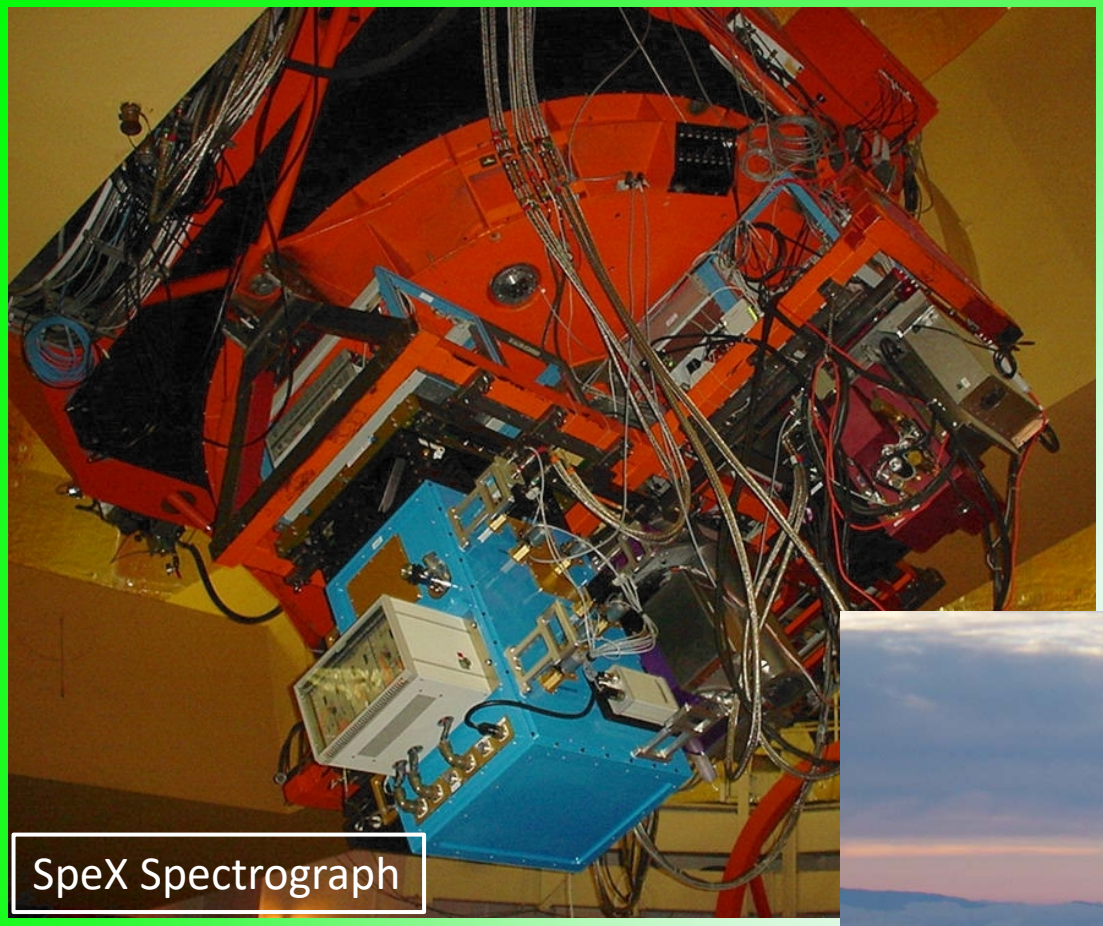
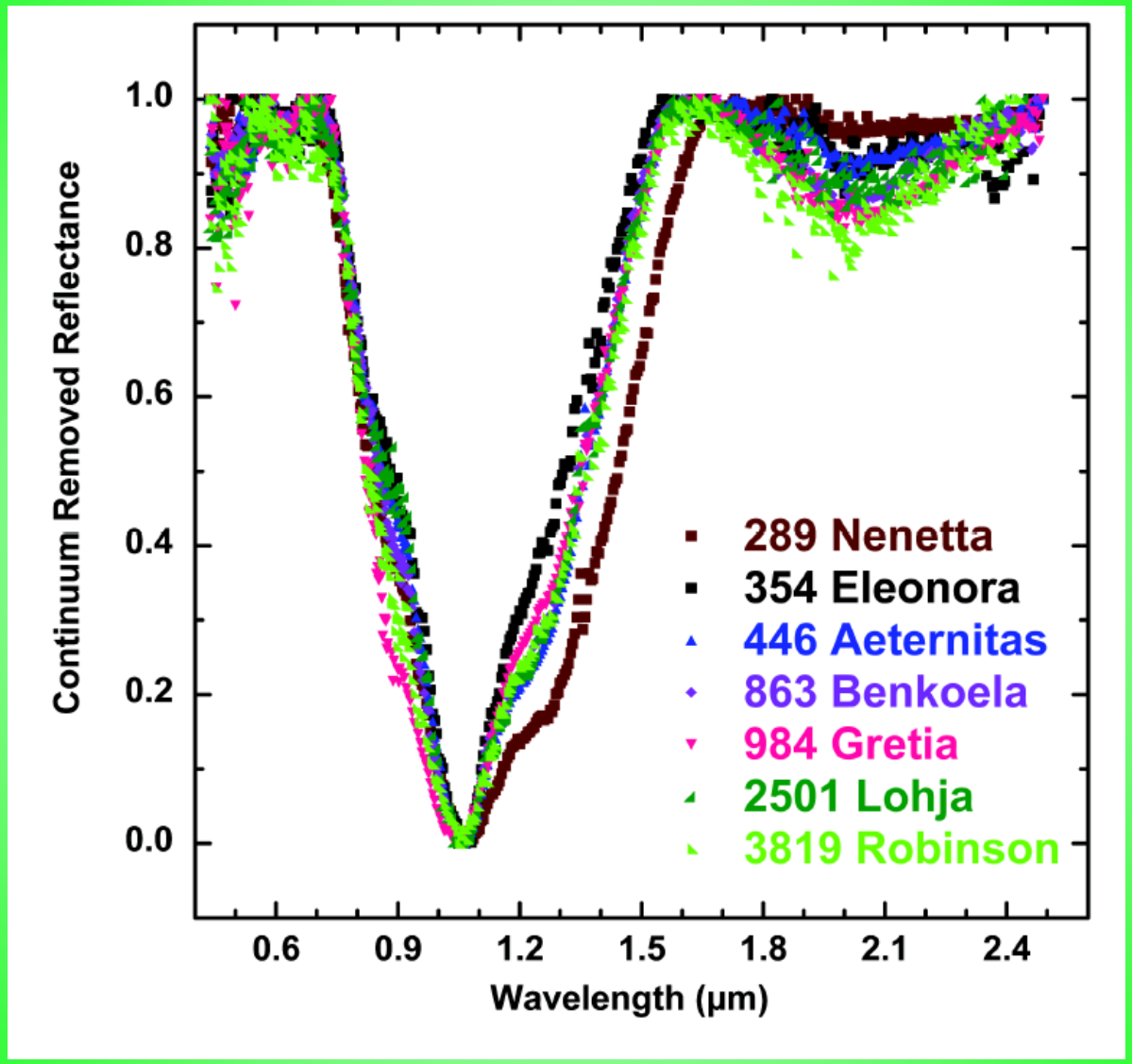
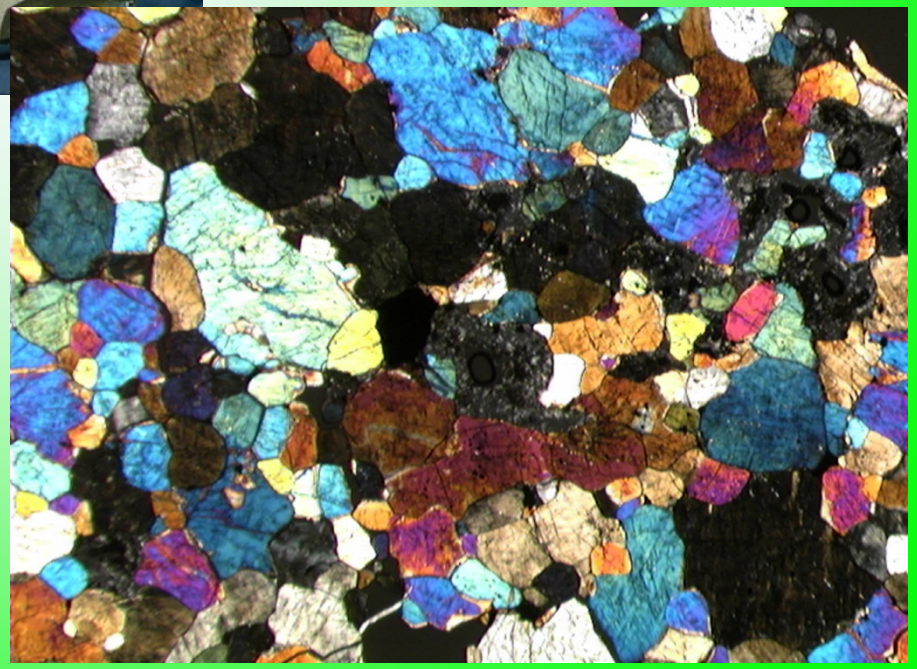
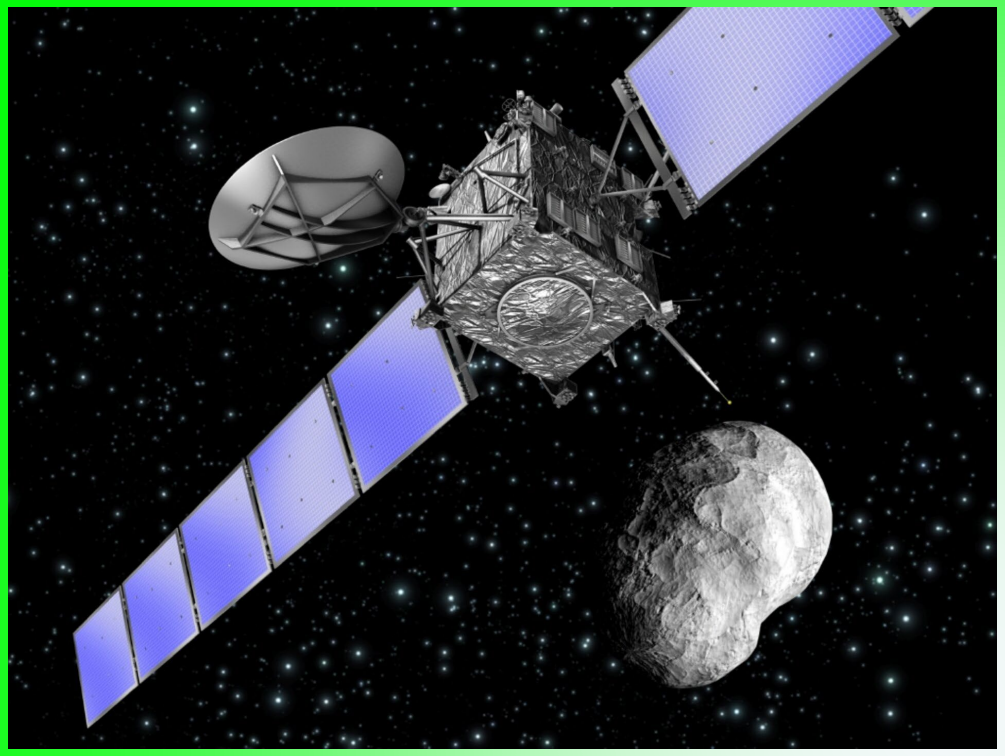

Meteorites
Undifferentiated
Chondrites
Class
Carbonaceous C
Ordinary O
Enstatite E
Clan
CI
CM-CO
CV-CK
CR clan
H-L-LL
EH-EL
Group
CI
CM
CO
CV
CK
CR
CH
CB
H
L
LL
EH
EL
R
K
Subgroup
CV_A
CV_B
CV_red
CB_a
CB_b
Primitive Achondrites
Clan
ACA-LOD
WIN-IAB-IICD
Group
URE
BRA
ACA
LOD
WIN
IAB
IIICD
Differentiated
Achondrites
Clan
Vesta?
Moon
Mars
Group
ANG
AUB
EUC
DIO
HOW
MES
MG PAL
EG PAL
PP PAL
IC
IIAB
IIC
IID
IIE
IIIAB
IIIE
IIIF
IVA
IVB
SHE
NAK
CHA
OPX

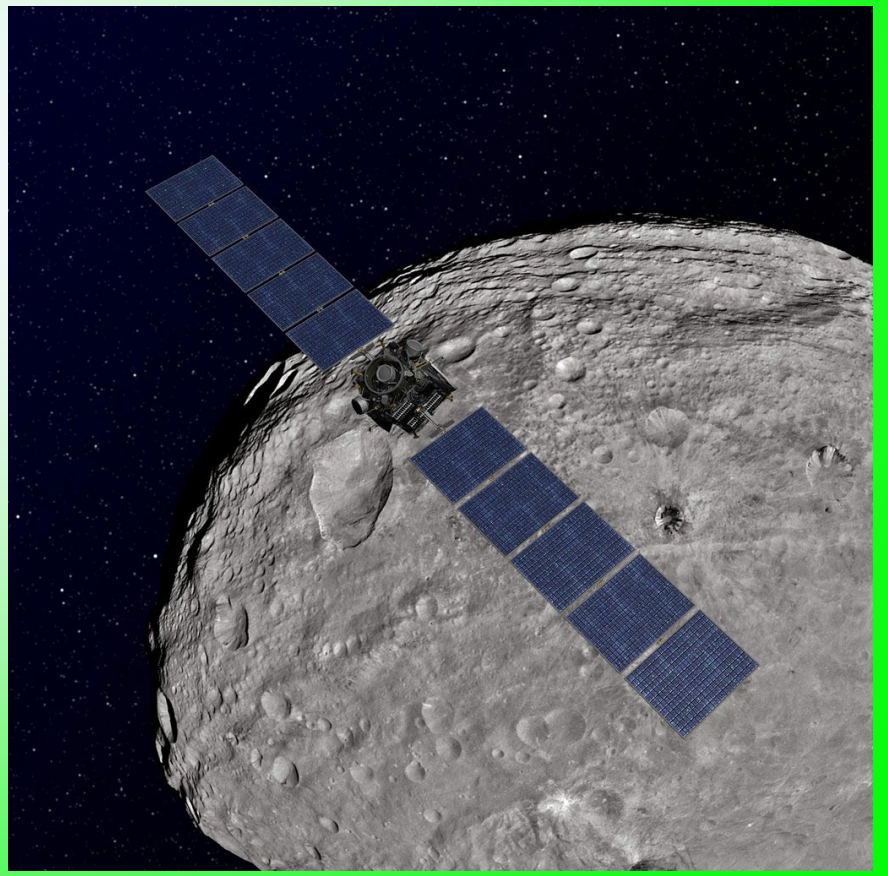


SpeX Spectrograph


Continuum Removed Reflectance
1.0
0.8
0.6
0.4
0.2
0.0
0.6
0.9
1.2
1.5
1.8
2.1
2.4
Wavelength (μm)
289 Nenetta
354 Eleonora
446 Aeternitas
863 Benkoela
984 Gretia
2501 Lohja
3819 Robinson

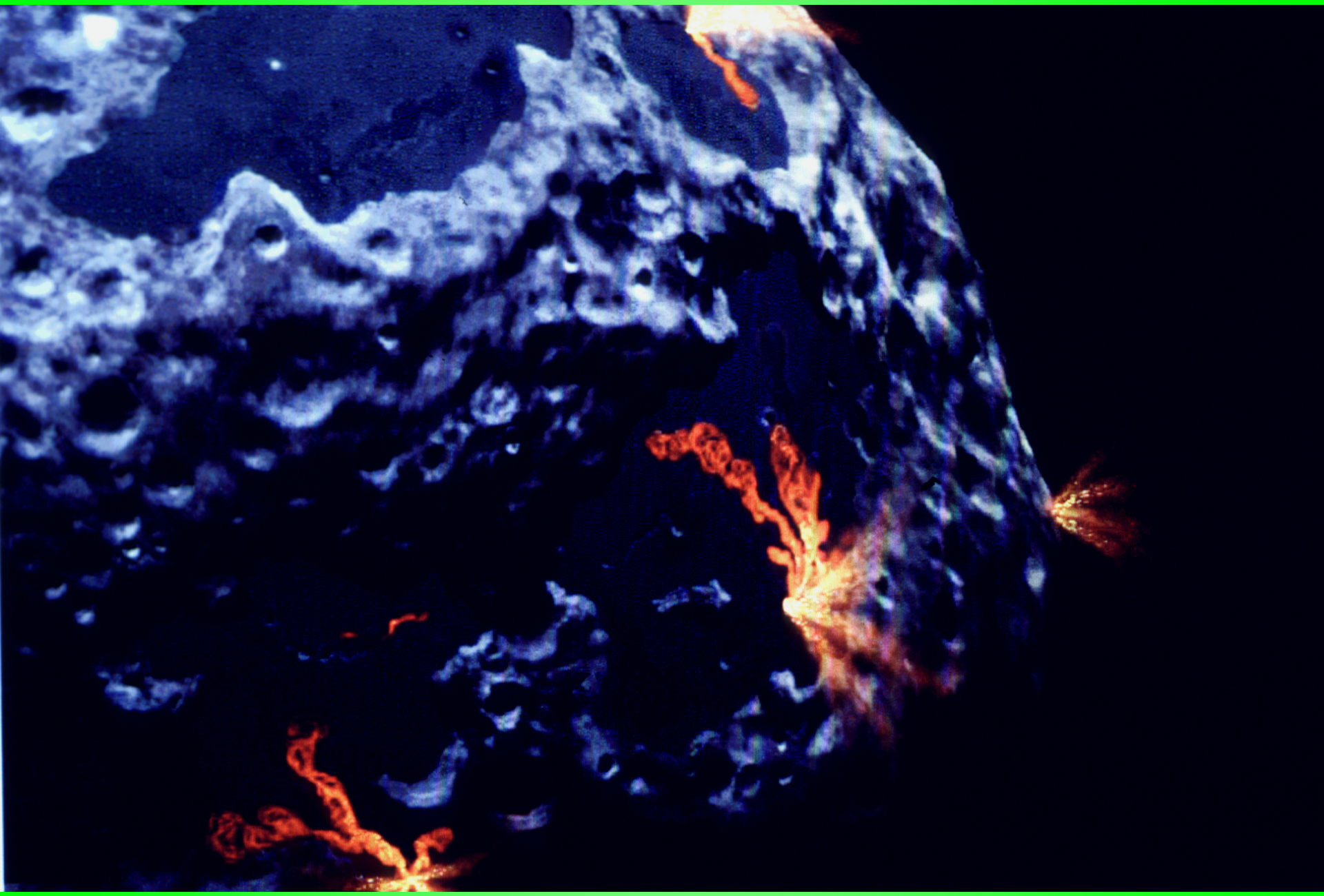


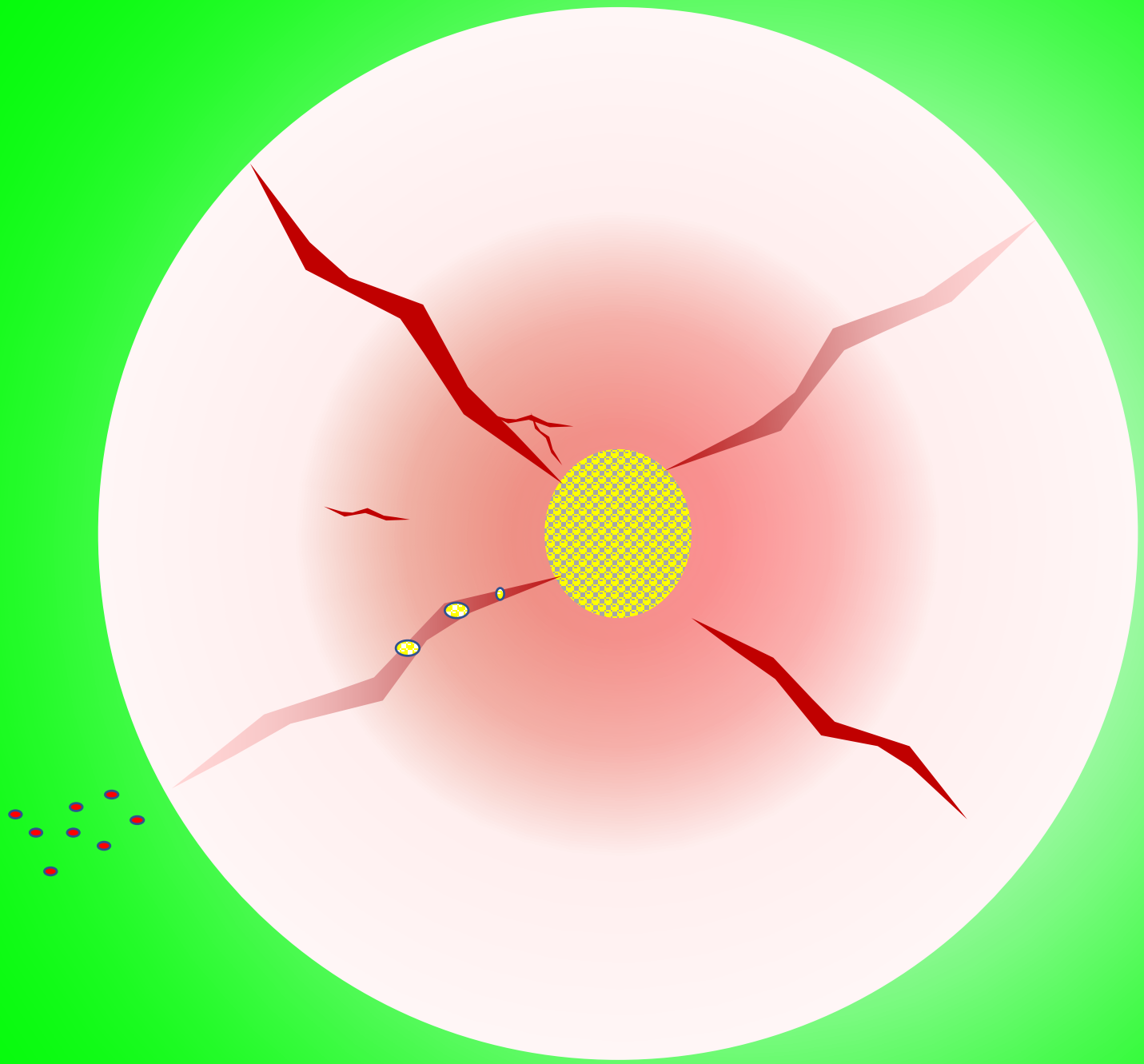


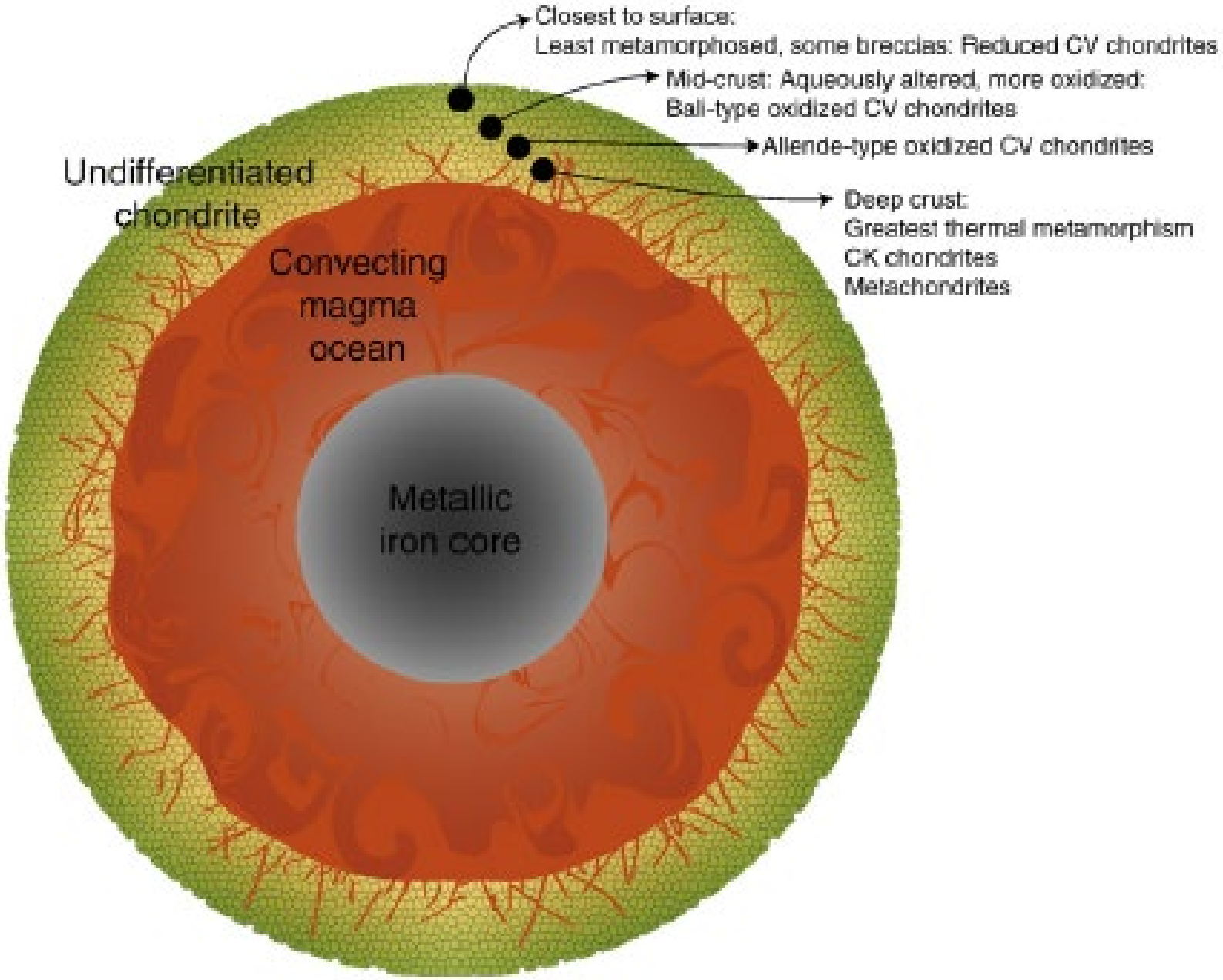


Big questions

- **Nature of a partially-differentiated asteroid**
- **Formation of silica-rich crust**
- **Nature of asteroid mantles**
- **Hit-and-run collisions**
- **What happened to the sulfur**
- **The role of ice and time in differentiation**

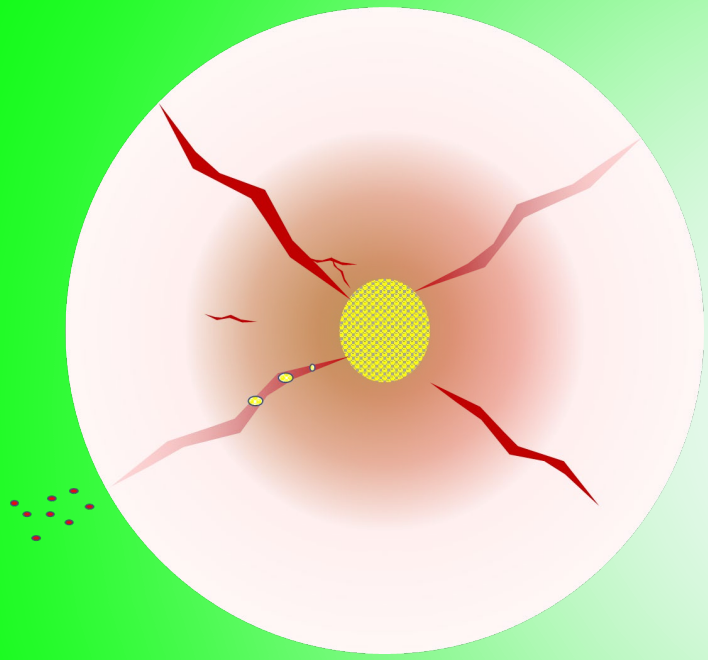




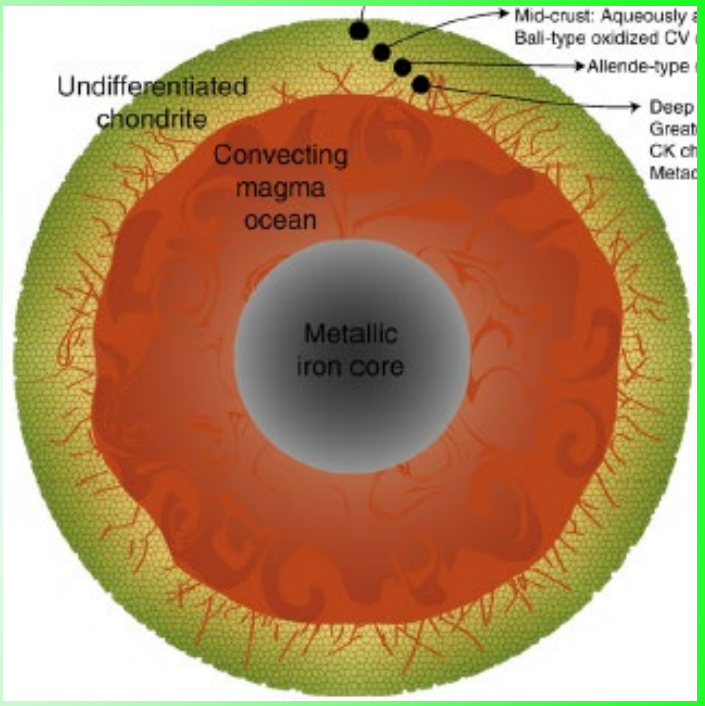


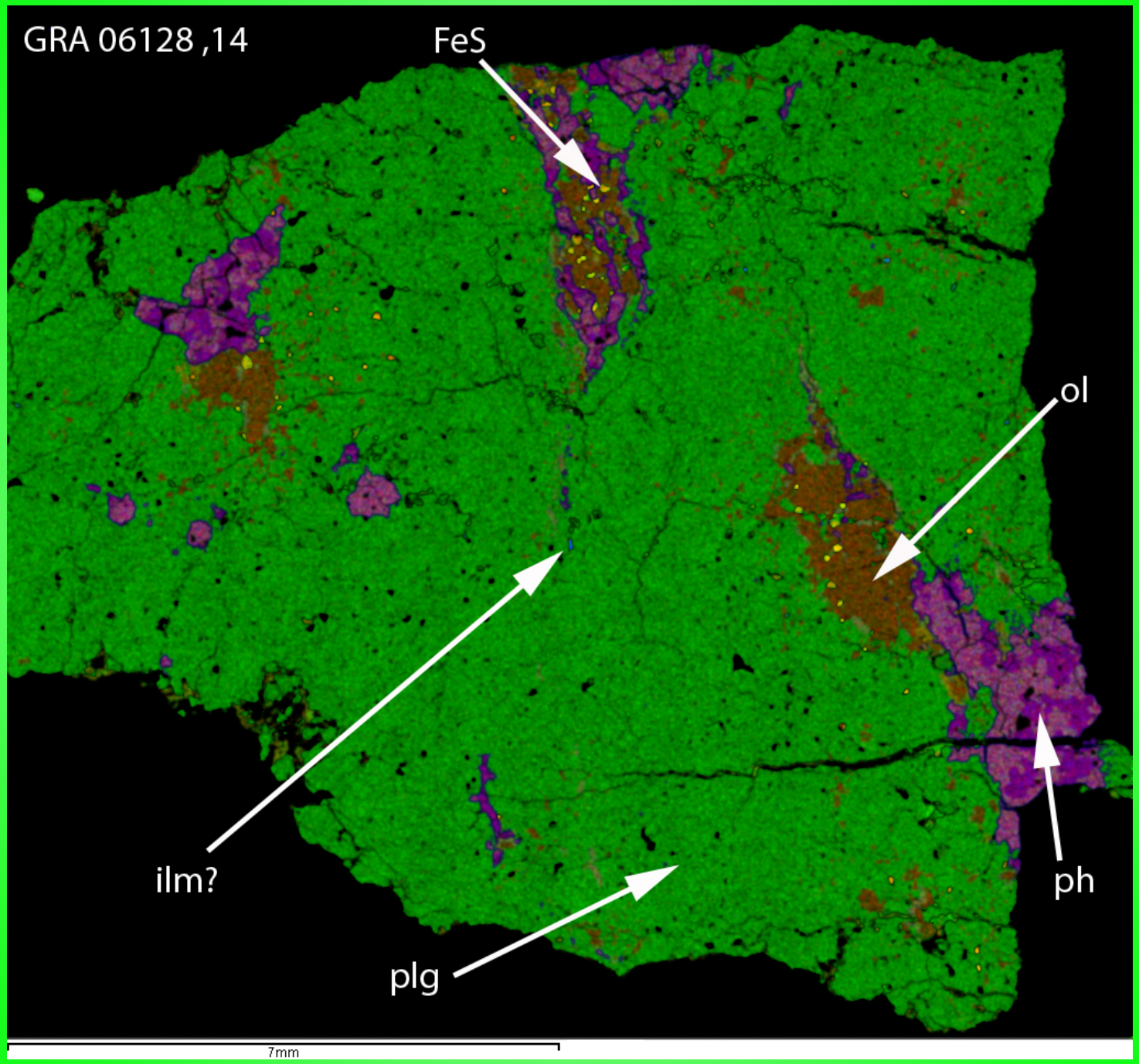
Elkins-Tanton et al. (2011)

Nature of a partially-differentiated asteroid

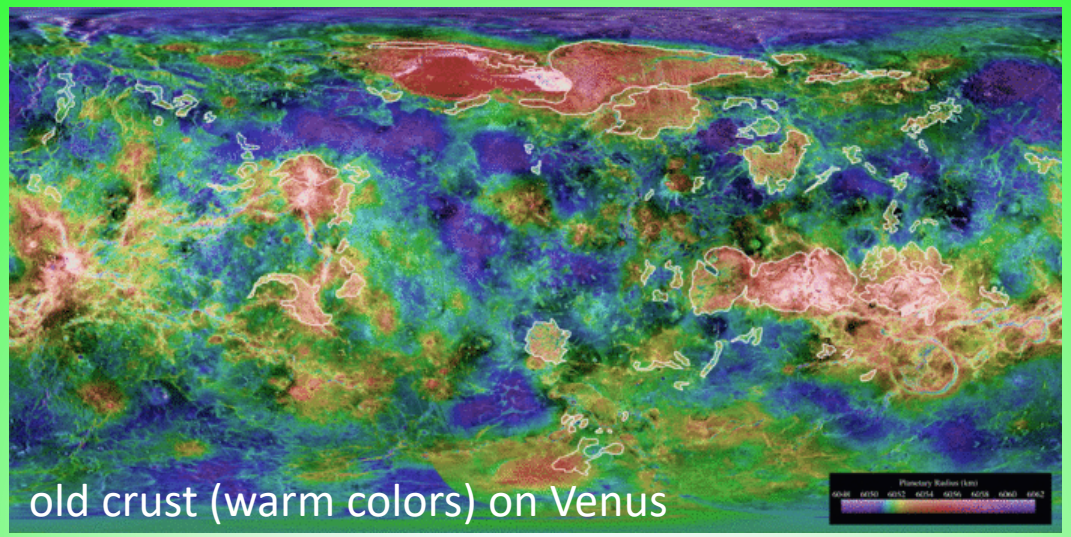


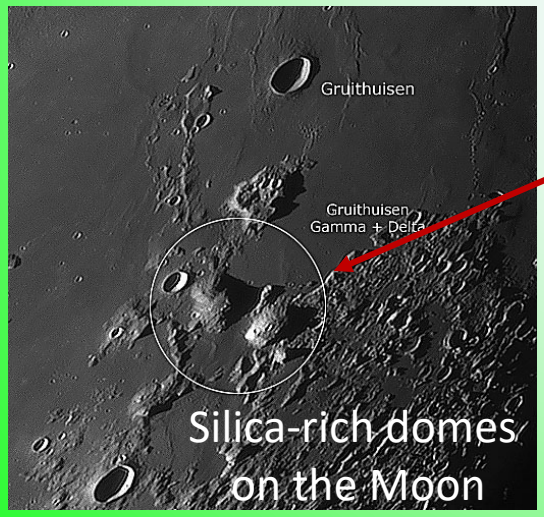
vs



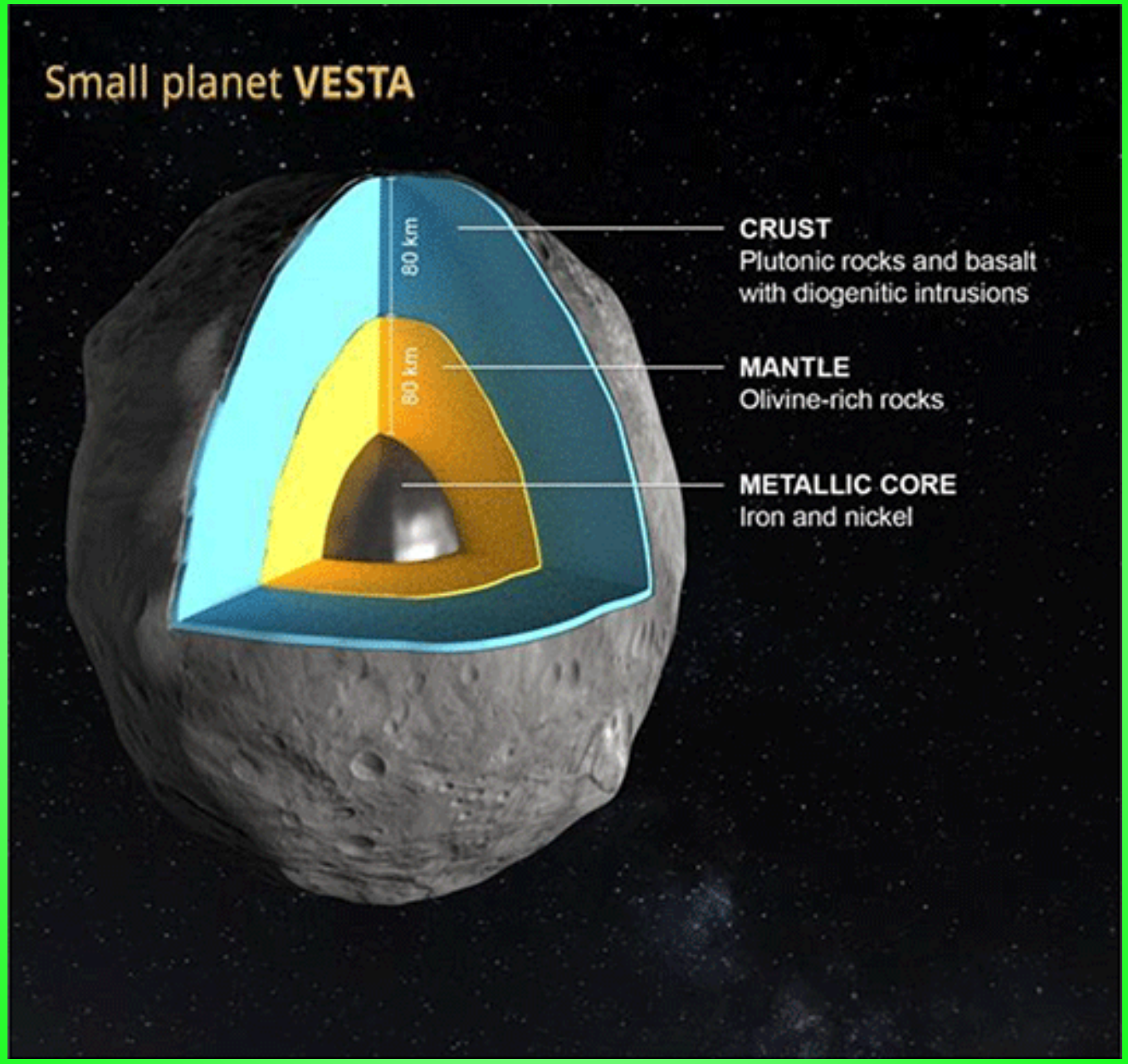

GRA 06128 ,14
FeS
ol
ilm?
ph
plg
7mm

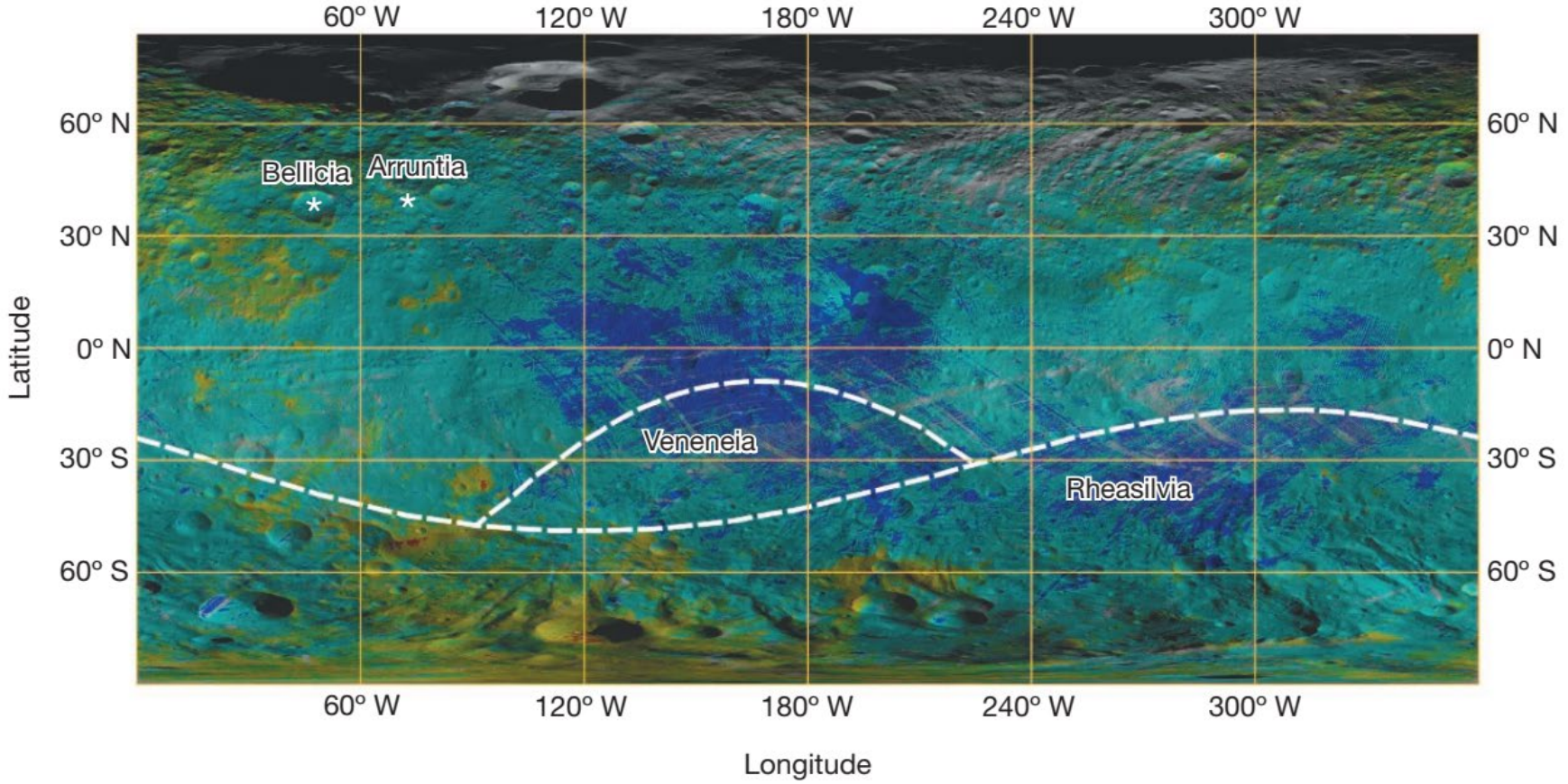
Silica-rich Crust in the Solar System

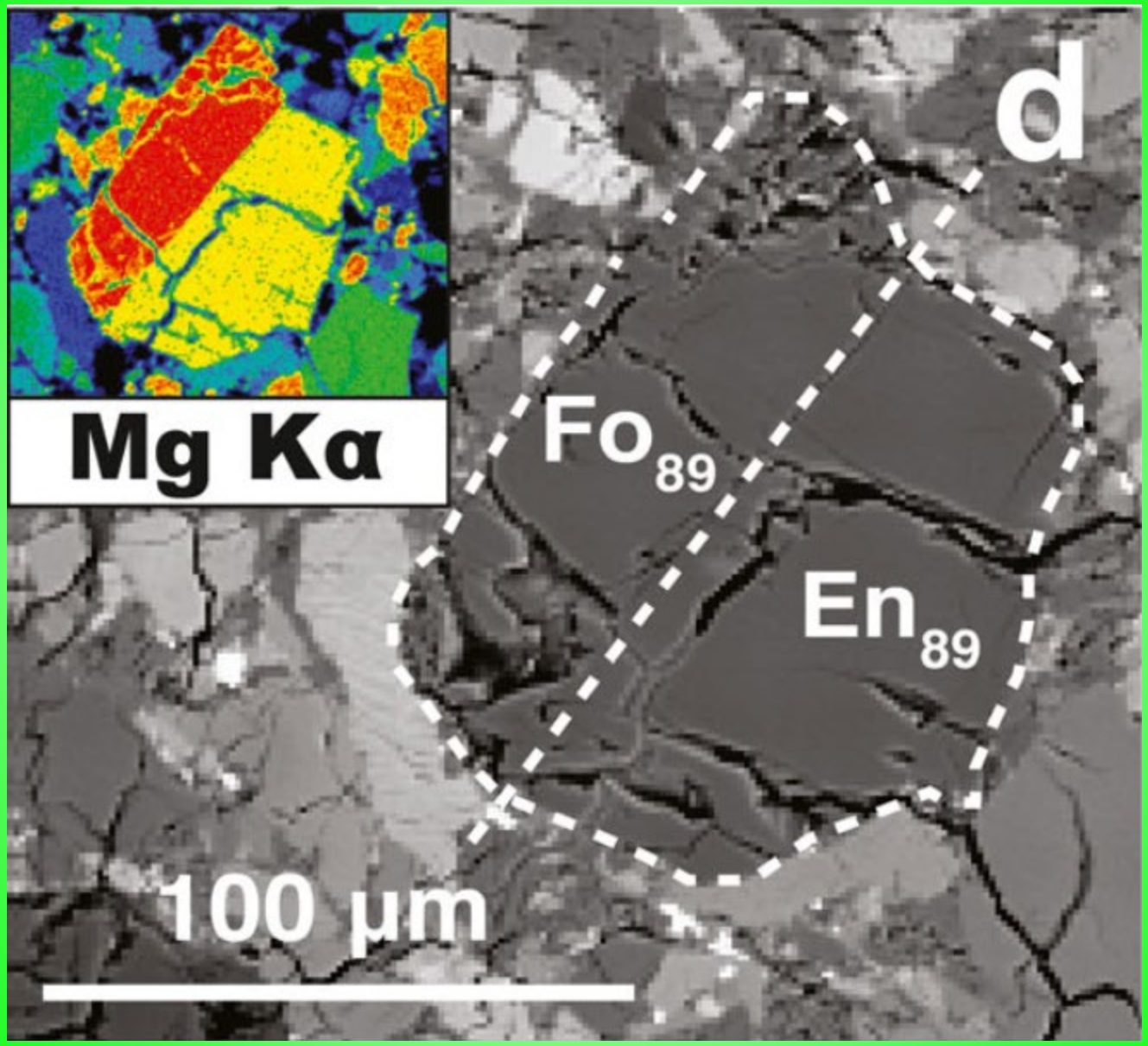




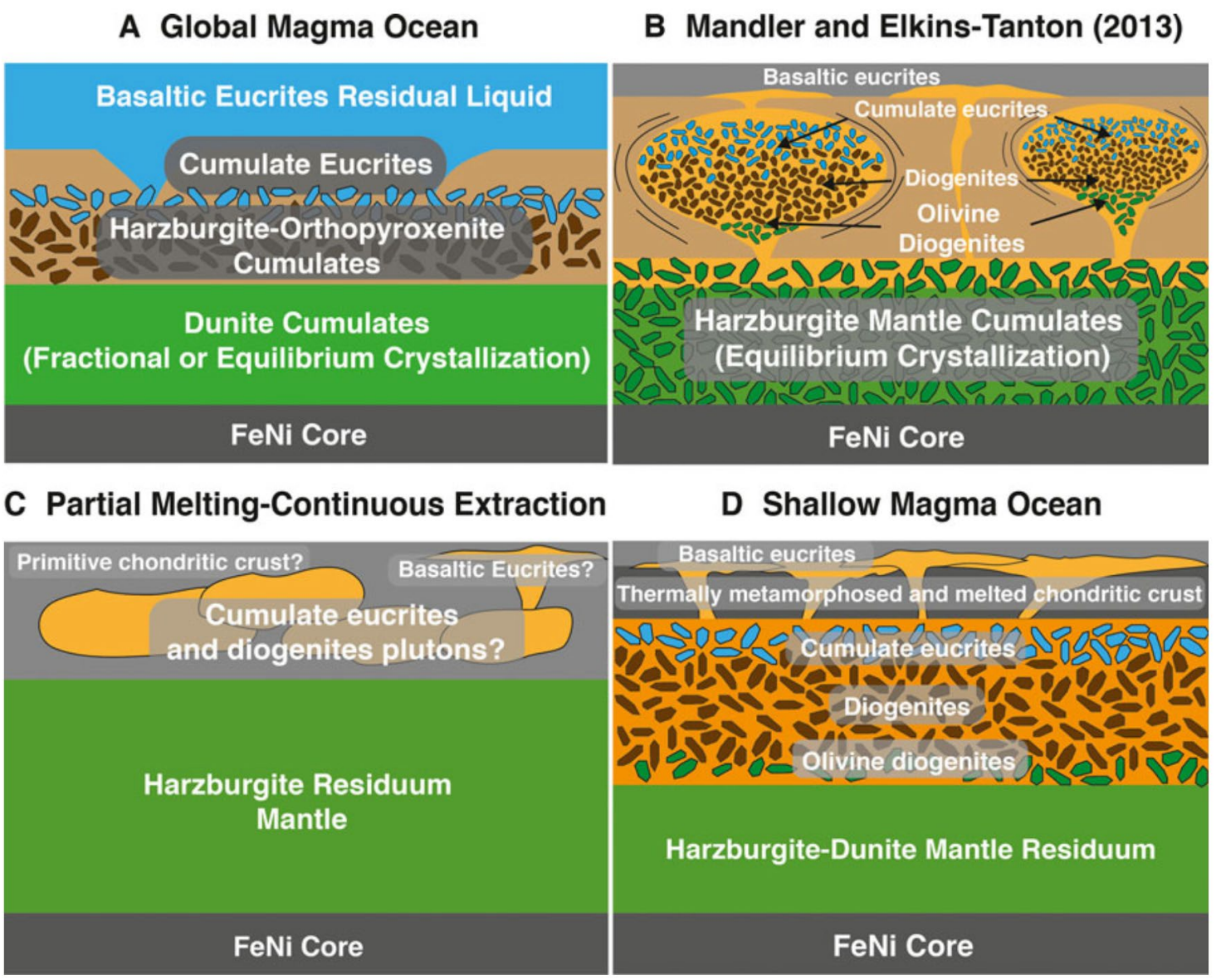
Where might silica-rich rocks (like Earth's continental crust) exist on other bodies within our solar system and how would they form?

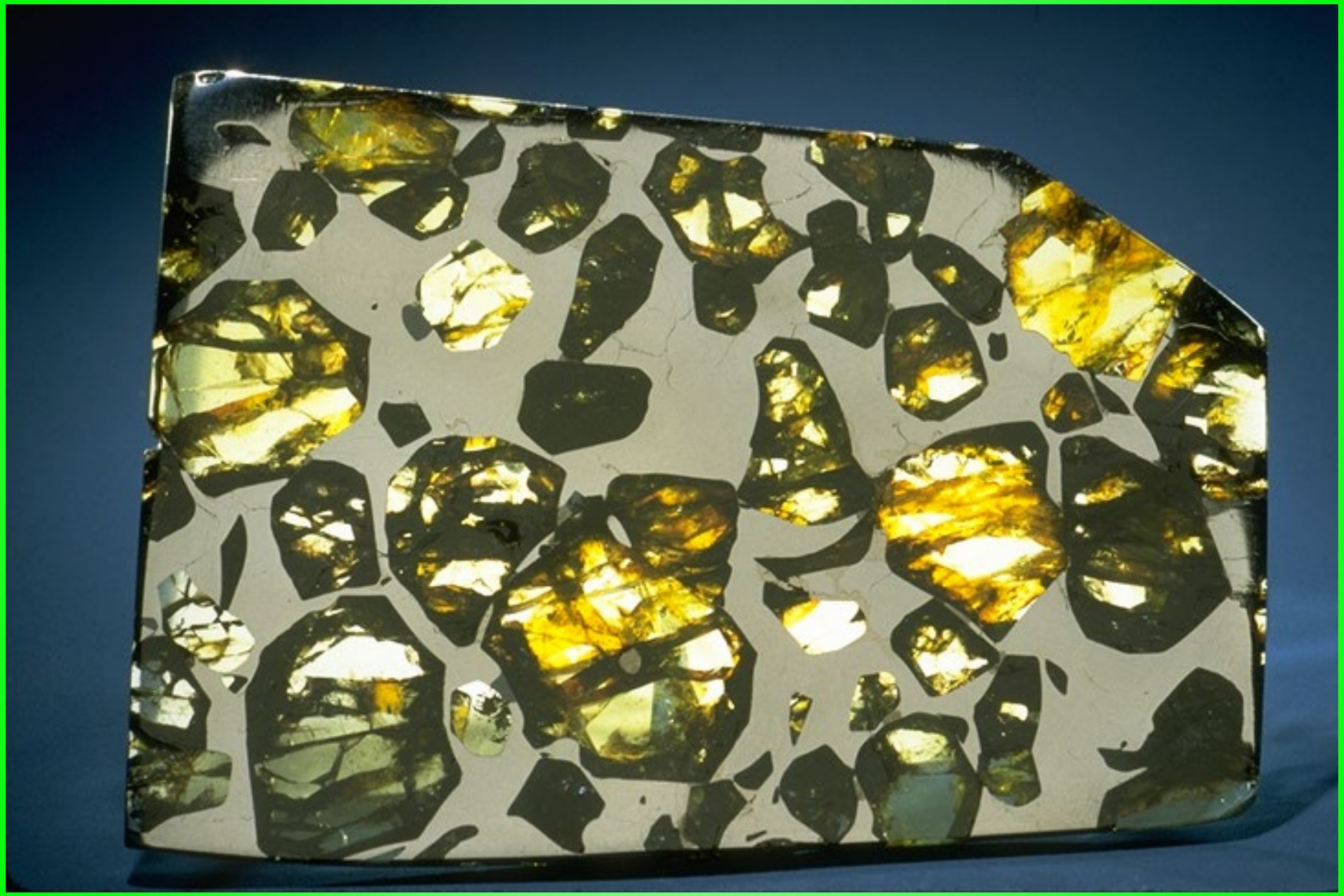

Small planet VESTA
80 km
80 km
CRUST
Plutonic rocks and basalt
with diogenitic intrusions
MANTLE
Olivine-rich rocks
METALLIC CORE
Iron and nickel

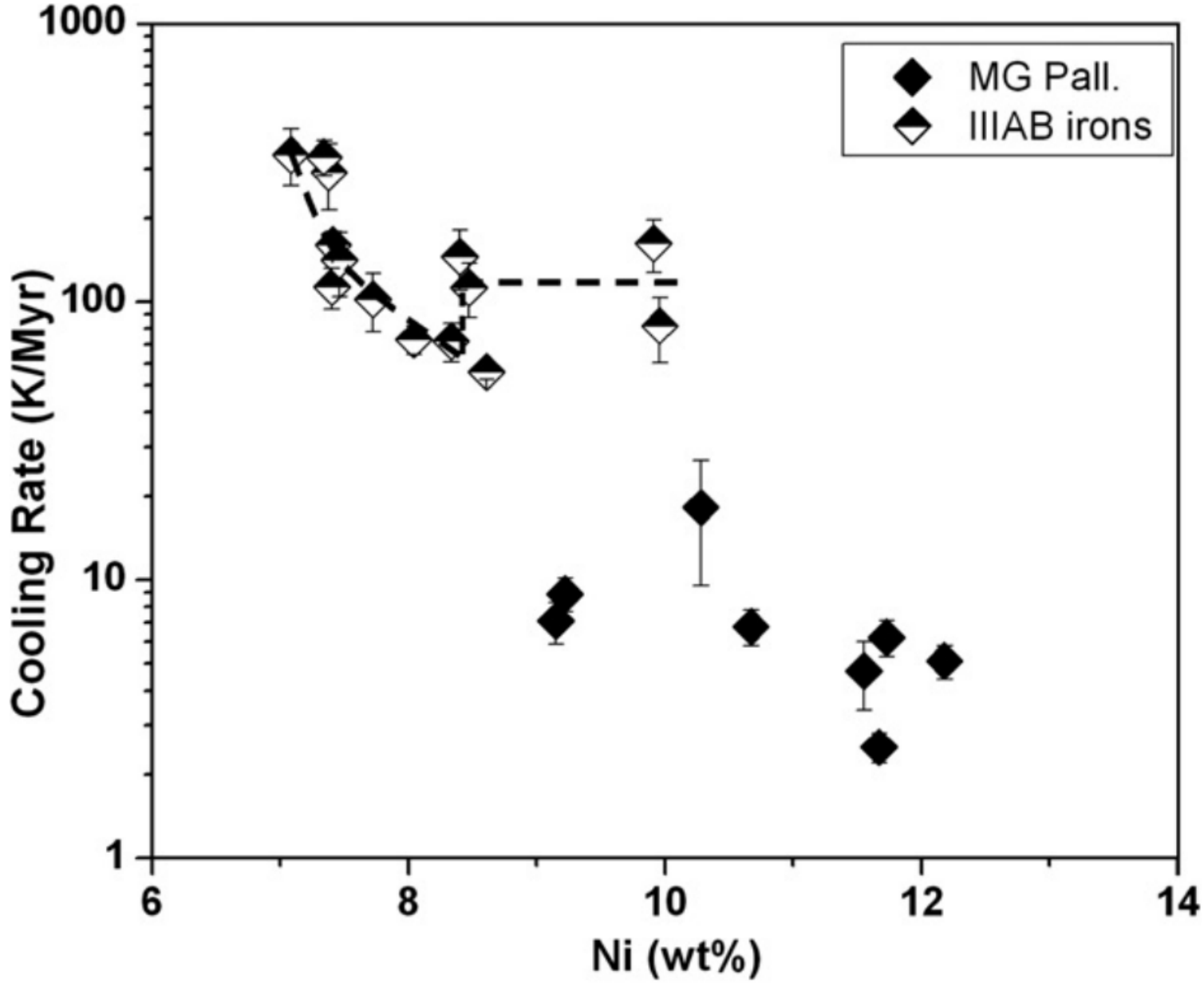

60° W
120° W
180° W
240° W
300° W
60° N
30° N
0° N
30° S
60° S
Latitude
Bellicia
Arruntia
Veneneia
Rheasilvia
Longitude


d
Mg Kα
Fo89
En89
100 µm

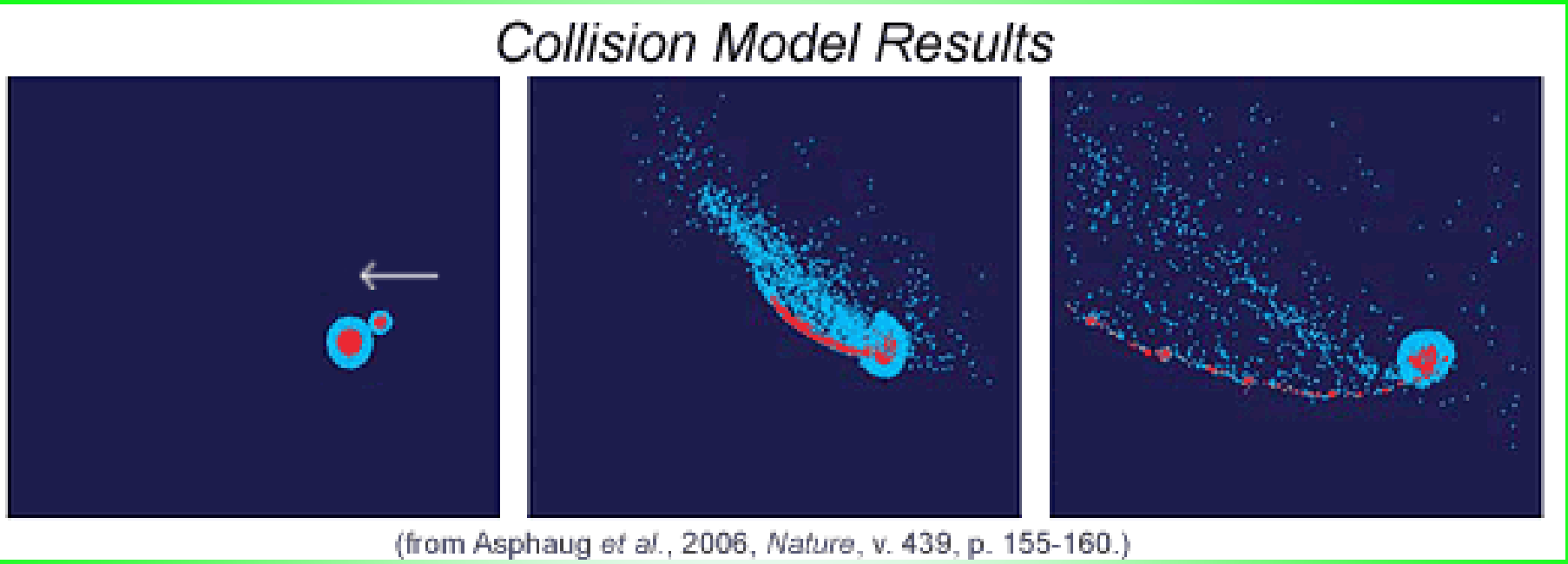
Nature of asteroid mantles



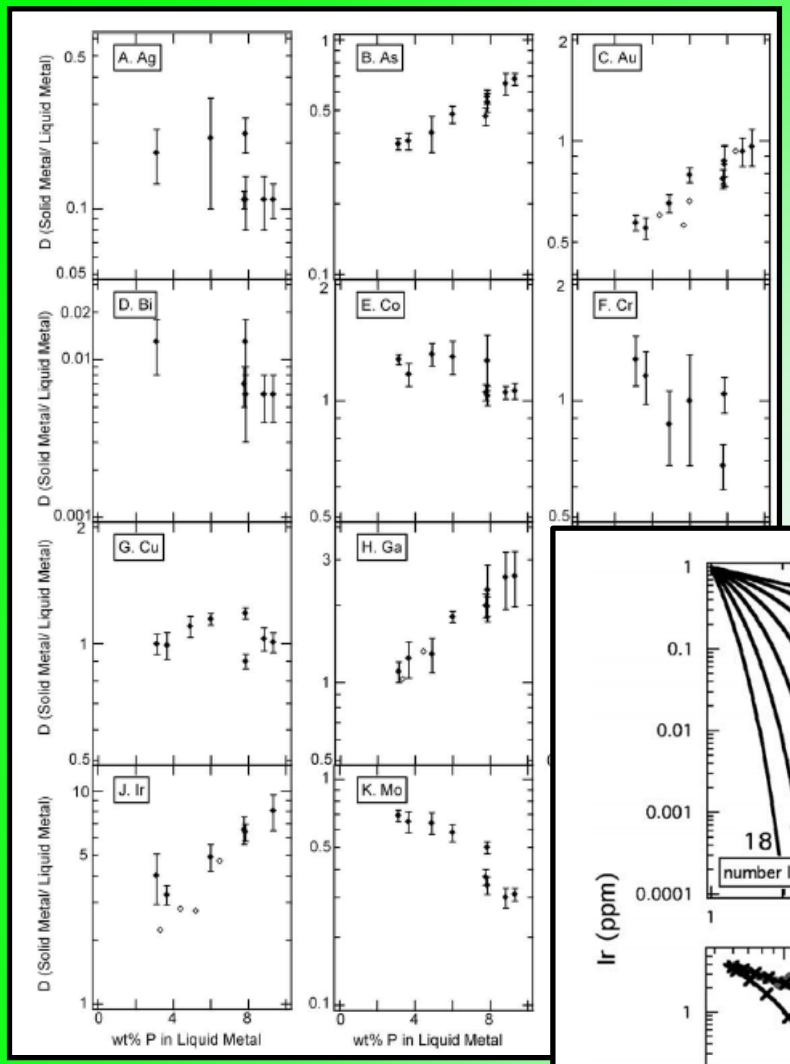


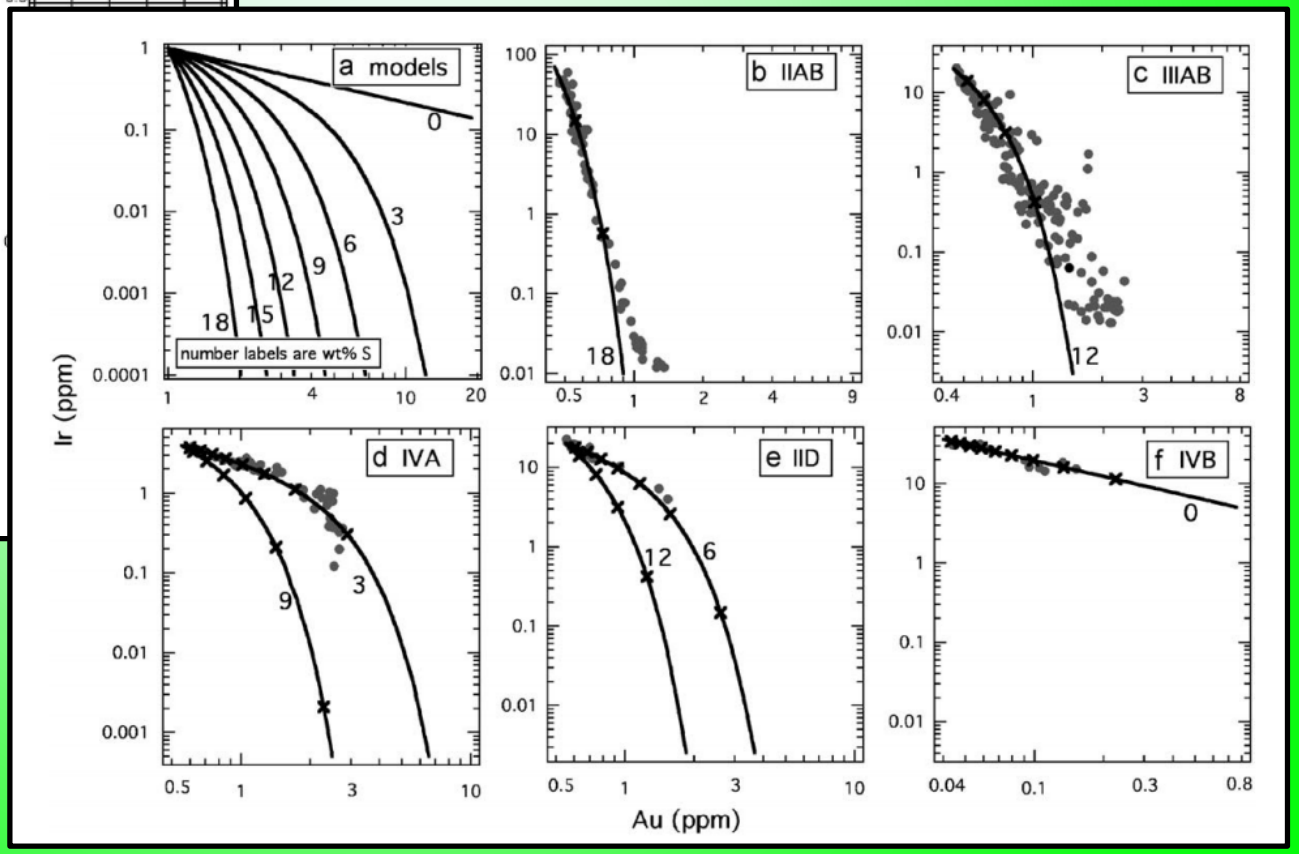

1000
100
10
1
Cooling Rate (K/Myr)
6
8
10
12
14
Ni (wt%)
MG Pall.
IIIAB irons

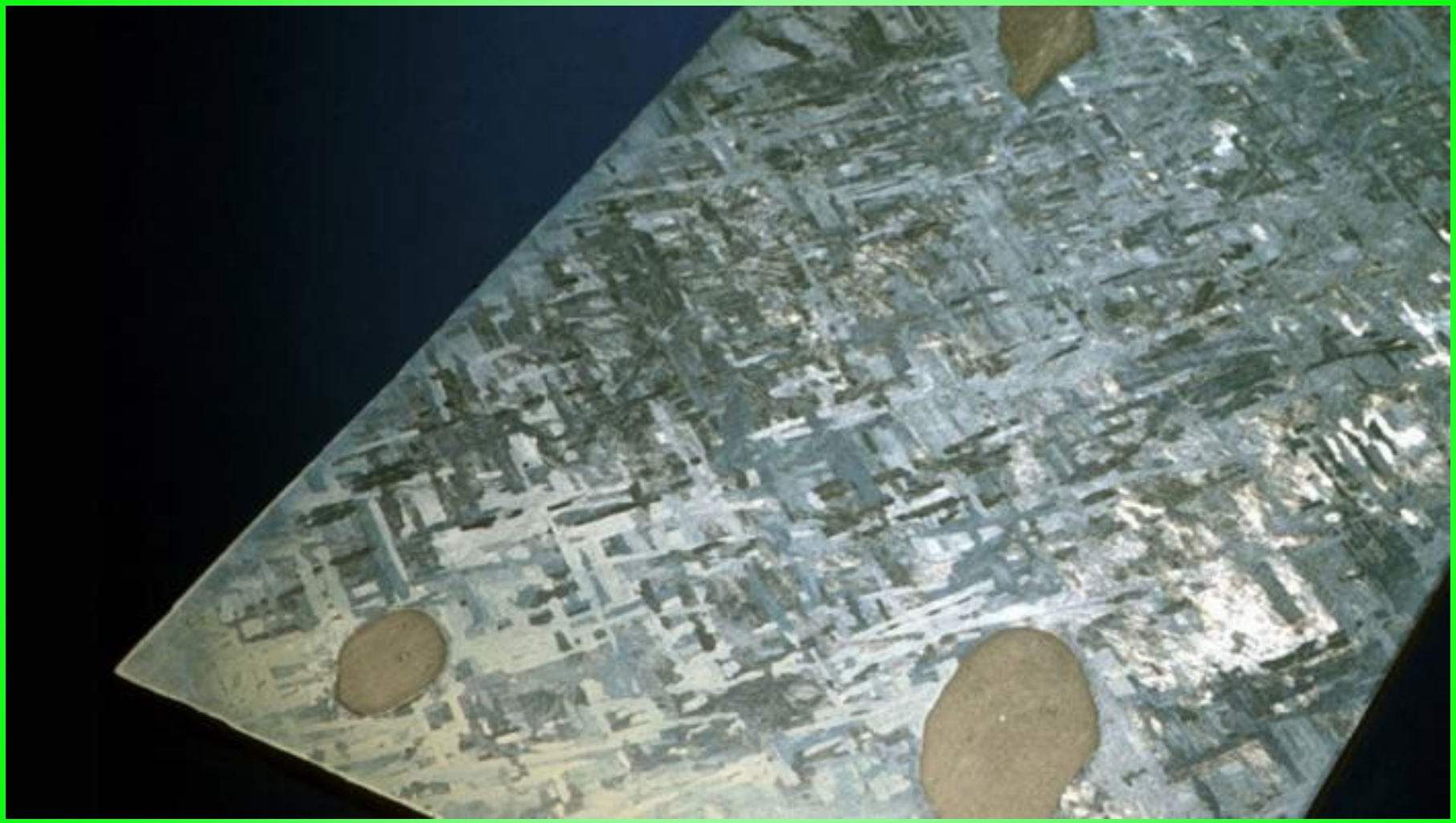
Hit-and-run collisions

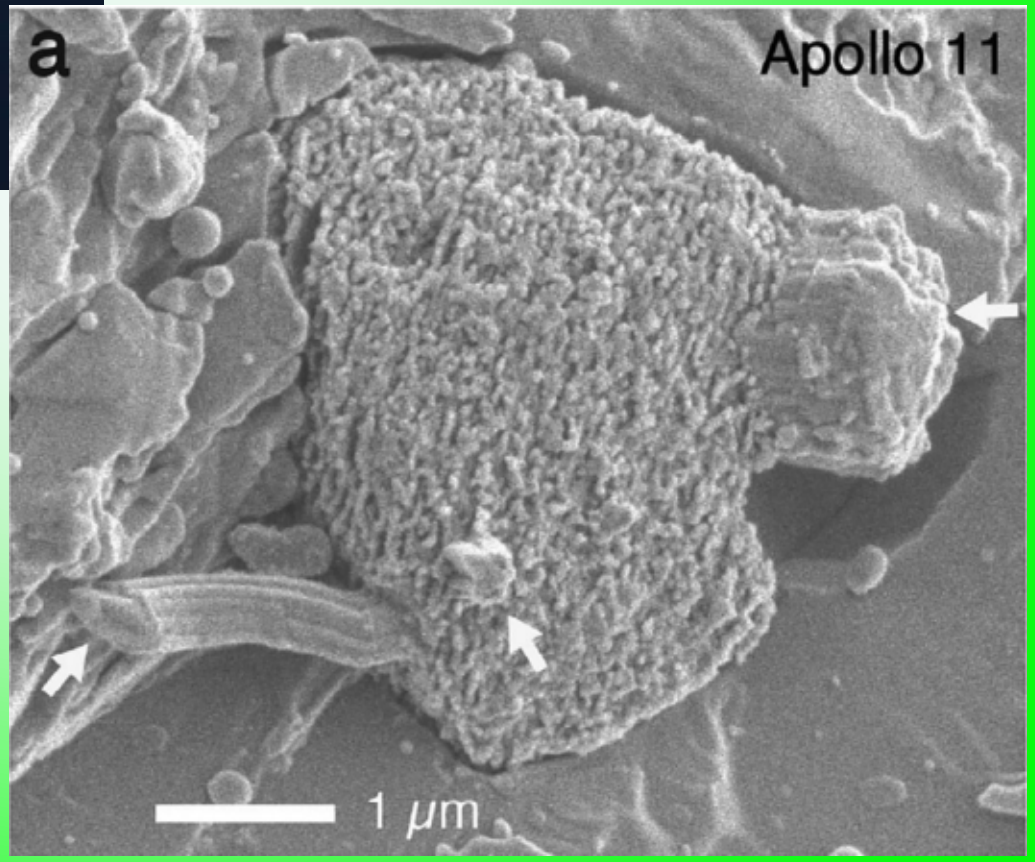


(from Asphaug *et al.*, 2006, *Nature*, v. 439, p. 155-160.)

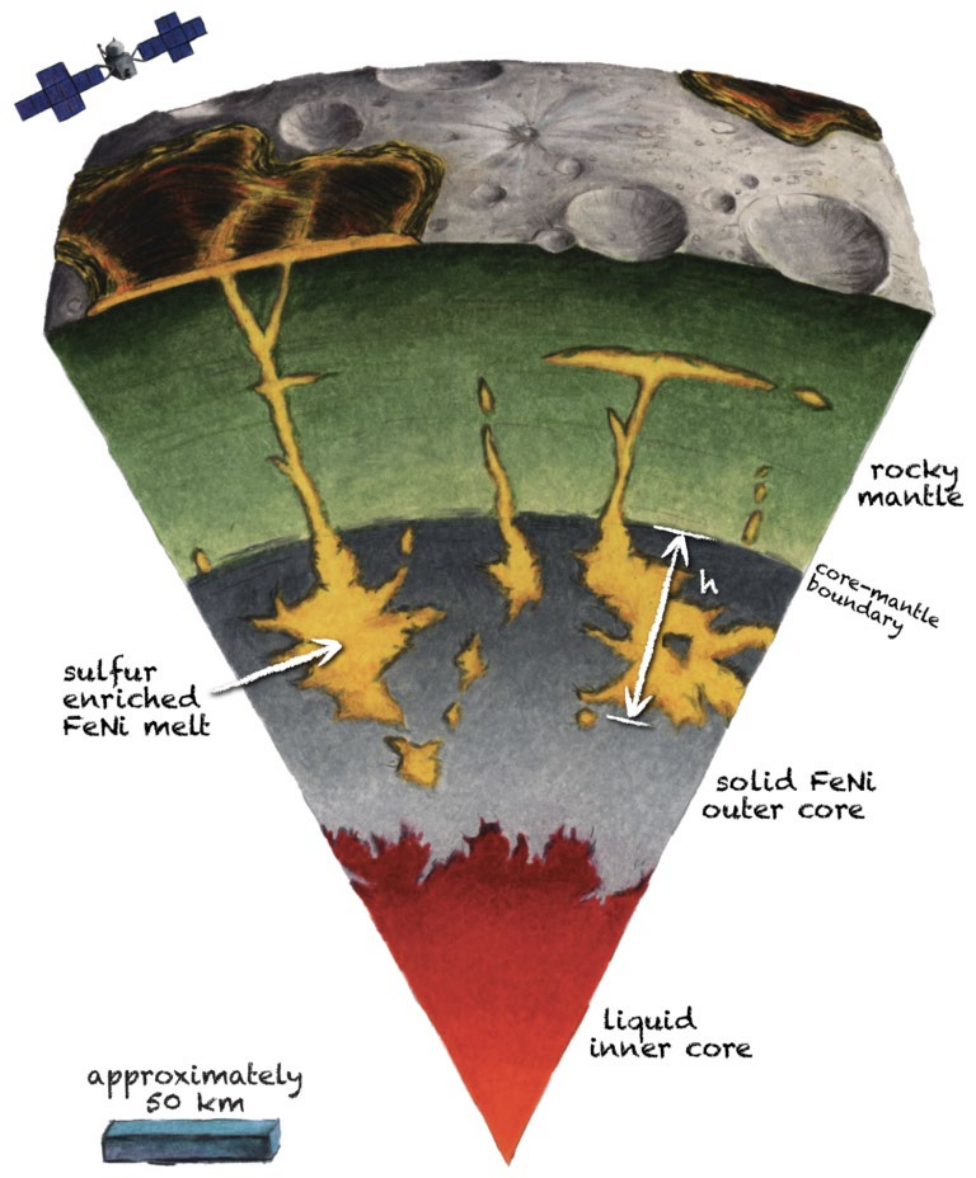

A. Ag
B. As
C. Au
D. Bi
E. Co
F. Cr
G. Cu
H. Ga
J. Ir
K. Mo
D (Solid Metal/ Liquid Metal)
wt% P in Liquid Metal
wt% P in Liquid Metal

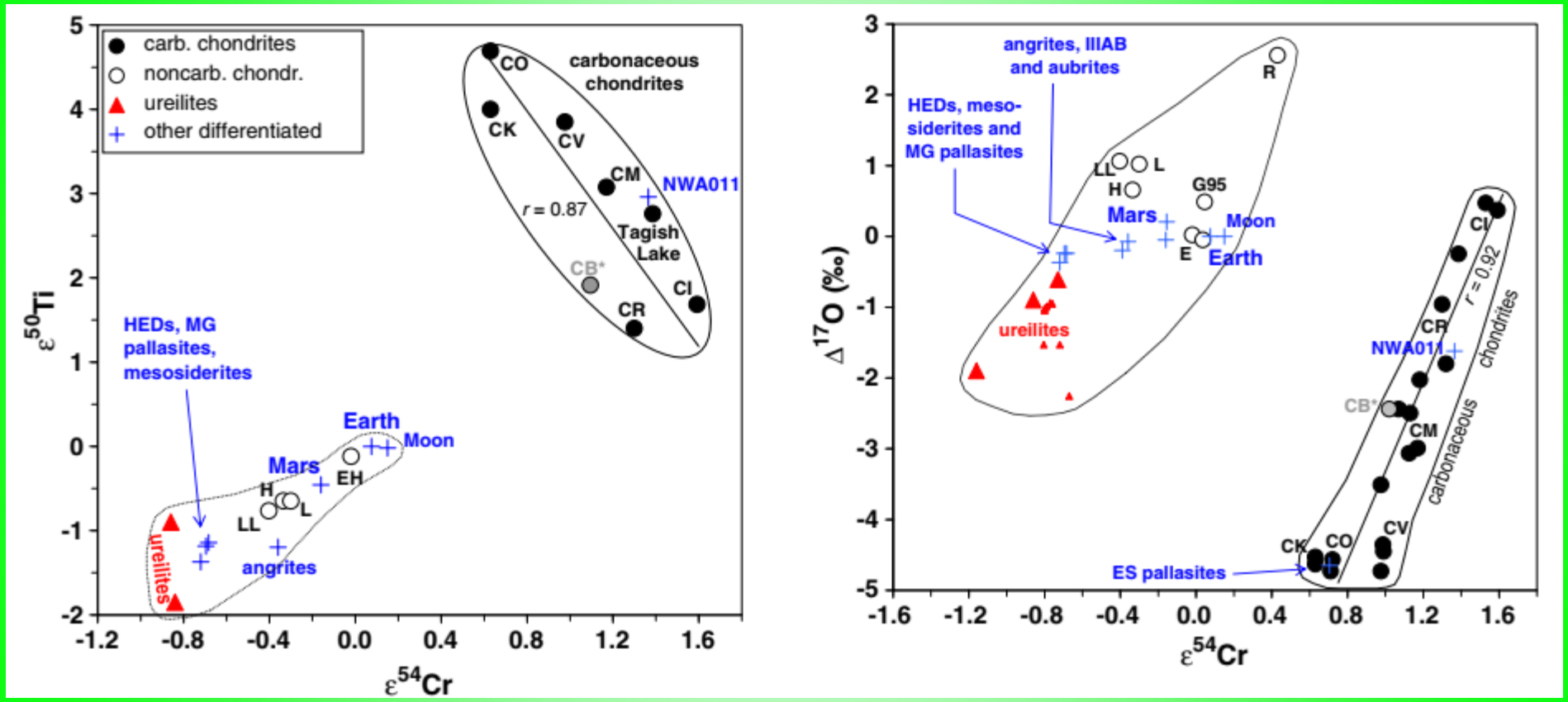

a models
0
3
6
9
12
15
18
number labels are wt% S
b IIAB
18
c IIIAB
12
d IVA
9
3
e IID
12
6
f IVB
0
Ir (ppm)
Au (ppm)

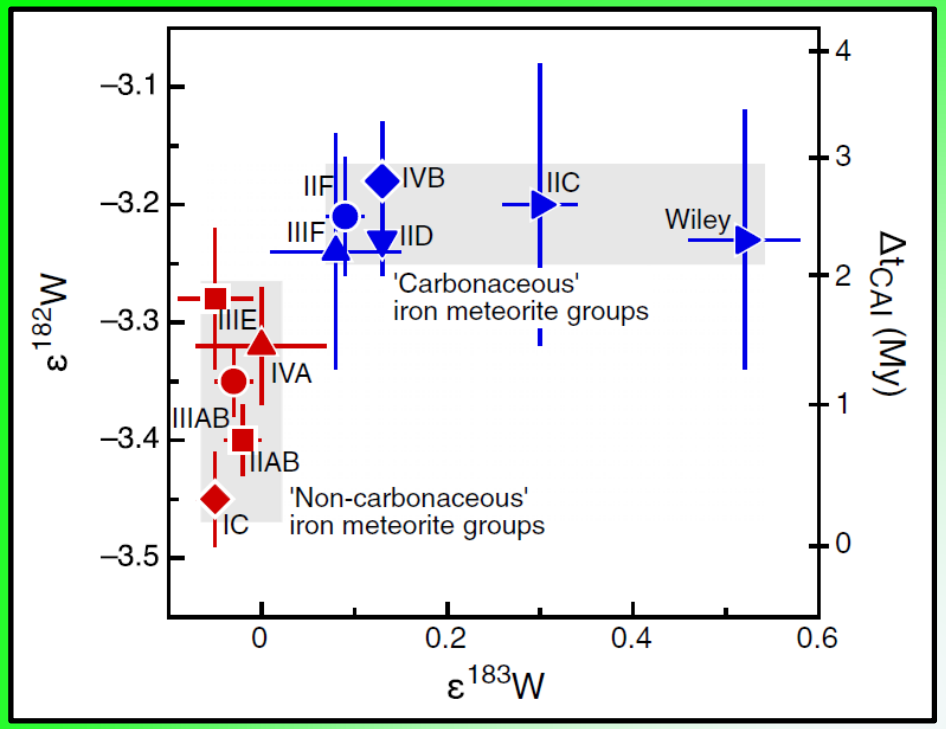


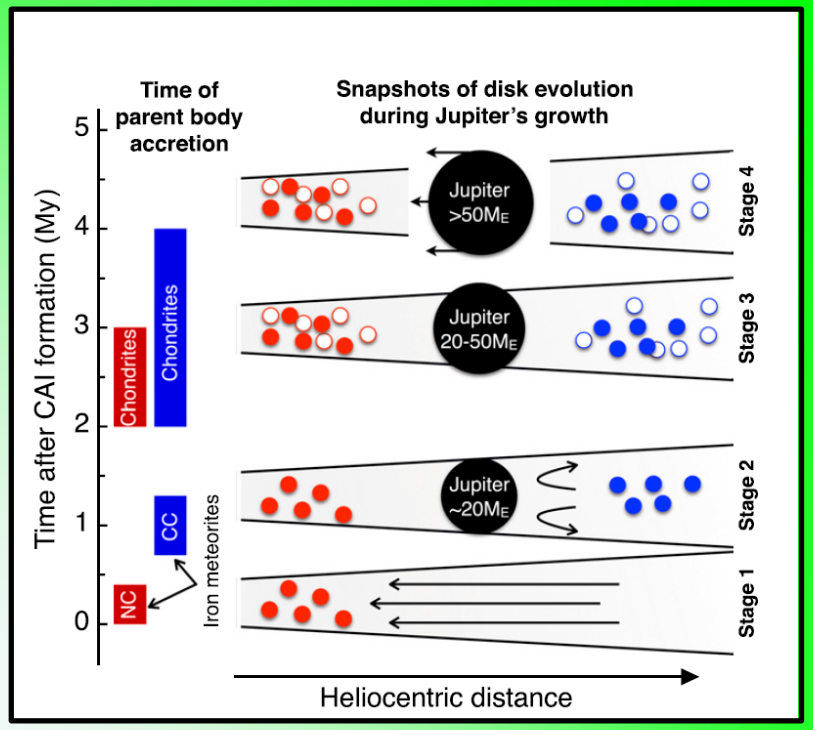

a
Apollo 11
1 μm

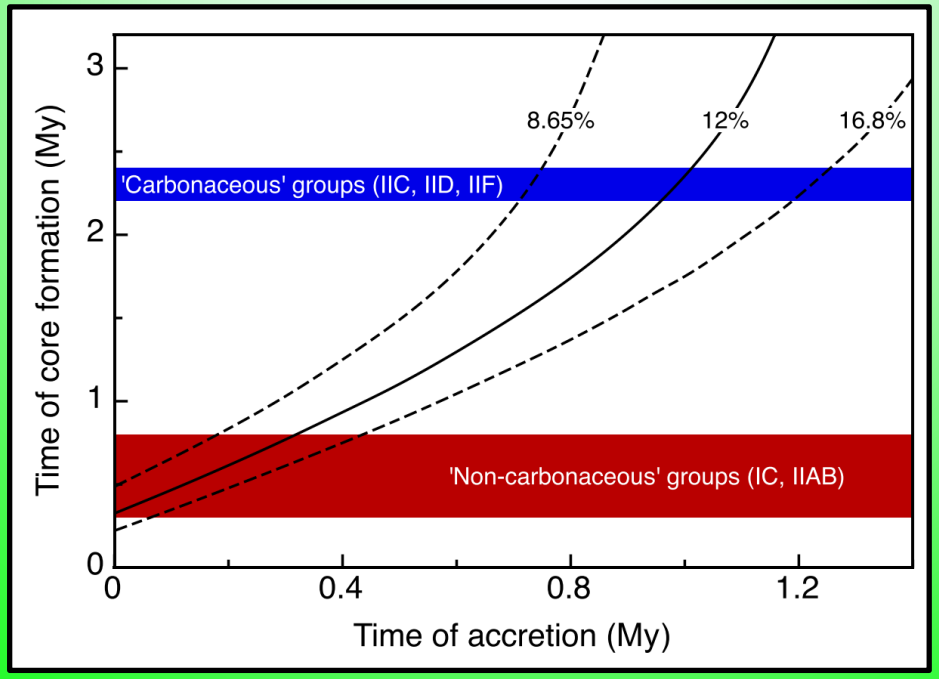
What happened to the sulfur



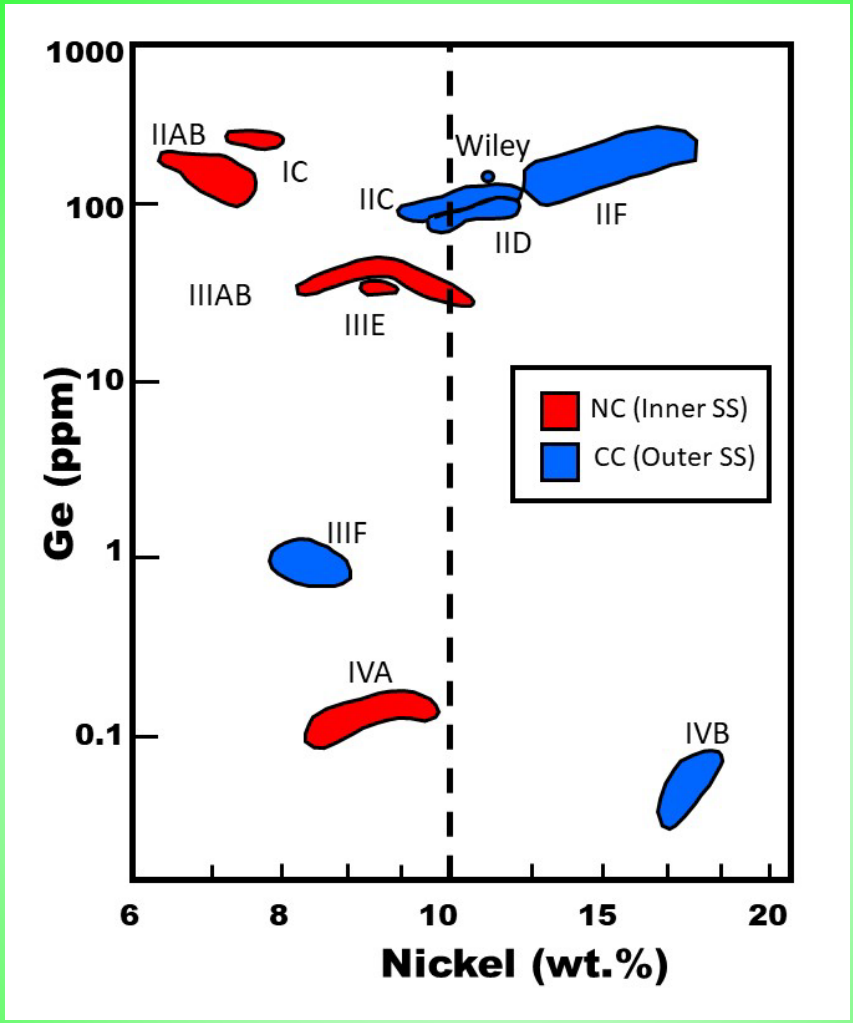

carb. chondrites
noncarb. chondr.
ureilites
other differentiated
carbonaceous chondrites
CO
CK
CV
CM
NWA011
r = 0.87
Tagish Lake
CB*
CR
CI
HEDs, MG pallasites, mesosiderites
Earth
Moon
Mars
EH
H
L
LL
ureilites
angrites
ε50Ti
ε54Cr
angrites, IIIAB and aubrites
HEDs, meso-siderites and MG pallasites
R
LL
L
H
G95
Mars
Moon
E
Earth
ureilites
CI
CR
NWA011
CB*
CM
carbonaceous chondrites
r = 0.92
CV
CK
CO
ES pallasites
Δ17O (‰)
ε54Cr


–3.1
–3.2
–3.3
–3.4
–3.5
ε182W
0
0.2
0.4
0.6
ε183W
4
3
2
1
0
ΔtCAI (My)
IIF
IVB
IIC
IIIF
IID
Wiley
'Carbonaceous'
iron meteorite groups
IIIE
IVA
IIIAB
IIAB
IC
'Non-carbonaceous'
iron meteorite groups


Time of
parent body
accretion
Snapshots of disk evolution
during Jupiter's growth
Time after CAI formation (My)
5
4
3
2
1
0
Chondrites
Chondrites
CC
NC
Iron meteorites
Jupiter
>50ME
Jupiter
20-50ME
Jupiter
~20ME
Stage 4
Stage 3
Stage 2
Stage 1
Heliocentric distance


Time of core formation (My)
3
2
1
0
8.65%
12%
16.8%
'Carbonaceous' groups (IIC, IID, IIF)
'Non-carbonaceous' groups (IC, IIAB)
0
0.4
0.8
1.2
Time of accretion (My)

The role of ice and time in differentiation



Increasing oxidation →

Increasing metal-ice reaction →

Later accretion Time →

Decreasing Heat Source →

Big questions

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