Geochemistry of Mars from SNCs meteorites

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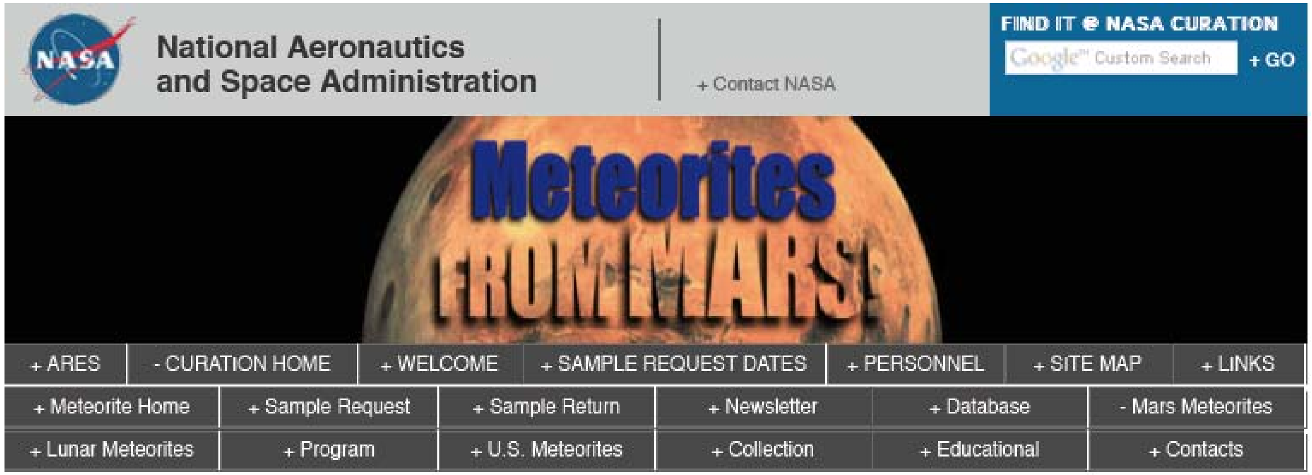
- Their composition : from mineralogy to major elements, trace elements, isotopes (their age)
- Informations on the early evolution of Mars



The Mars Meteorite Compendium

Compiled by Charles Meyer

http://curator.jsc.nasa.gov/antmet/mmc/

A few recent reviews :

- Halliday A. N. et al. (2001) The accretion, composition and early differentiation of Mars. *Chronology and evolution of Mars*, 96 197-230.
- McSween H. Y. (2002) The rocks of Mars, from far and near. *Meteoritics & Planetary Science* 37, 7-25.
- Nyquist L. E. et al. (2001) *Ages and geologic history of Martian meteorites. Chronology and evolution of Mars*, 96 105-164
- PSRD at University of Hawaii (http://psrd.hawaii.edu)

A familly of ≈ 45 meteorites, called SNC, (Shergotty, Nakhla, Chassigny) are believed to come from Mars

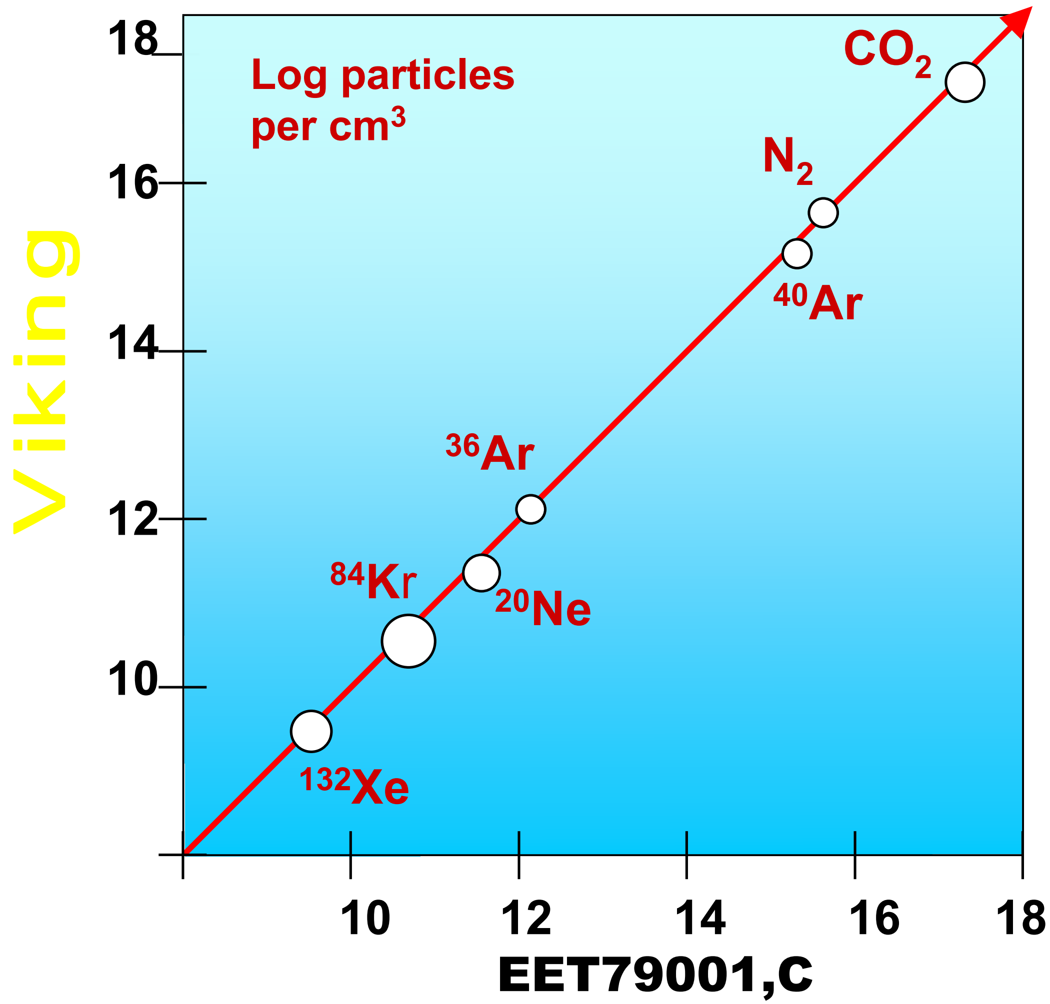
• their age is young (≈ 180 Ma for shergottites)

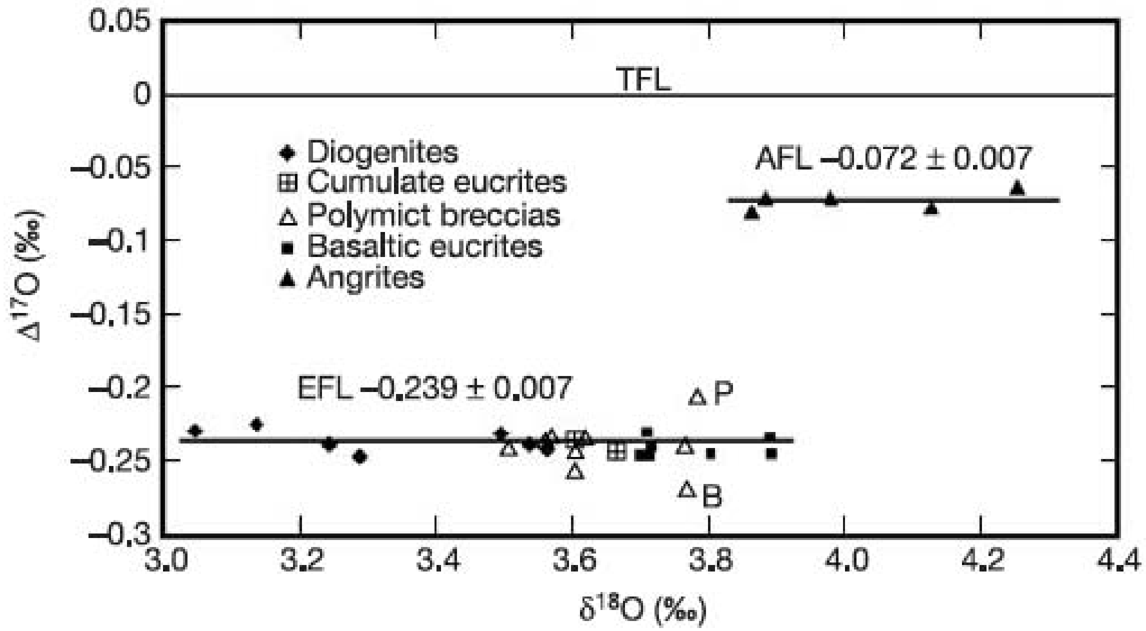
• the gas trapped in impact-melted glass (maskelynite) are similar to that measured on Mars by Viking

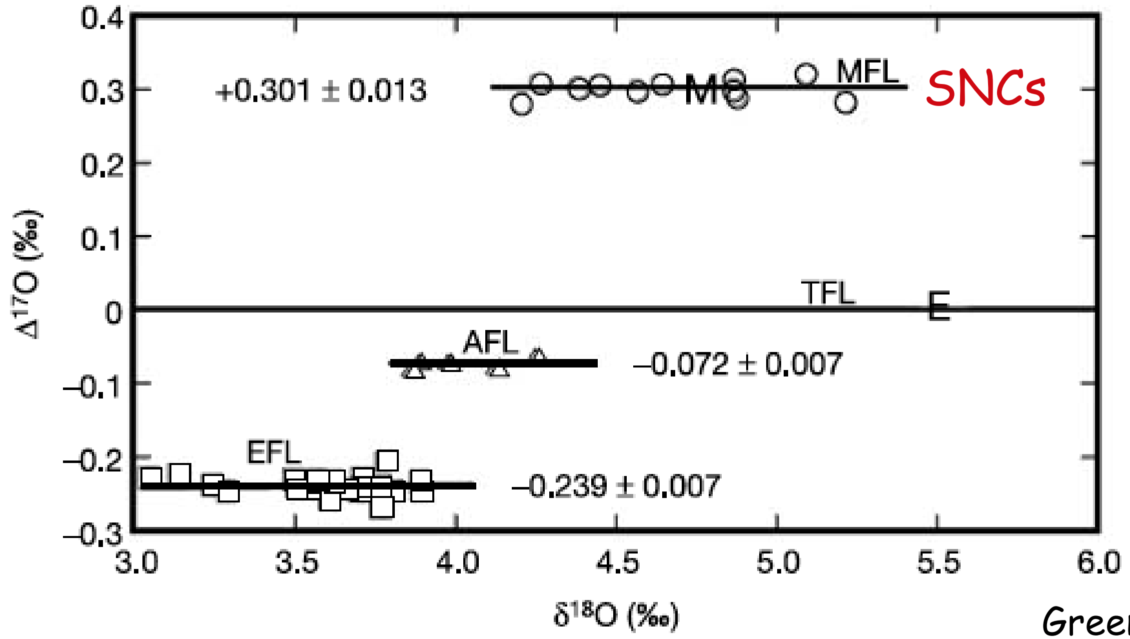
$\delta^{15}N$ = +620 ± 160 ‰ (Viking)
> 300 ‰ (SNCs)

$^{129}Xe/^{132}Xe$ = 2.4 (Viking)
= 2.6 (SNCs)

$^{40}Ar/^{36}Ar$ = 3000 ± 500 (Viking)
= 2400 (SNCs)



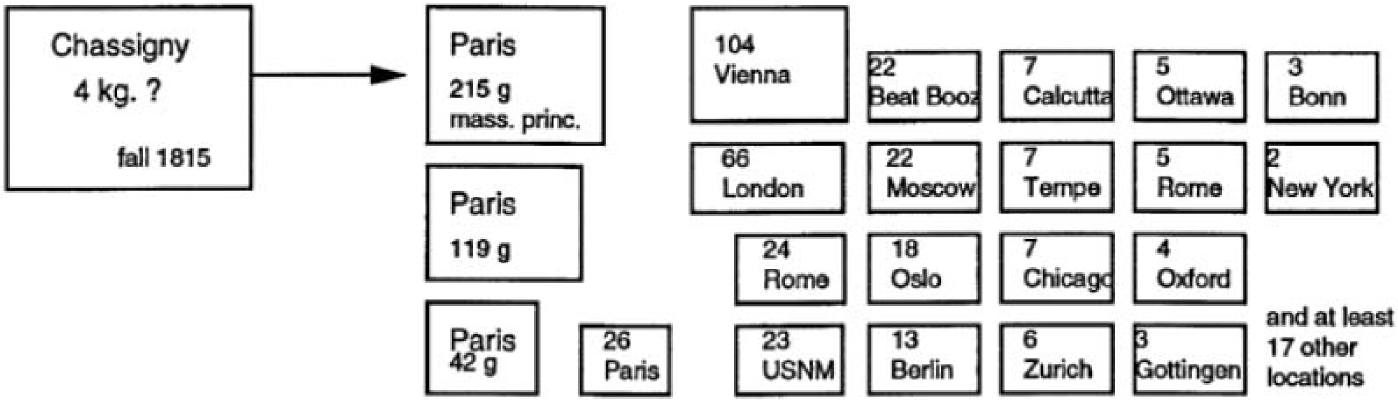




SNCs have the same oxygen isotopic composition (^{16}O deficit, written $\Delta^{17}O$).

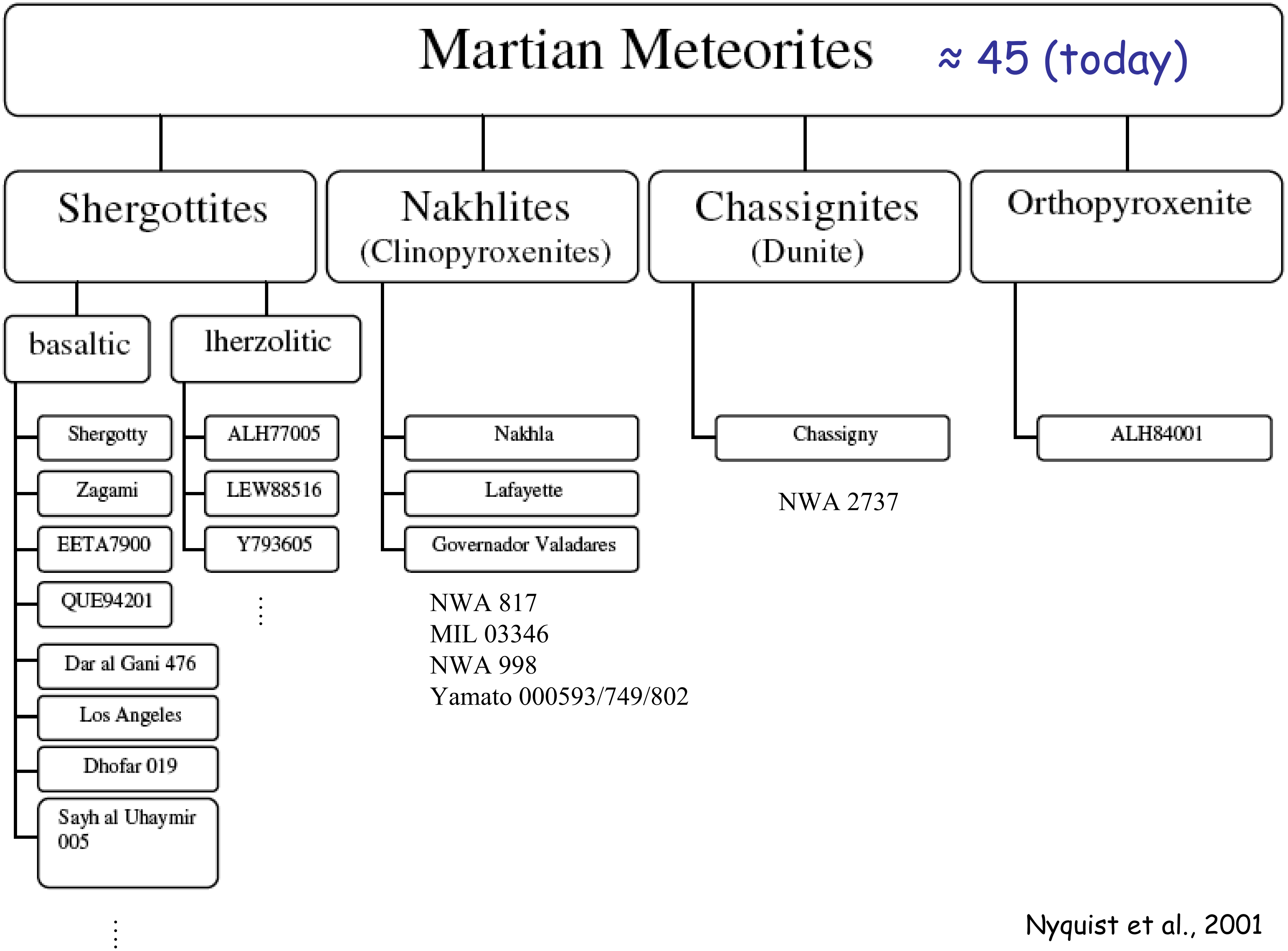
(homogeneity of $\Delta^{17}O$ considered as a strong hint for a magma ocean)

Greenwood et al. (2005)



C Meyer 1996

Thin sections: Berlin, Gottingen, London
Paris, Vienna, Washington



Nyquist et al., 2001

Classification of ultramafic igneous rocks

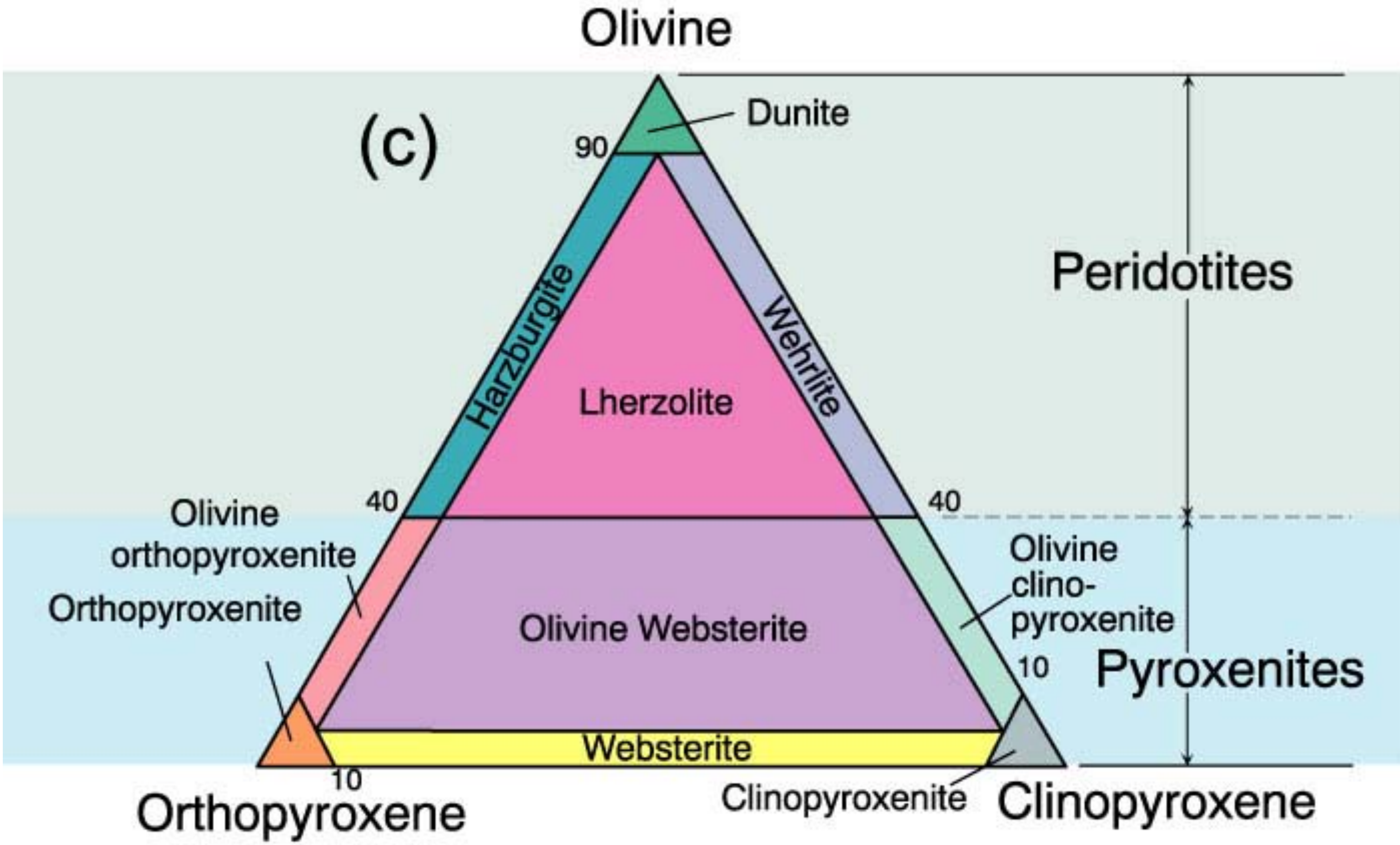
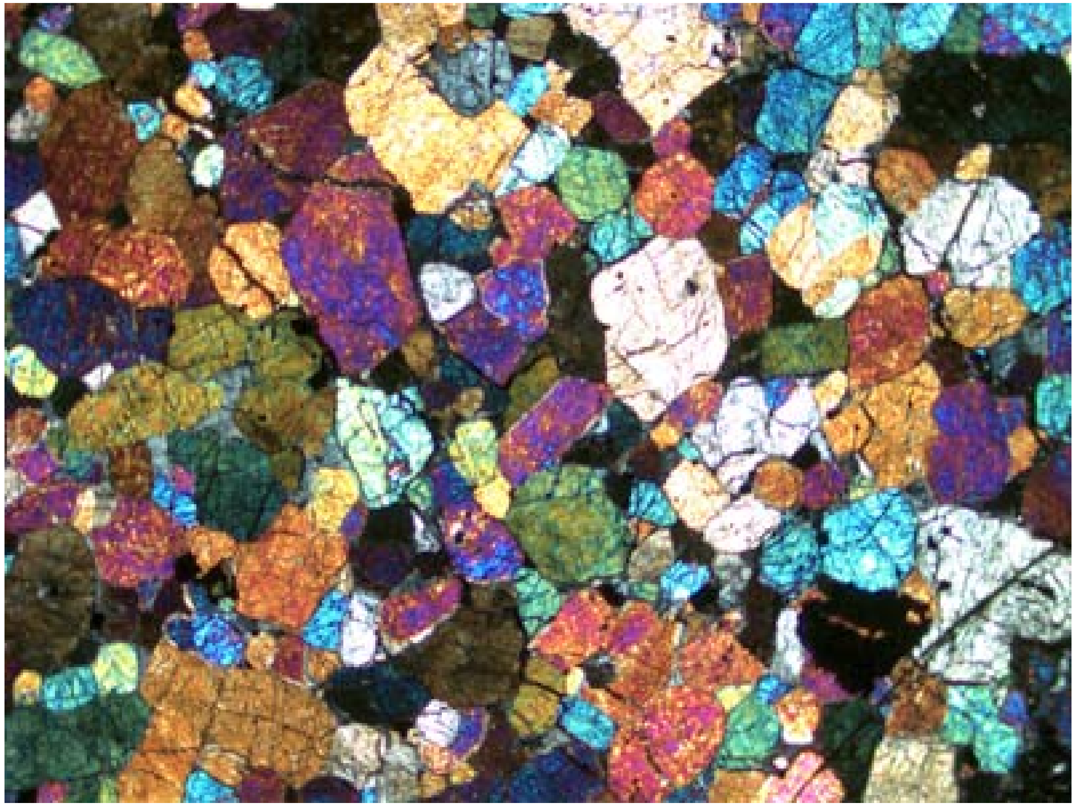


Fig John Winter

Ultramafic SNCs are not pieces of the martian mantle : they are martian mantle liquids which crystallized more or less rapidly either as subsurface lava flows or in dikes or in layered intrusions



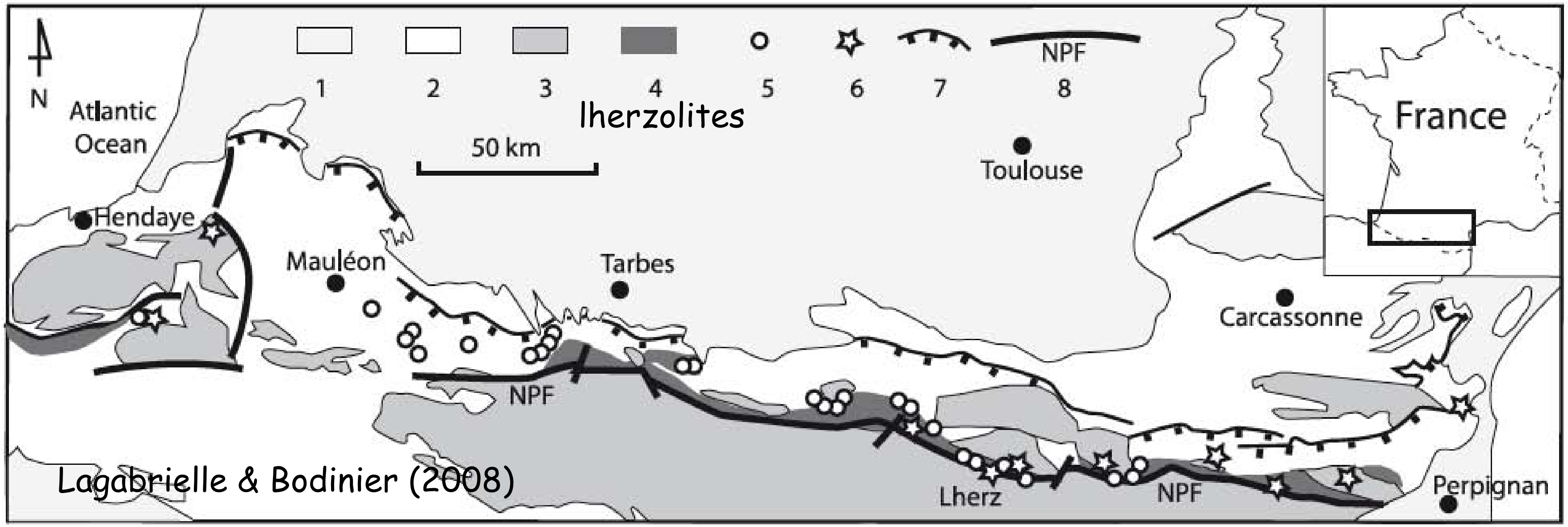
Thin section of Chassigny (© MNHN- Paris)

Slow crystal fractionation of an ultramafic body

Nakhlites = cumulate formed by slow cooling in oxydizing conditions

Lherzolites at
Etang de Lherz (Pyrénées)
are pieces of the mantle
emplaced in the crust
by tectonic processes
(rotation of Iberia)

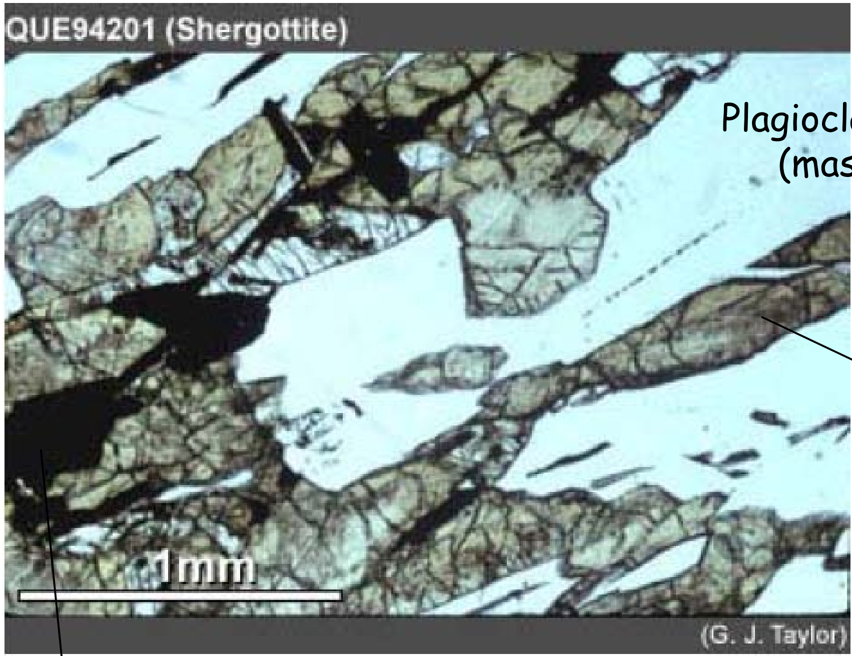
©JP. Lorand | MNHN



On Mars, with no plate tectonics, pieces of the mantle might be brought to the surface as xenoliths in basalts

Massif Central France, ©JP. Lorand | MNHN

Basaltic shergottites are clearly lava flows



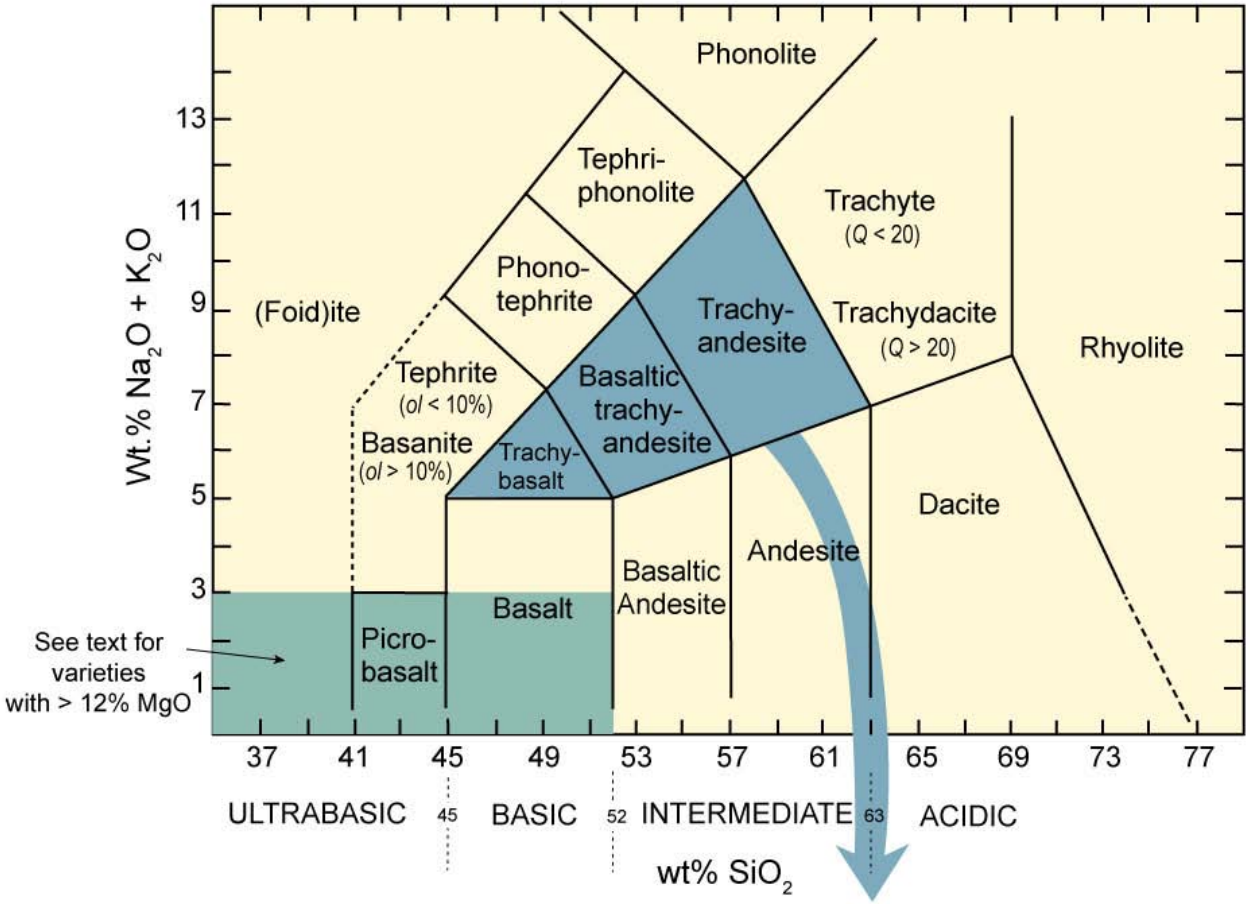
Plagioclase feldspar
(maskelynite)

clinopyroxene

magnetite

(© MNHN- Paris)

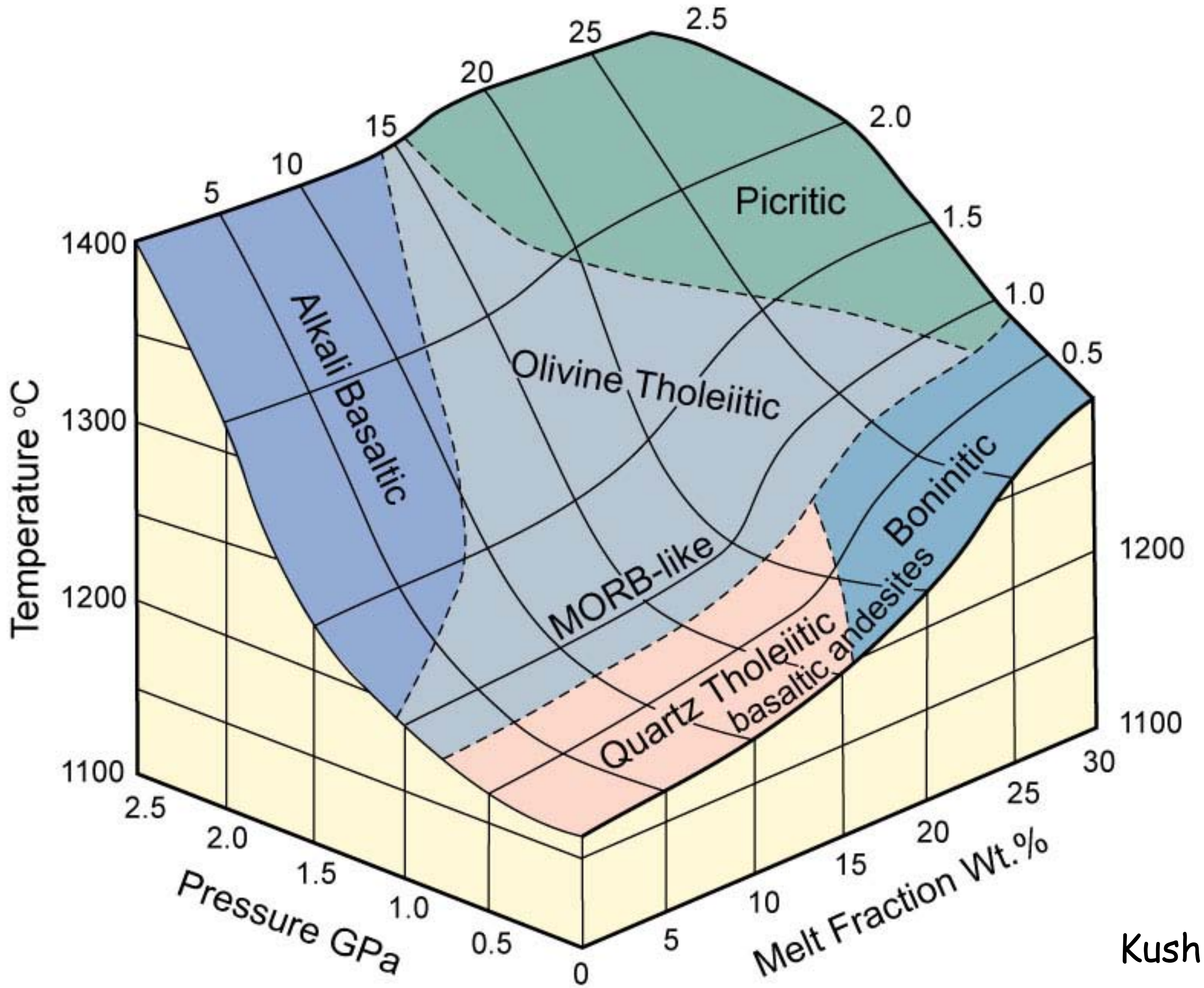
Classification of basalts from their SiO_2 and alkalis contents (alkalis are incompatible). Variations in this diagram reflect the sum of variations in source composition, conditions of melting and of crystallization)



Further subdivisions of shaded fields	Trachybasalt	Basaltic Trachyandesite	Trachyandesite
$Na_2O - 2.0 \geq K_2O$	Hawaiite	Mugearite	Benmoreite
$Na_2O - 2.0 < K_2O$	Potassic Trachybasalt	Shoshonite	Latite

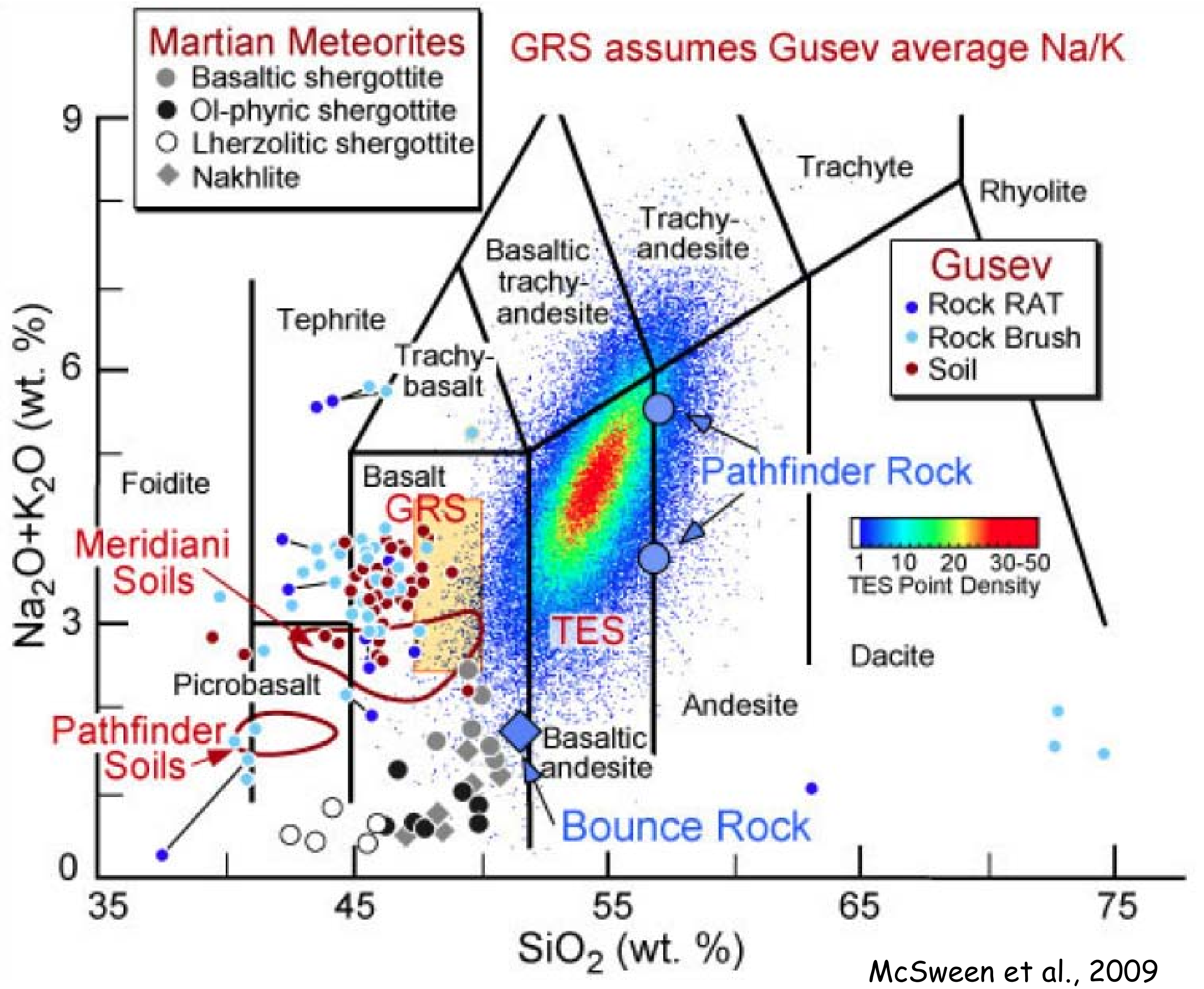
Fig John Winter

Experimental melting of a fertile garnet lherzolite shows that alkaline basalts are favored by high P and low F



Kushiro (2001)

Martian basalts are close to terrestrial basalts (tholeiites formed at mid ocean ridges or oceanic islands - mantle melts). Shergottites show some differences.

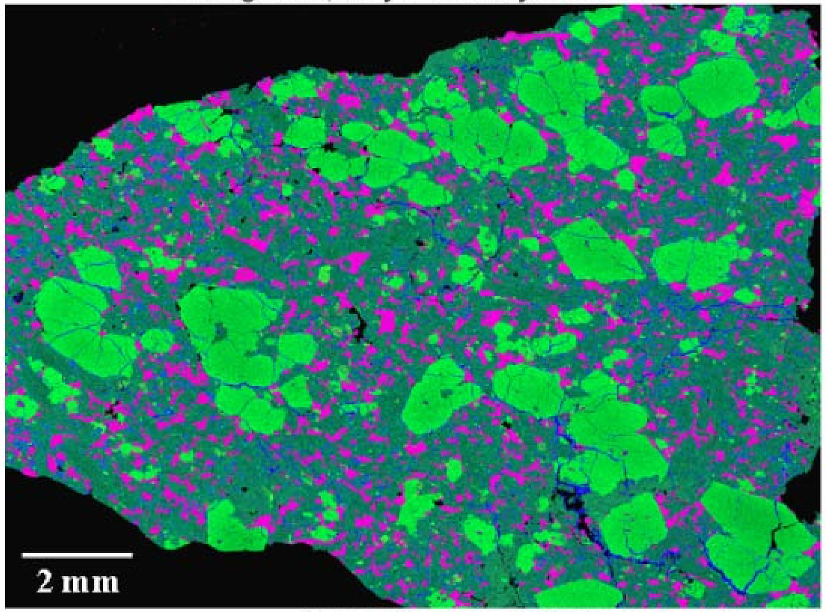


McSween et al., 2009

How to infer the chemical and mineralogical composition of the interior of Mars from SNCs ?

• SNCs are igneous rocks from Mars, but among them only basaltic shergottites are crystallized from liquids produced by partial melting of the Martian mantle (the others are cumulates, the composition of which is controlled by crystal fractionation in magma chambers or dikes).

Shergottite, Sayh al Uhaymir 005



(Courtesy of Cyrena Goodrich, Kingsborough Community College.)

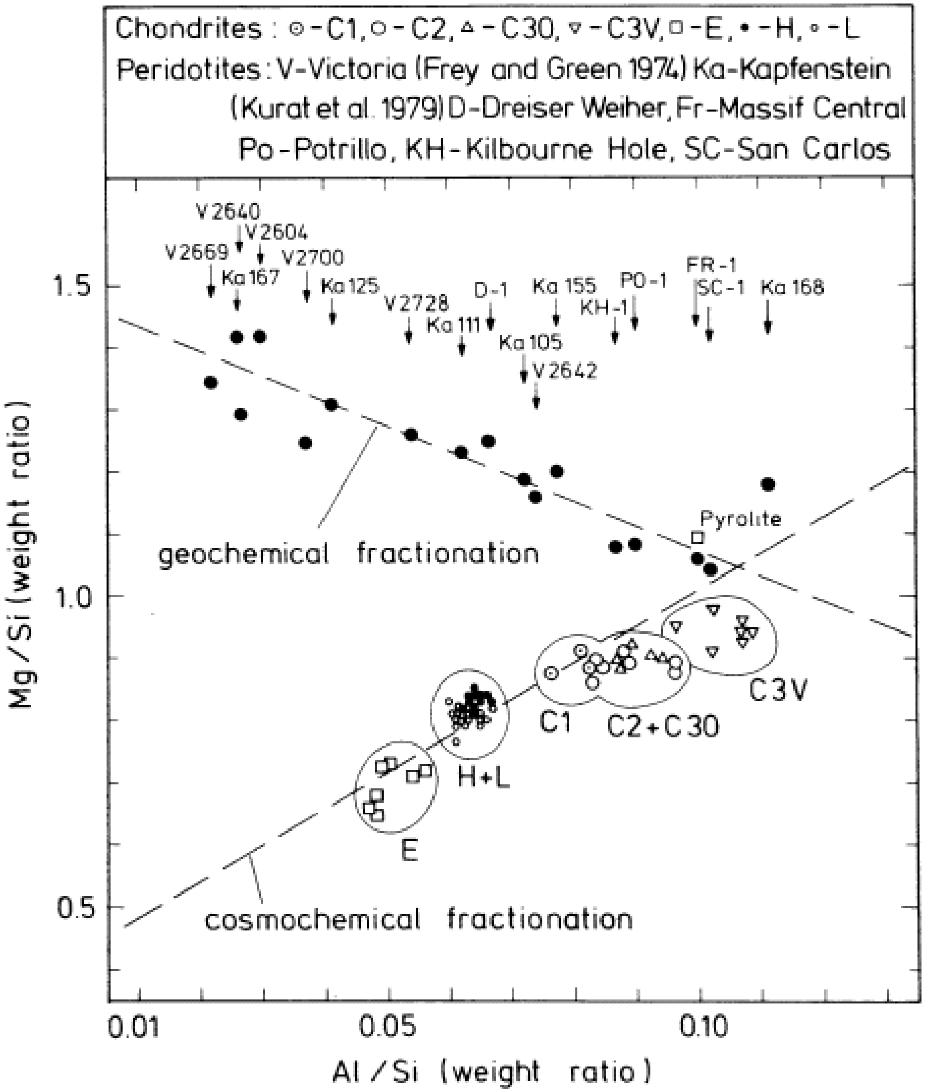
Caveats:

• assume a chondritic composition (carbonaceous chondrite C1 ?) for bulk Mars (by analogy with accretion models for the Earth)

• assume that the martian mantle is homogeneous and that the source region of SNCs is representative of this mantle (play with concentrations of elements in SNCs to infer source composition from what is known on chemical fractionation during melting and crystallization)

• assume a temperature profile versus depth in Mars and establish the minerals stable in function of pressure and composition (from high P experiments)

Why to assume a chondritic bulk composition for Mars ?



Jagoutz et al., 1979

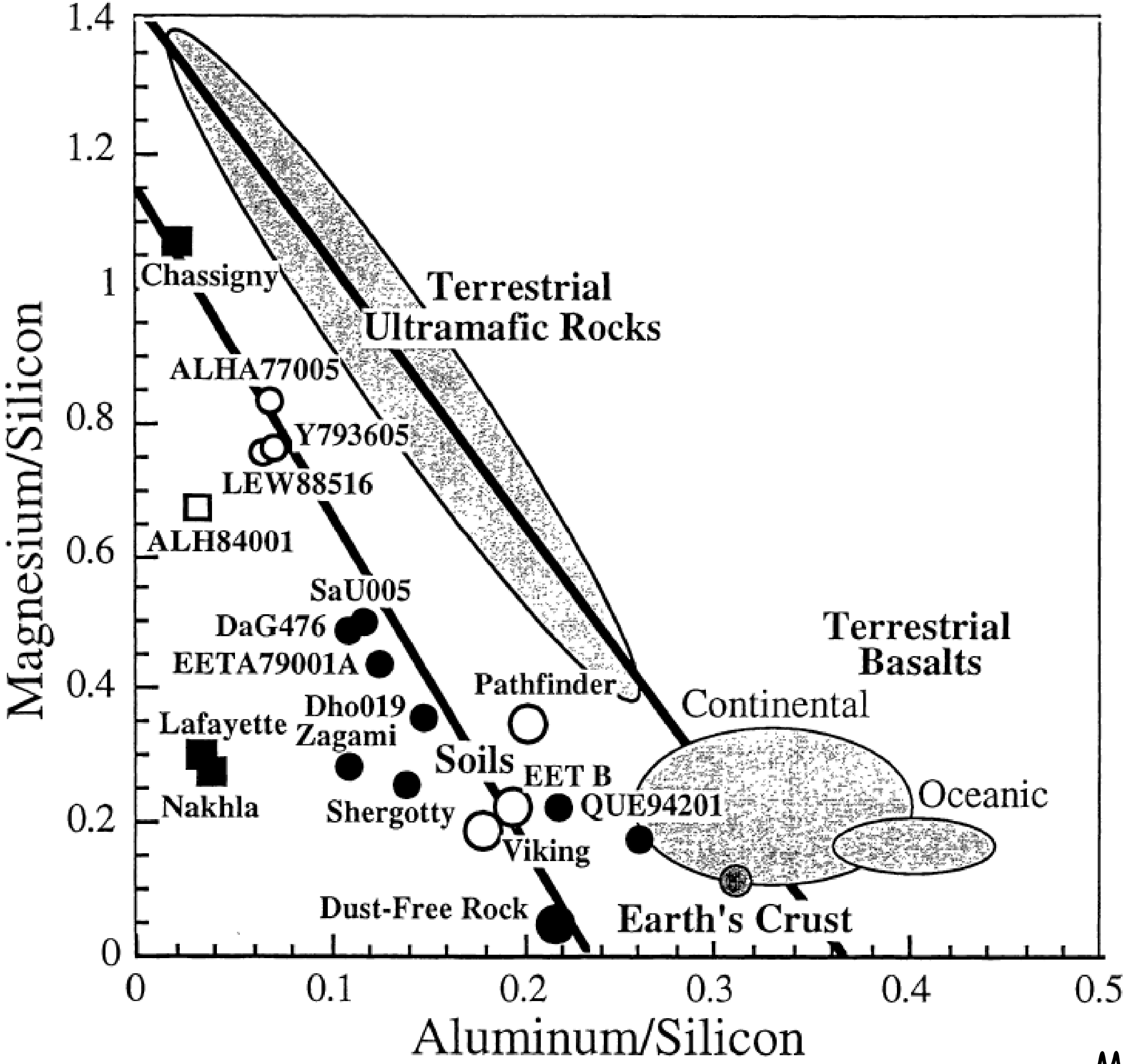
• Same approach than for the Earth : the chondrites show a range of compositions (related to fractionation due to volatility) which intersects the range (due to magmatic fractionation) of mantle samples (Jagoutz et al., 1979)

• The pyrolitic composition (Ringwood, 1975), = 1/4 basalt + 3/4 peridotite, is closed to the intersection.

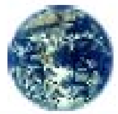
• Possible refinements:
(i) Do not consider any a priori chondrite type and do not use Si which can enter the core (Allègre et al., 1995). Calculate the composition of the core by mass balance

(ii) Rely on isotopic compositions ($\Delta^{17}O$) instead of chemical composition: enstatite chondrite model (Javoy, 1995)

For Mars, the geochemical fractionation trend (for SNCs but not all soils and rocks) intersects closer to CI carbonaceous chondrites



McSween, 2002

Compositions of the rocky portions of Mars and Earth (wt.%)		
Compound	Mars 	Earth 
SiO_2	44.4	45.1
TiO_2	0.1	0.2
Al_2O_3	3.0	4.0
Cr_2O_3	0.8	0.5
MgO	30.2	38.3
FeO	17.9	7.8
MnO	0.5	0.1
CaO	2.4	3.5
Na_2O	0.5	0.3
K_2O	0.04	0.03

Wänke & Dreibus, 1994

For major elements (refractory & lithophile) one can consider that they are present ≈ in CI abundances (MgO, SiO_2, Al_2O_3, CaO), but this is not true for Fe

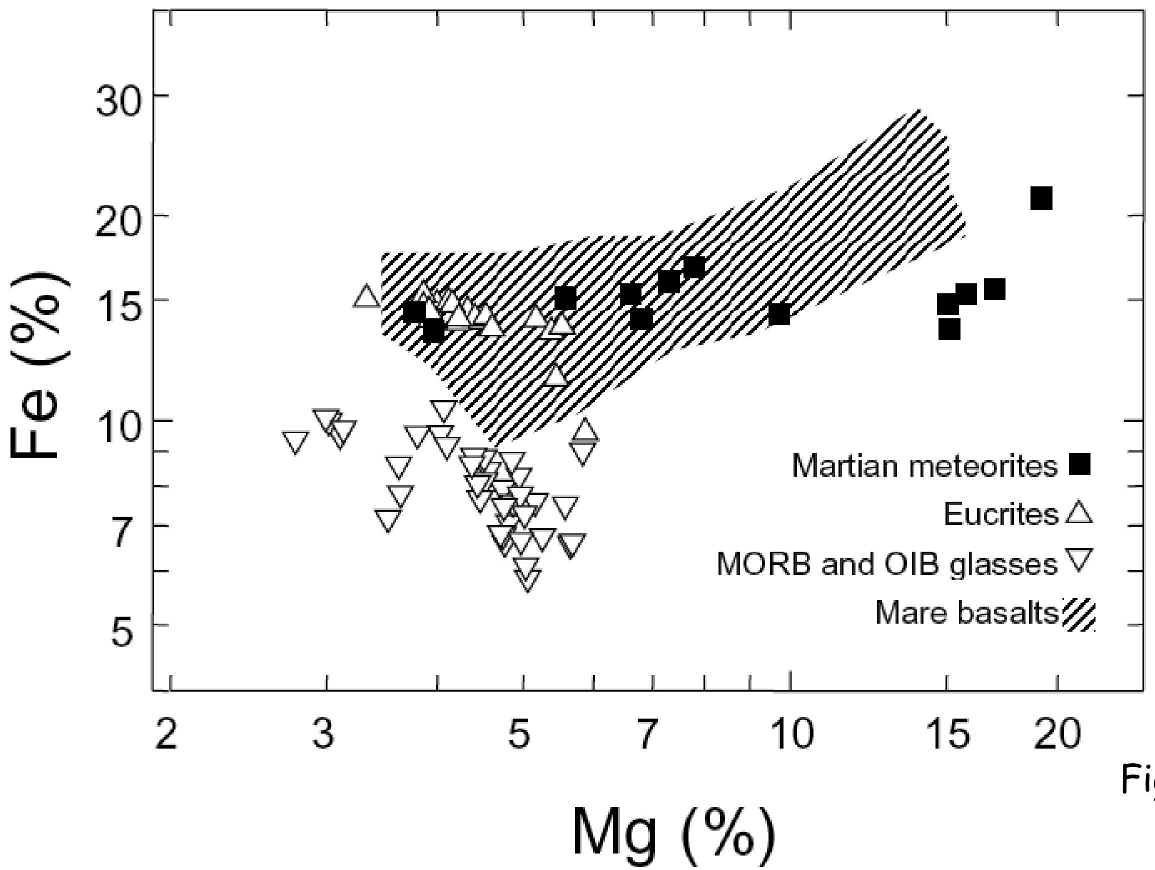
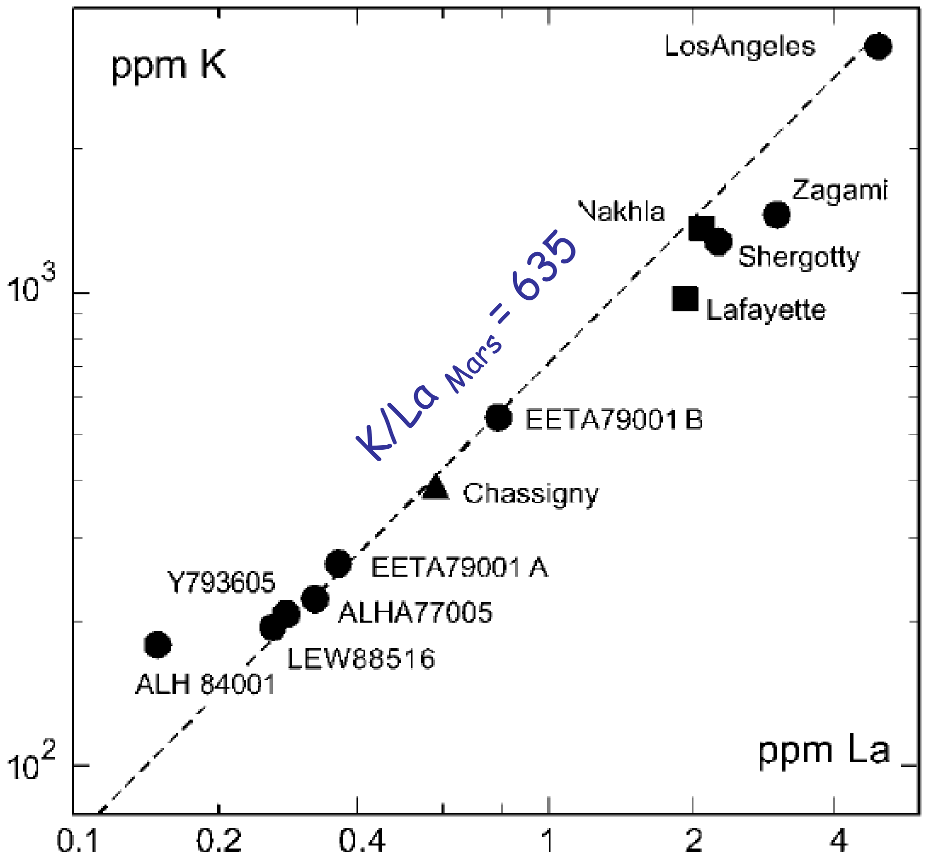


Fig Halliday et al., 2001

Shergottites are richer in FeO (≈ 18.9 wt%) compared to terrestrial basalts (≈ 8 wt%) but they are chondritic for MnO (0.48 wt% and 0.46 wt% in CI).
Because, bulk partition coefficients between mantle (ol+px+cpx) and basaltic liquid are ≈ 1, the martian mantle contains ≈ 2 times more FeO than the Earth mantle

For trace elements, ex: K & La

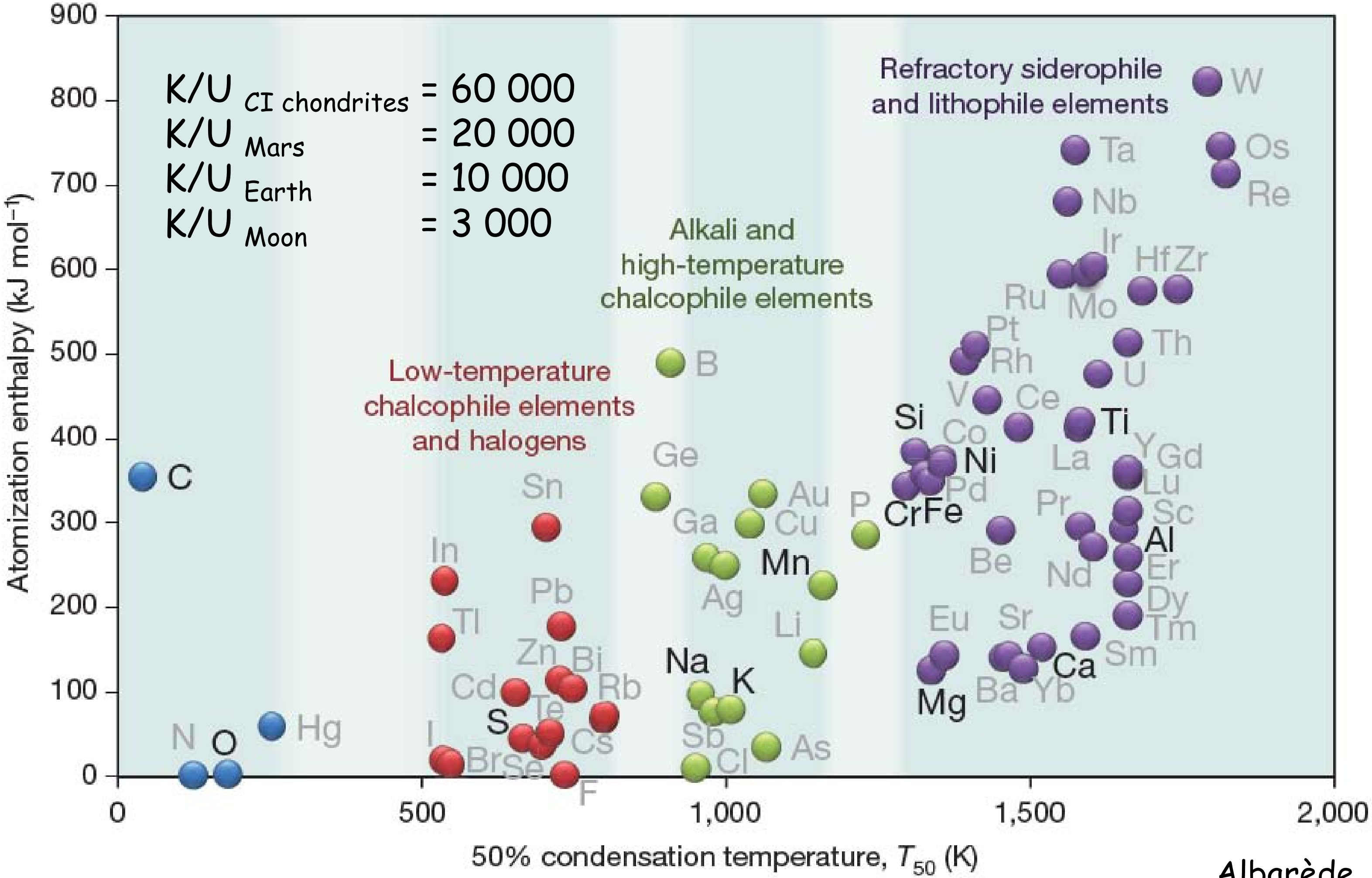


Halliday et al., 2001

$K/La_{CI} = 2110$

If the difference in K/La between SNCs and CI is only due to K (assuming that La was not fractionated because of its refractory nature), then K_{Mars} = 0.3 times CI (normalized to Si)

Consequence of the low K content on the accretion of other volatiles (water): incomplete accretion (the Earth lacks ≈ 85% K and Mars ≈ 60-70%) because K is not isotopically fractionated by evaporation or else



Albarède, 2009

Water must have been accreted lately on Mars, ≈ 100 My after the start of the Solar system according to I-Xe constraints (a similar time scale is likely for the Earth). But, contrary to the Earth, water on Mars was not transferred to the mantle (30-40 ppm H_2O in the Martian mantle ; 150-300 ppm H_2O in the Earth mantle)

- water could have been used to oxidize metallic Fe :

$$Fe + H_2O = FeO + H_2$$

  - This would explain the oxidized nature of the Martian mantle and the lower mass of the core in Mars relative to the Earth (21% total mass for Mars and 31% for the Earth)
  - H_2 would be lost by hydrodynamic escape (lower mass of Mars)

- effect of the mass of Mars on the depth of the lower mantle and of the transition zone where water could be stored ?

- cause of the lack of plate tectonic on Mars ?

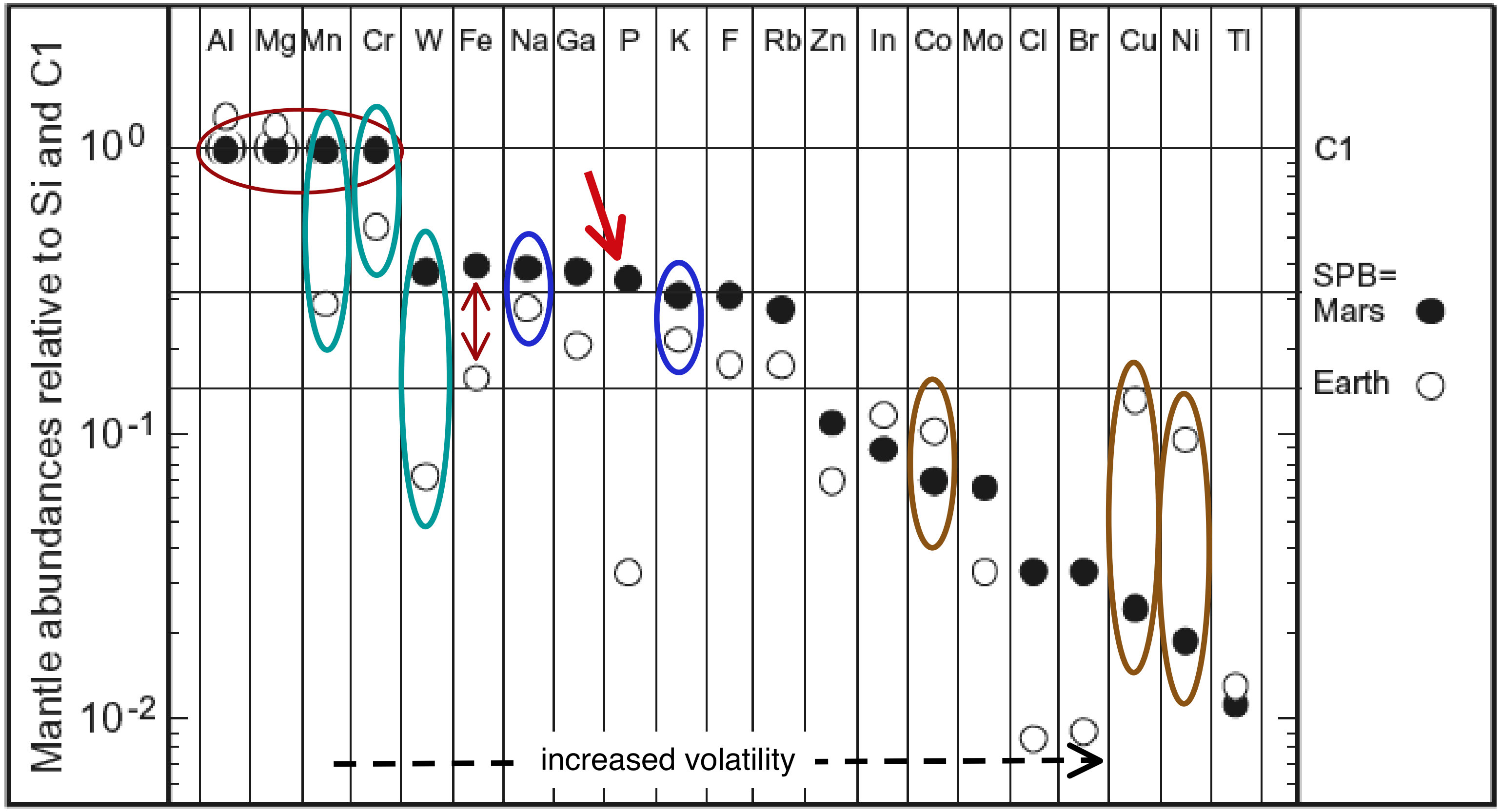
One way to describe geochemically the accretion of Mars (and of the Earth) is to consider two “putative” components (Ringwood, 1979 ; Wänke, 1981) :

- Component A : Highly reduced and free of all elements with volatility higher than Na (all refractory elements are in CI abundances).
- Component B : Oxidized and containing all elements including the volatiles in CI abundances.

≈ incomplete accretion with late addition of volatiles

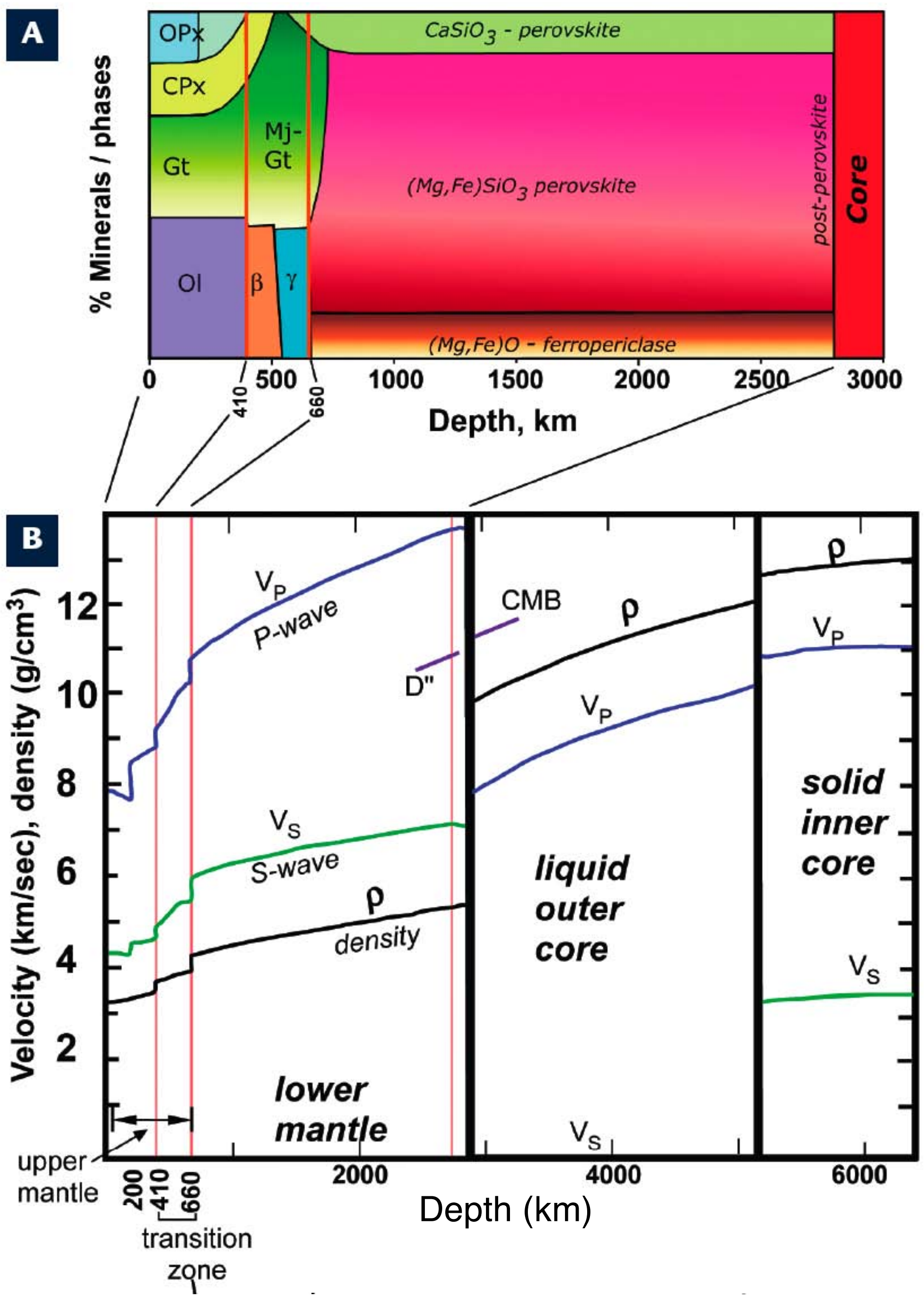
For the Earth : 85% A + 15% B
For Mars : 60% A + 40% B

Chemical composition of the Martian mantle



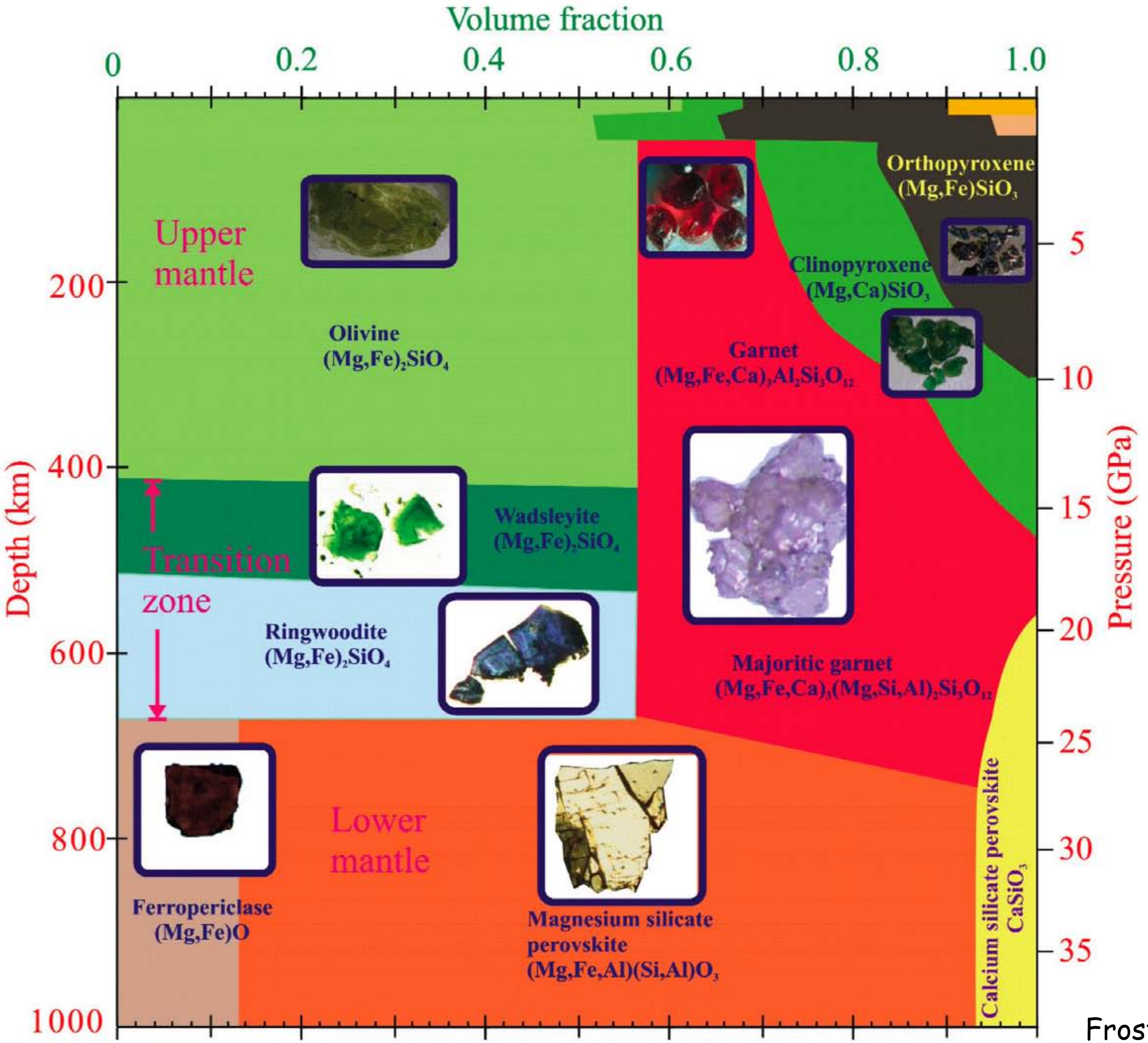
Halliday et al., 2001

- Chondritic for all major elements (Al, Mg, Mn, Cr) except Fe
- All moderately volatile elements (Na, Ga, K, F, Rb, Zn) are enriched by a factor of ≈ 2 relative to the Earth
- Siderophiles which are not chalcophiles (Mn, Cr, W) are enriched in Mars relative to the Earth
- Siderophiles which are chalcophiles (Co, Cu, Ni) are depleted in Mars relative to the Earth
- Mars enriched in P relative to the Earth (phosphates concentrate REE and U)



Internal structure of the Earth well known from seismology and phase stability experimentally determined

Bass, 2008

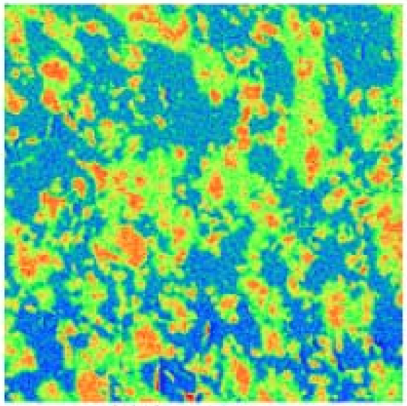

Volume fraction
0
0.2
0.4
0.6
0.8
1.0
Depth (km)
200
400
600
800
1000
Pressure (GPa)
5
10
15
20
25
30
35
Upper mantle
Transition zone
Lower mantle
Olivine
(Mg,Fe)$_2$SiO$_4$
Wadsleyite
(Mg,Fe)$_2$SiO$_4$
Ringwoodite
(Mg,Fe)$_2$SiO$_4$
Orthopyroxene
(Mg,Fe)SiO$_3$
Clinopyroxene
(Mg,Ca)SiO$_3$
Garnet
(Mg,Fe,Ca)$_3$Al$_2$Si$_3$O$_{12}$
Majoritic garnet
(Mg,Fe,Ca)$_3$(Mg,Si,Al)$_2$Si$_3$O$_{12}$
Ferropericlase
(Mg,Fe)O
Magnesium silicate perovskite
(Mg,Fe,Al)(Si,Al)O$_3$
Calcium silicate perovskite
CaSiO$_3$

Frost, 2008

Electron microprobe image of an experimental product colored according to chemical composition.

Pressure was 2 GPa. Temperature was 1100°C. The experimental run lasted for 48 hours.

≈ 160 km



width = 100 µm

2 GPa, 1100 °C for 48 hours

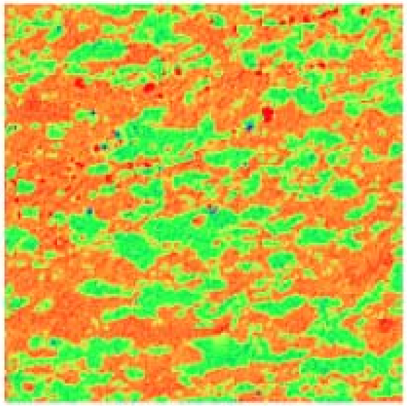
Minerals

- Olivine
- Orthopyroxene
- Clinopyroxene and Garnet

(Image courtesy of Dr. Connie Bertka, Geophysical Laboratory, Carnegie Institution of Washington.)

In this case, the pressure was 20 GPa. Temperature was 1750°C. The experimental run lasted for 3 hours.

≈ 1600 km



width = 100 µm

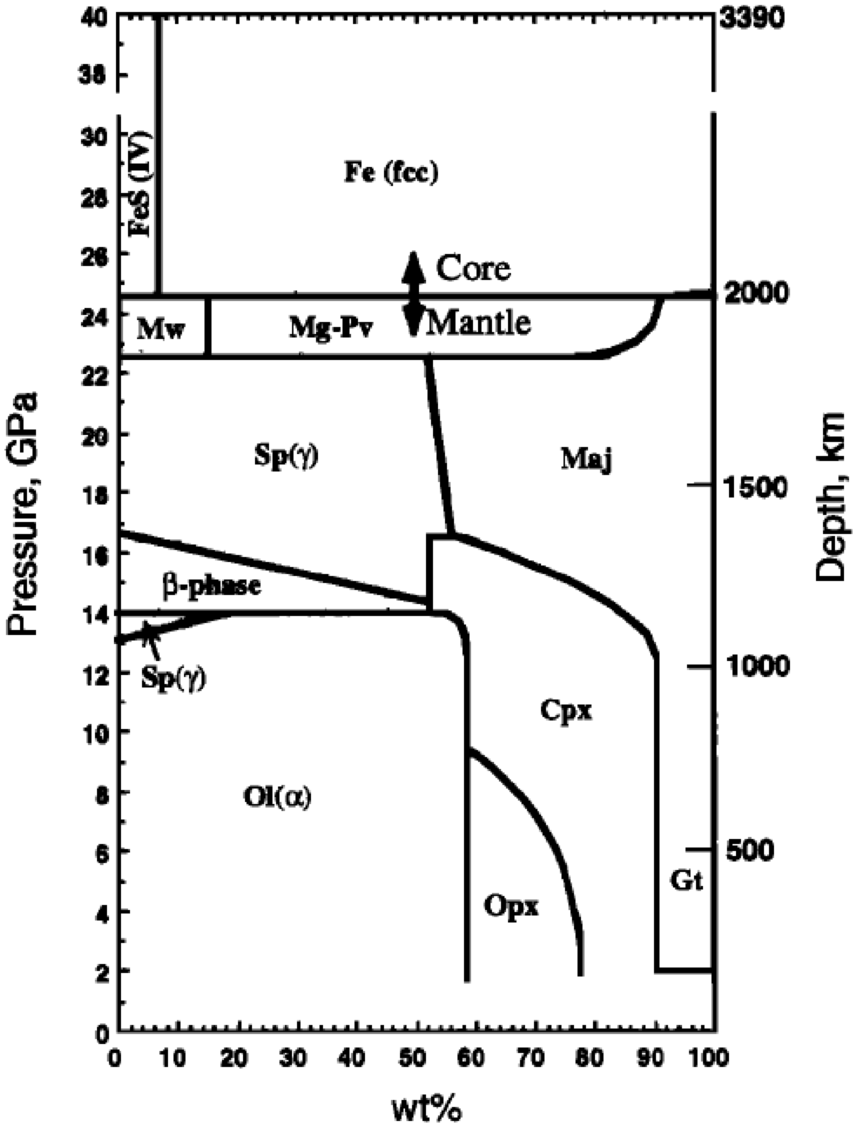
20 GPa, 1750 °C for 3 hours

Minerals

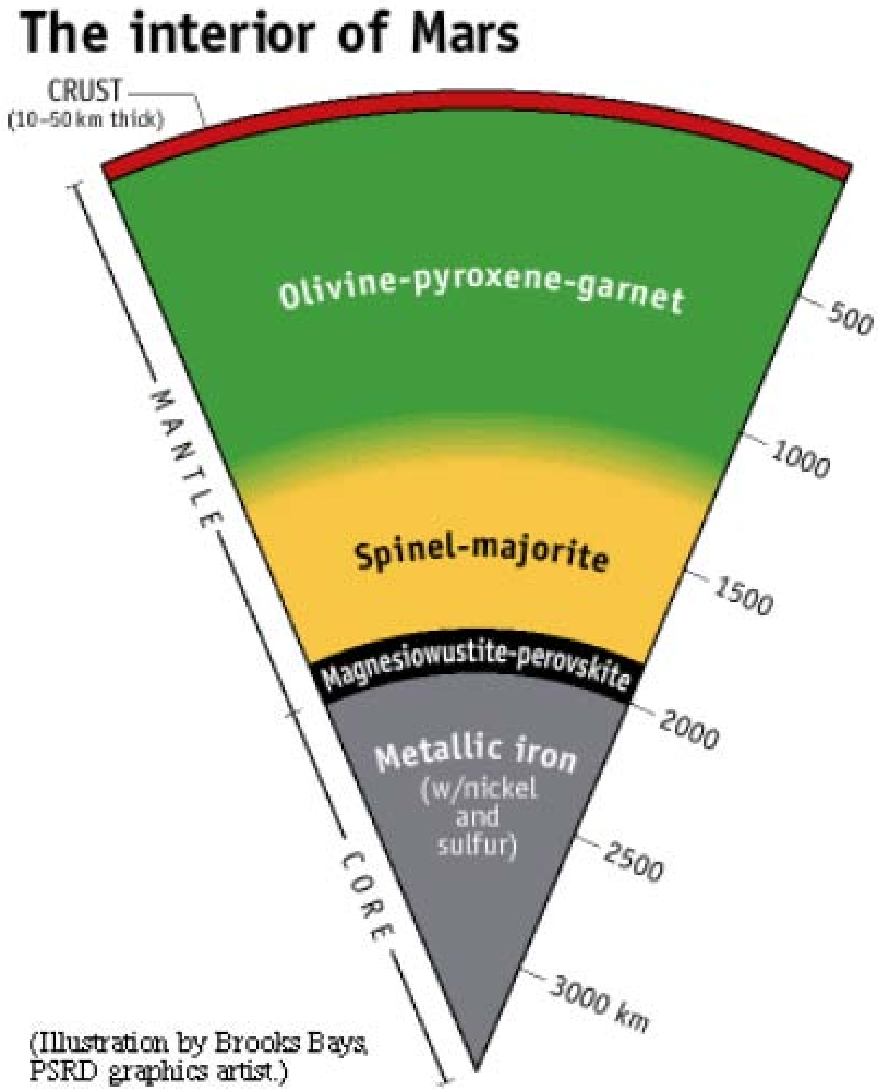
- Gamma-spinel
- Majorite

(Image courtesy of Dr. Connie Bertka, Geophysical Laboratory, Carnegie Institution of Washington.)

Bertka & Fei, 1997
Taylor, 1997 PSRD Hawaii

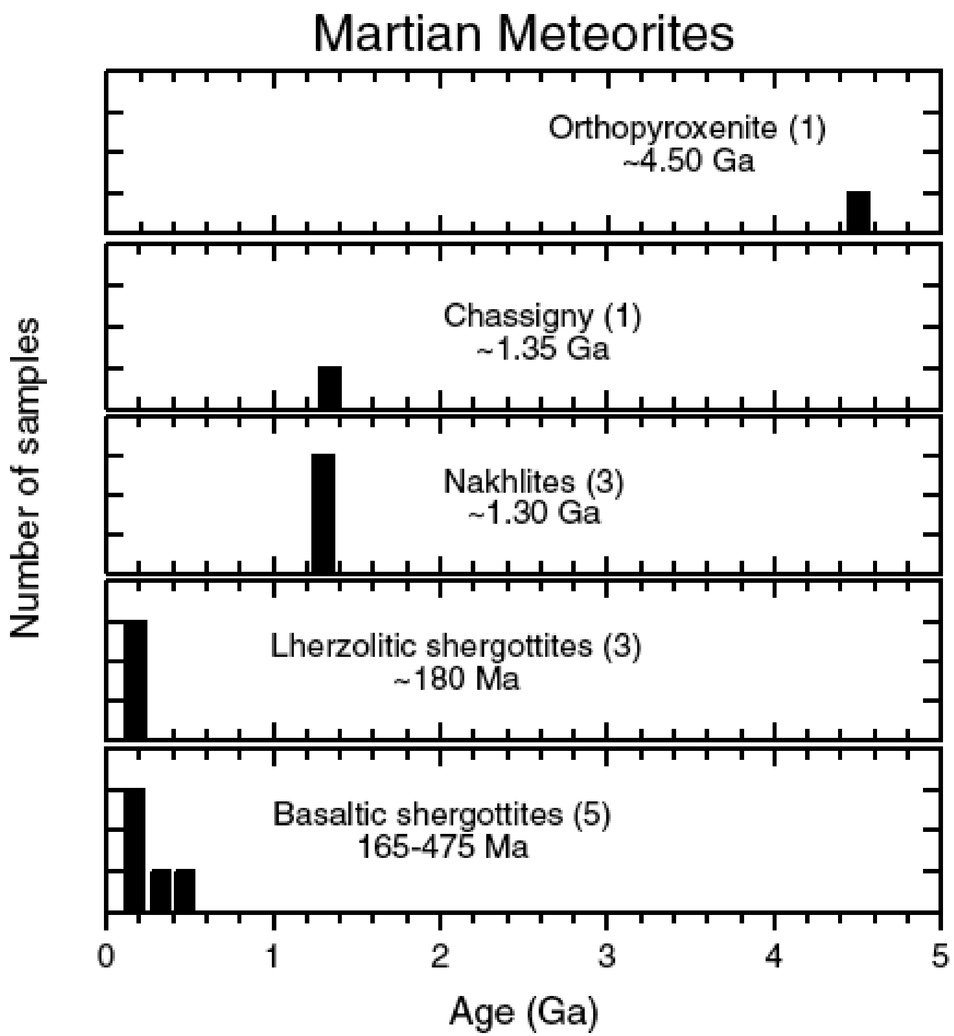


Bertka & Fei, 1997



(Illustration by Brooks Bays, PSRD graphics artist.)

What is the real crystallization age of SNCs ?

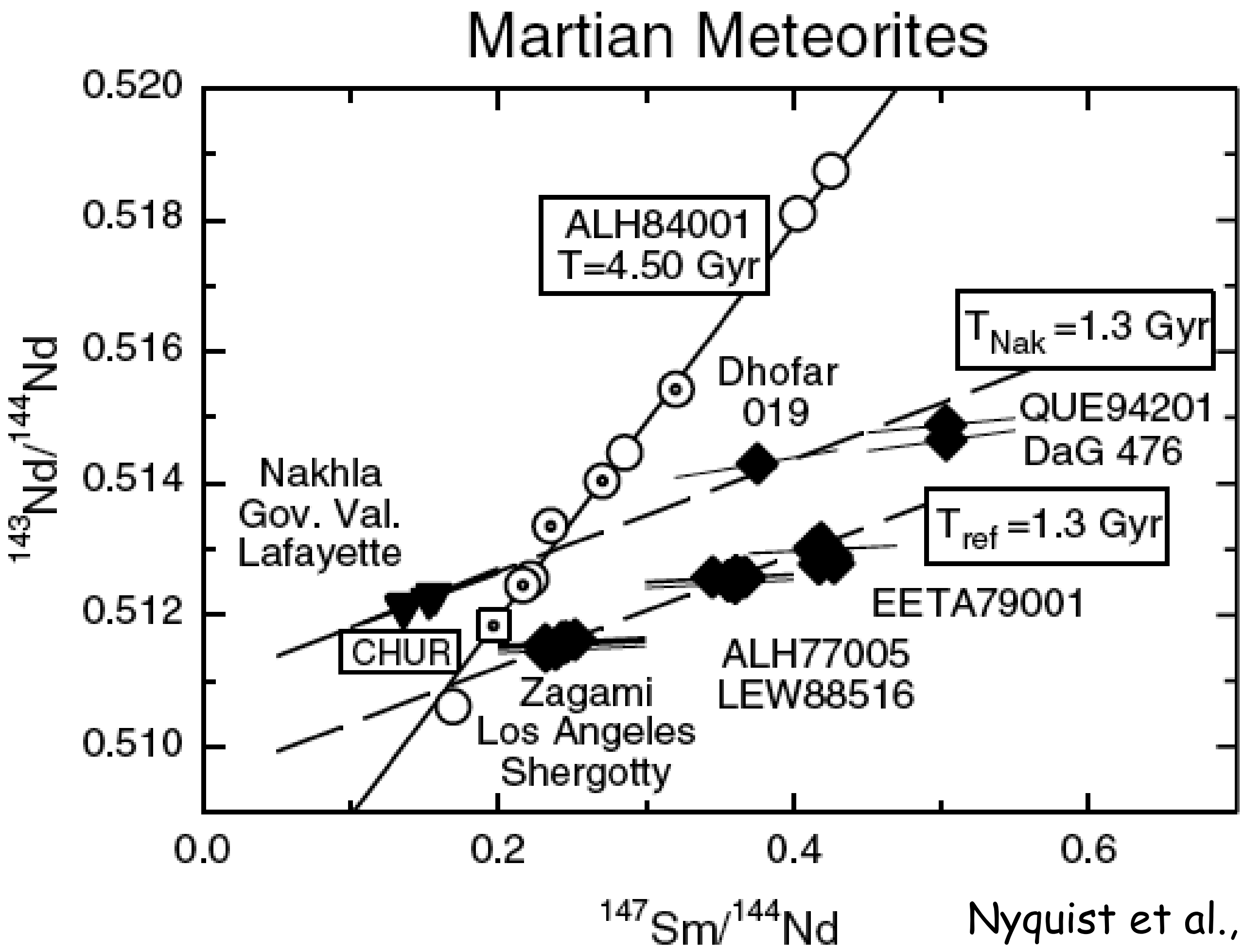


Nyquist et al., 2001

Are the "isotopic ages" of shergottites crystallization ages ?

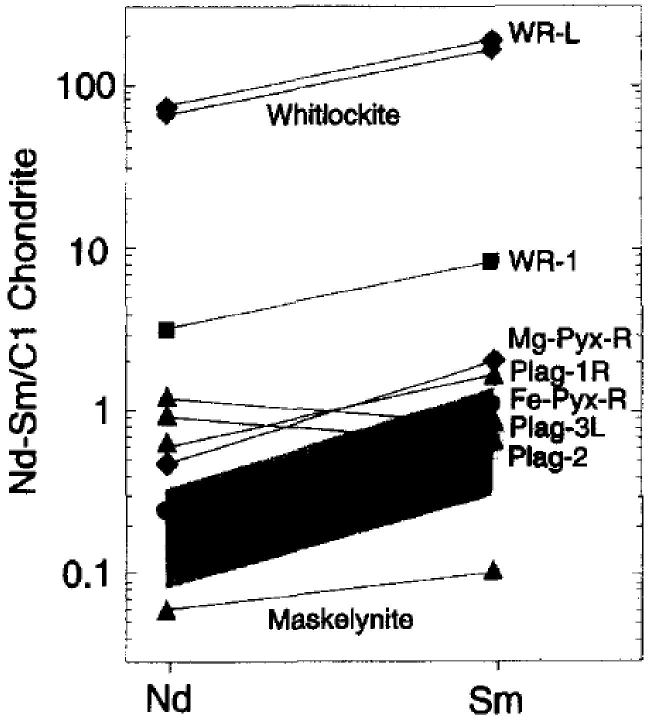
These three ages have been identified from mineral isochrons with the Sm-Nd, Rb-Sr, U-Pb systems (see review by Nyquist et al. 2001, and more recent papers by Borg et al.)

$$\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}} = \left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_0 + \frac{^{147}\mathrm{Sm}}{^{144}\mathrm{Nd}} \times (e^{\lambda t} - 1) \qquad T_{\frac{1}{2}} = 1.06 \times 10^{11}\,\mathrm{yrs}$$

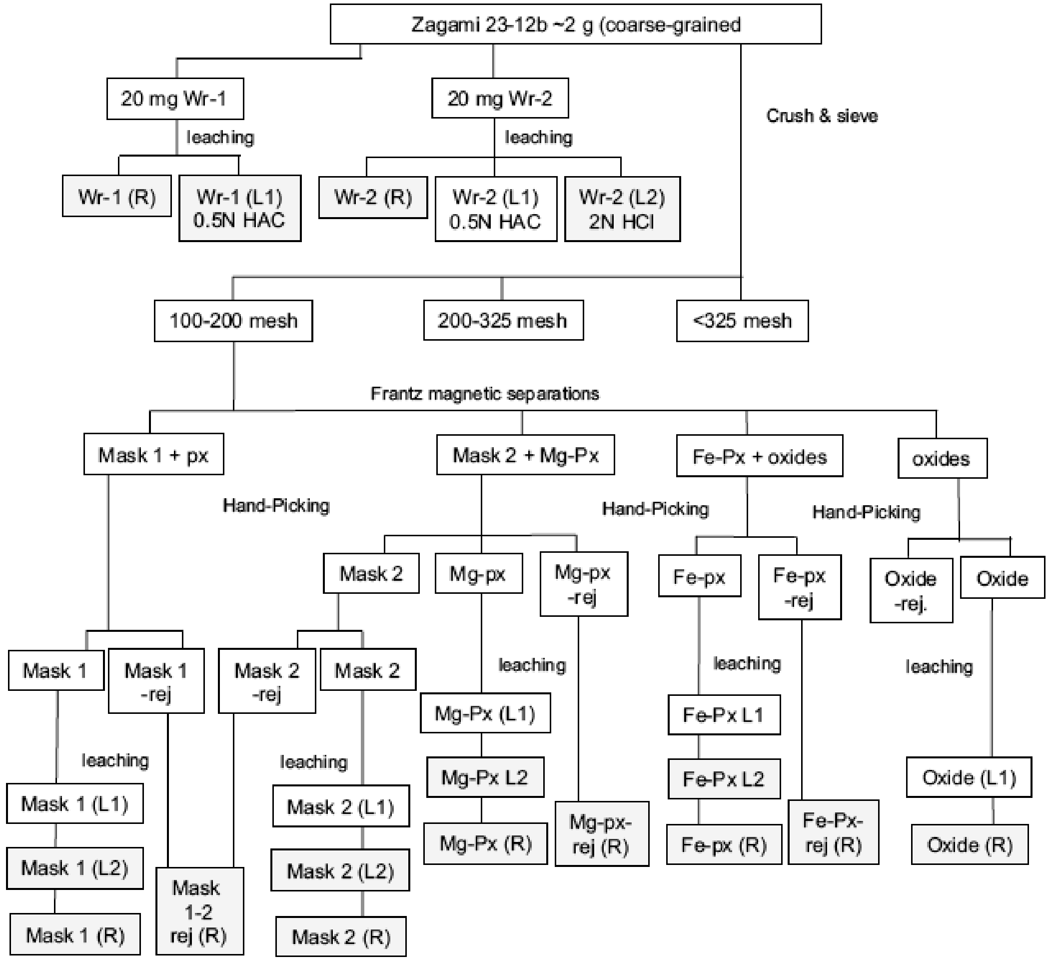


Nyquist et al., 2001

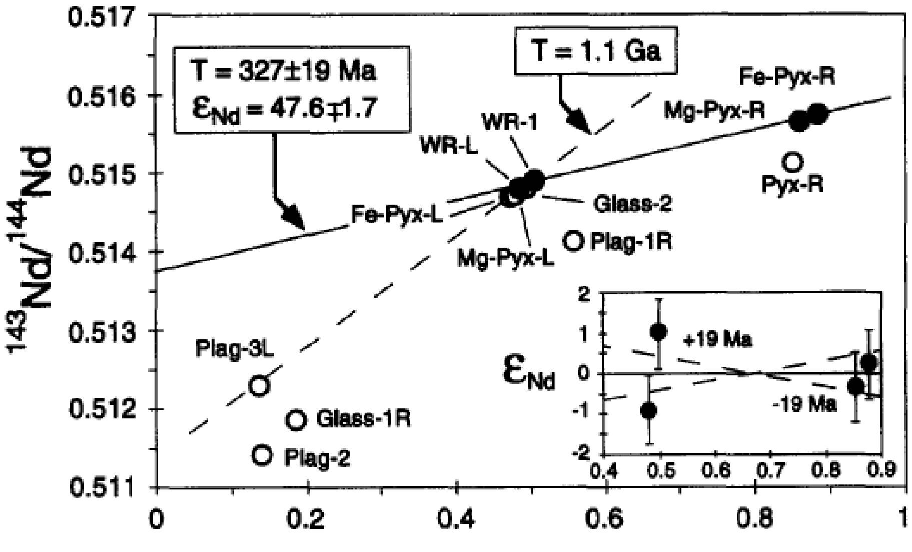
The problem is that the behavior of Sm and Nd (but also Rb, Sr, U, Pb) is quite complex in SNCs because their budget is mostly controlled by phosphates (either magmatic or low-temperature)



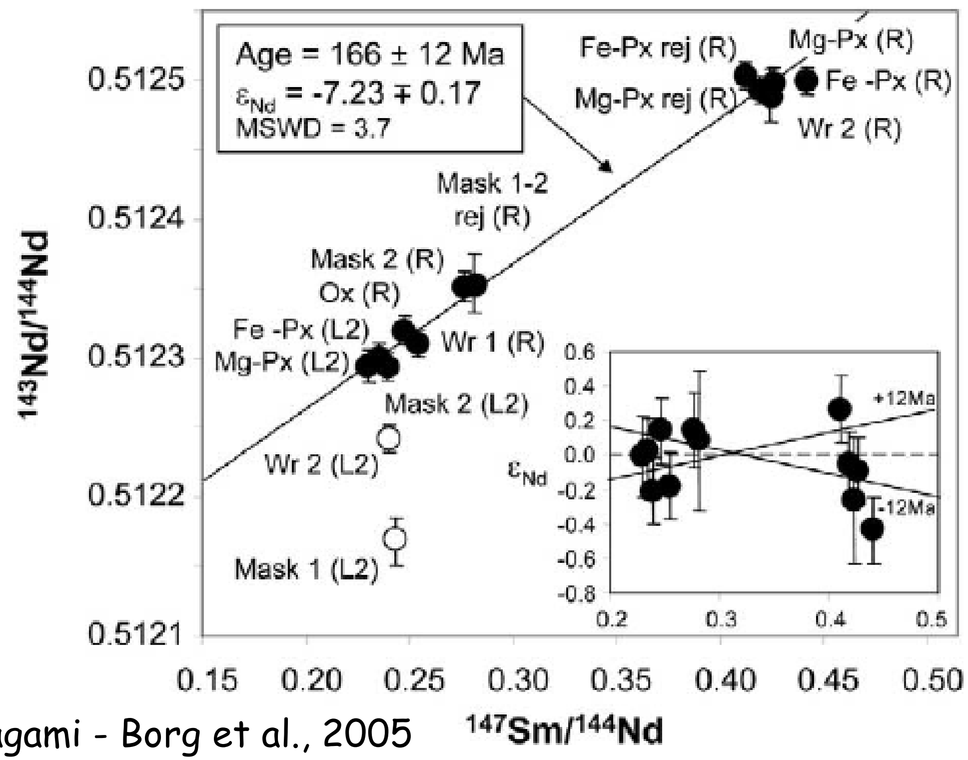
Budget of Sm and Nd in QUE 94201 Borg et al., 1997



Mineral separation procedure used for Zagami, Borg et al., 2005



QUE 94201 - Borg et al., 1997

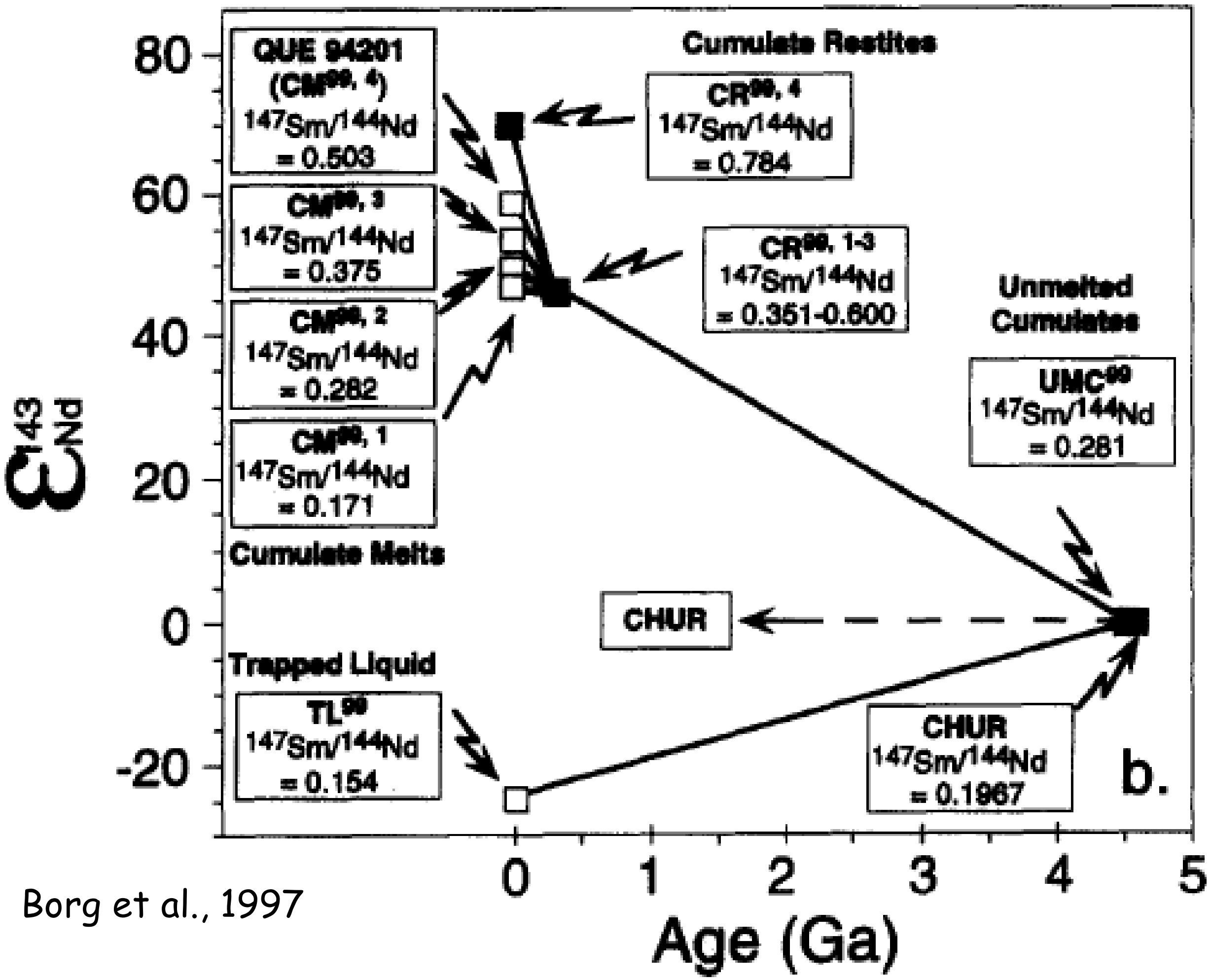


Zagami - Borg et al., 2005

- Good alignments can be obtained but mineral separates and leaches show the presence of different components
- Interpreting the $^{147}Sm/^{144}Nd$ variations in terms of magmatic fractionation is possible but complicated

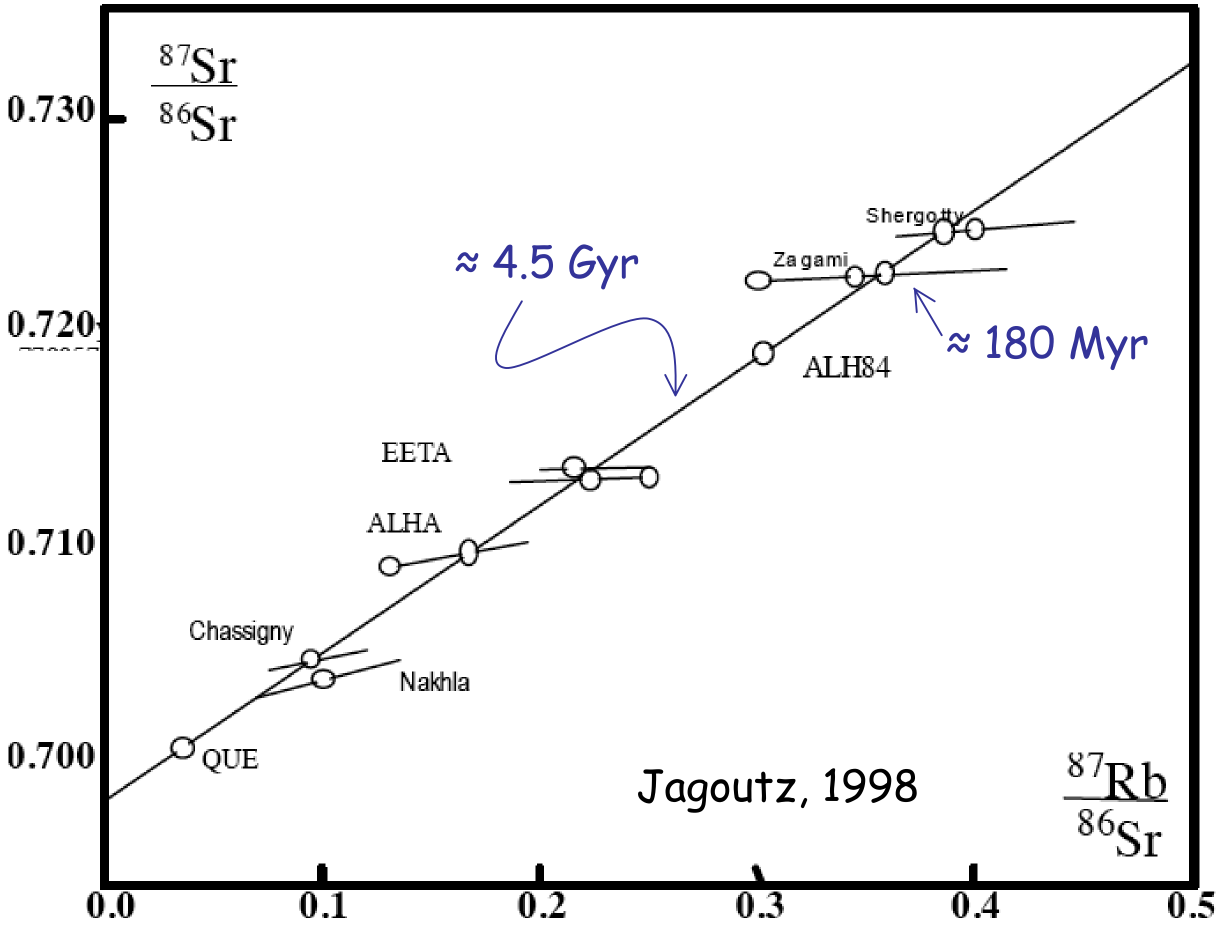
The $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios in QU 94201 can be modeled by magmatic fractionation for:

(i) crystallization of the magma ocean at 4.525 Ga
(ii) 4 episodes of melting at 327 Ma of the cumulates of the magma ocean



Borg et al., 1997

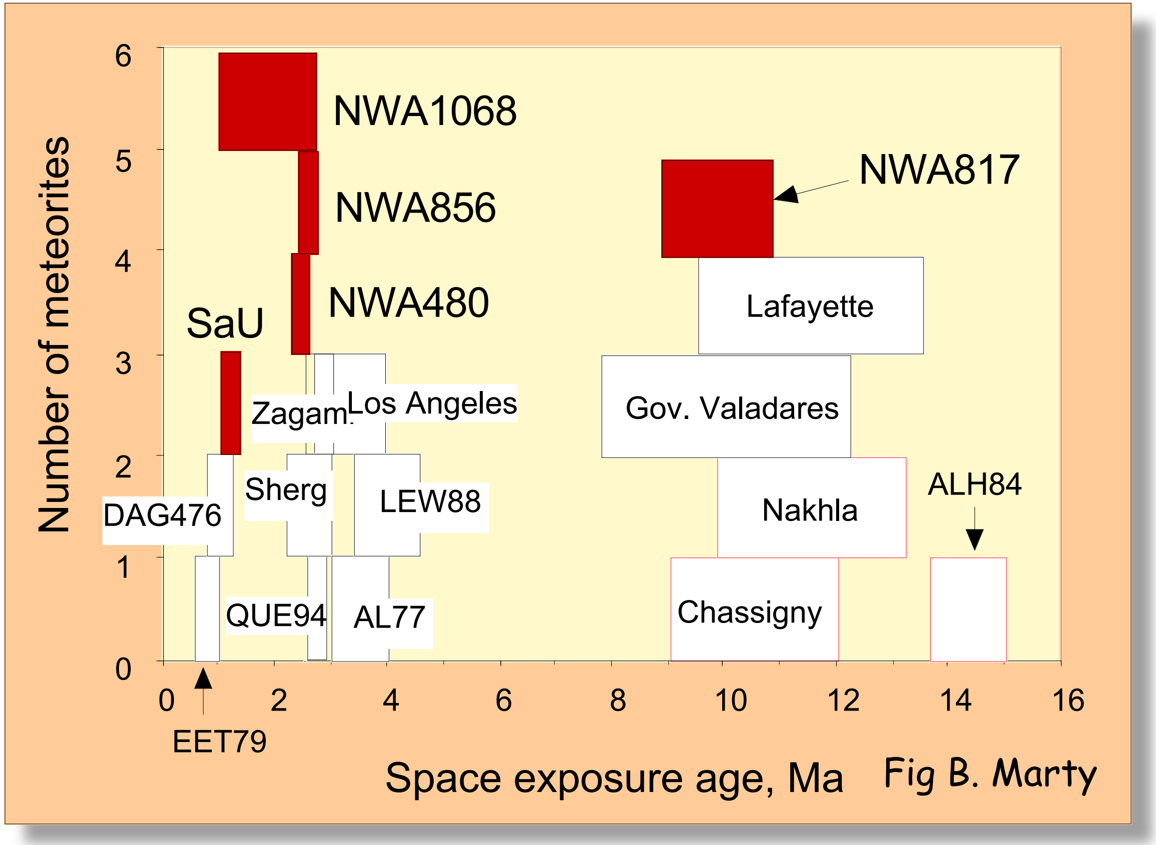
The young ages have strong implications on the geodynamics of the mantle of Mars. It must have remained unstirred between ≈ 4.5 Gyr and 180 Myr to preserve isotopic heterogeneities inherited from early differentiation



$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_0 + \frac{^{87}Rb}{^{86}Sr} \times (e^{\lambda t} - 1)$$

$$T_{\frac{1}{2}} = 4.8 \times 10^{10}\,\mathrm{yrs}$$

There is also an issue in terms of probability to sample by impacts only very young terranes

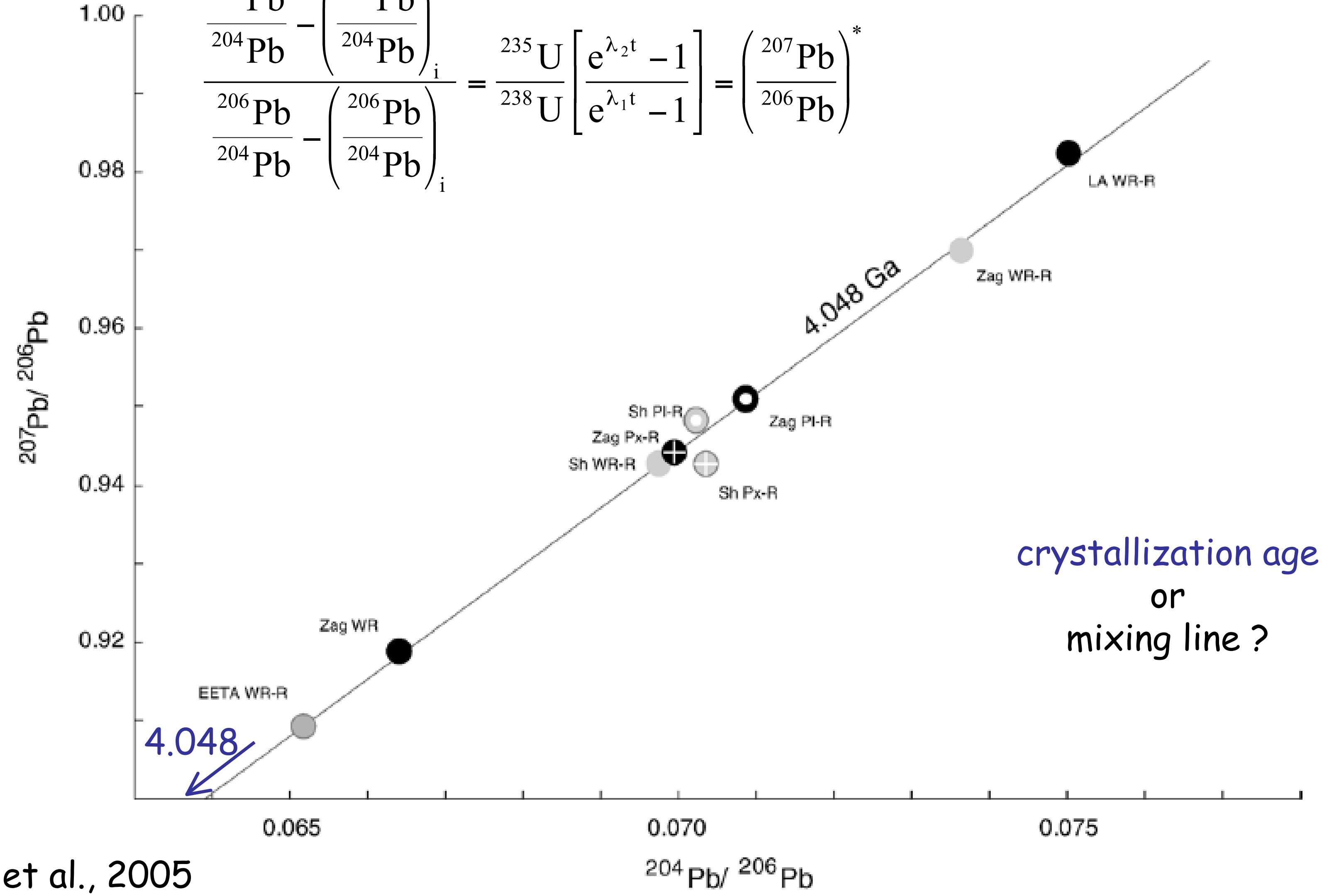


At least 7 ejection events are required (see review by Nyquist et al., 2001):

- ≈ 20 Ma for shergottite Dhofar 019
- ≈ 15 Ma for orthopyroxenite ALH 84001
- ≈ 12 Ma for nakhlites
- ≈ 4.5 Ma, 3 Ma, 1.3 Ma & 0.7 Ma for shergottites

For shergottites (basaltic and lherzolitic) whole rock and minerals residues after leaching define a Pb-Pb age of 4.05 Ga

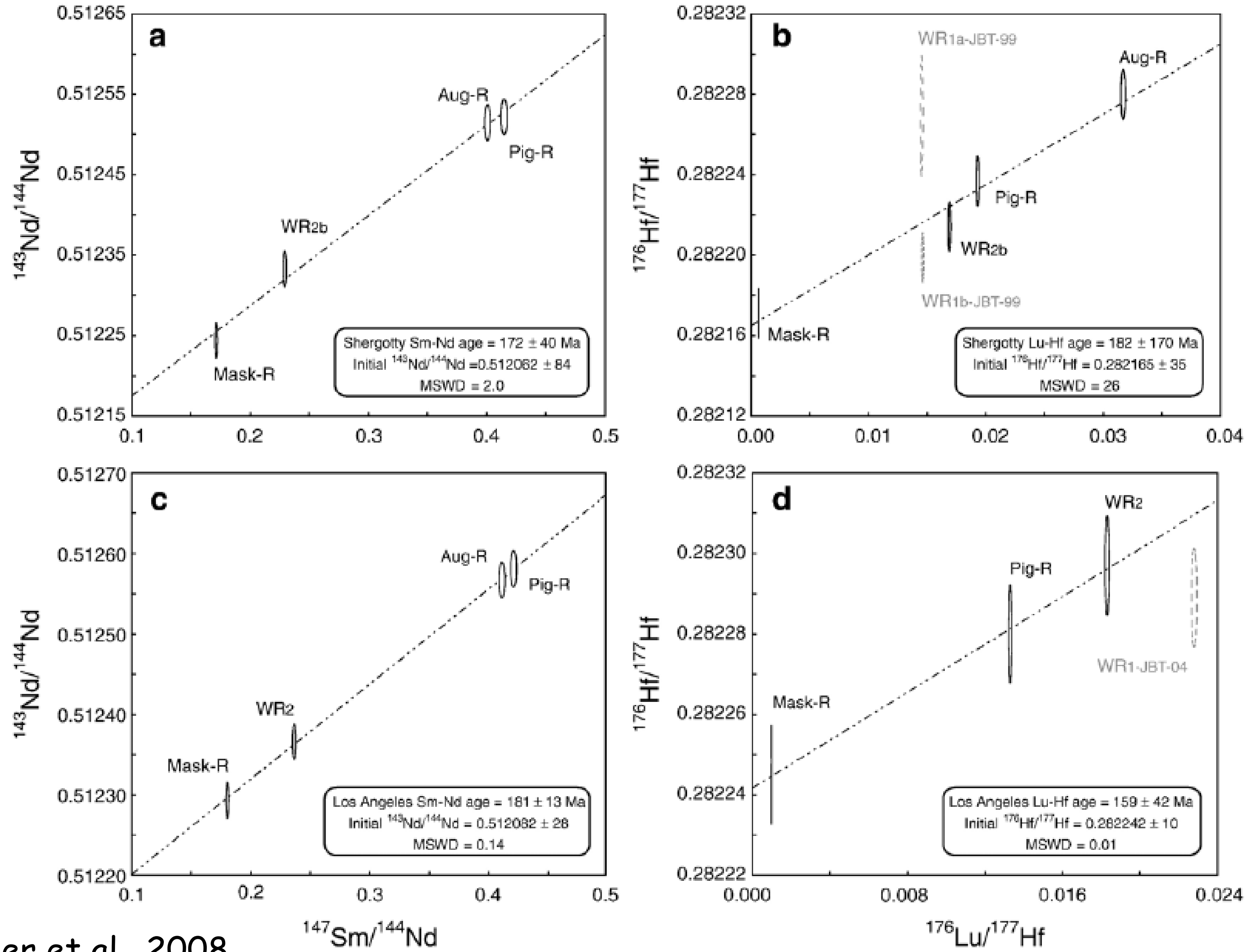
$$\frac{\frac{^{207}Pb}{^{204}Pb}-\left(\frac{^{207}Pb}{^{204}Pb}\right)_i}{\frac{^{206}Pb}{^{204}Pb}-\left(\frac{^{206}Pb}{^{204}Pb}\right)_i}=\frac{^{235}U}{^{238}U}\left[\frac{e^{\lambda_2 t}-1}{e^{\lambda_1 t}-1}\right]=\left(\frac{^{207}Pb}{^{206}Pb}\right)^*$$



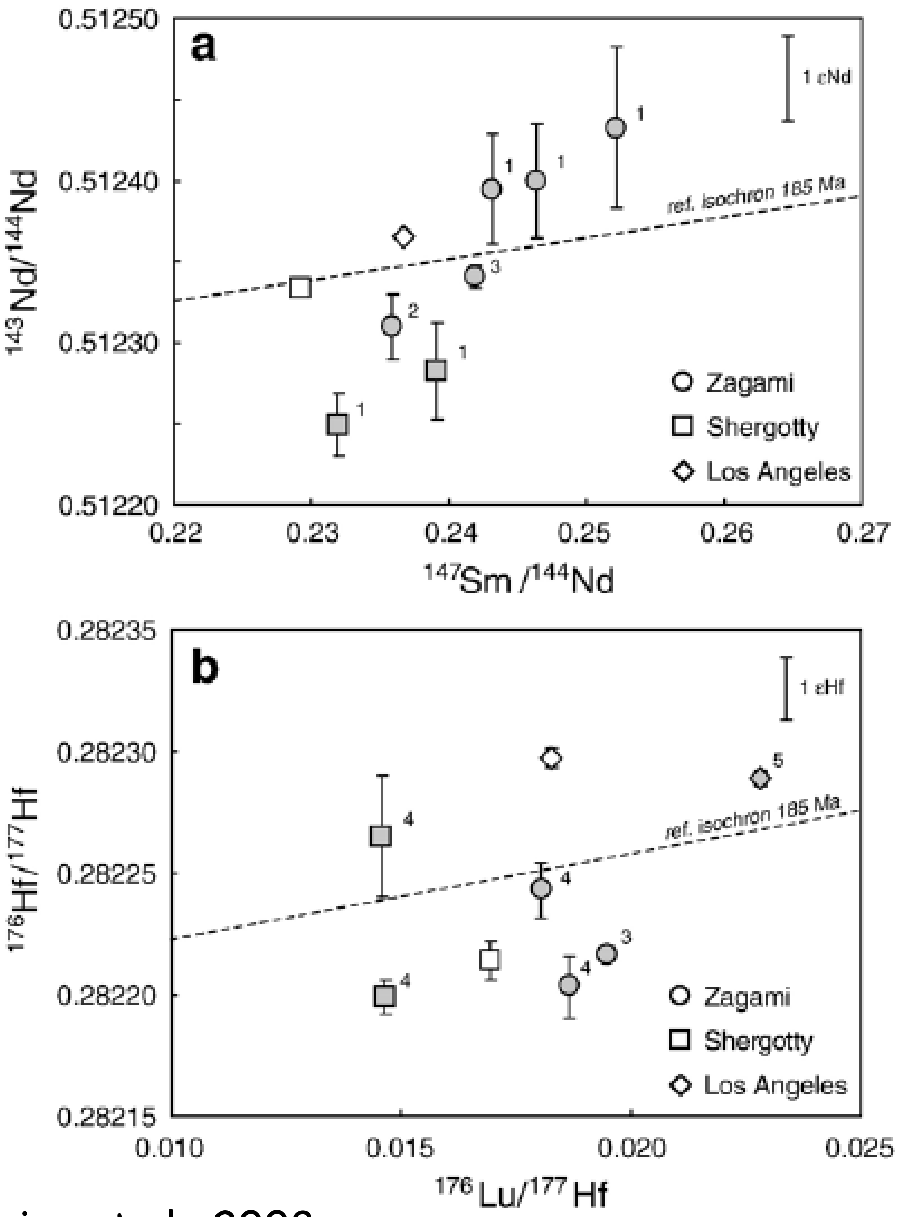
crystallization age
or
mixing line ?

Bouvier et al., 2005

For these samples there is no doubt that young isotopic ages can be found from mineral isochrons (after leaching …)



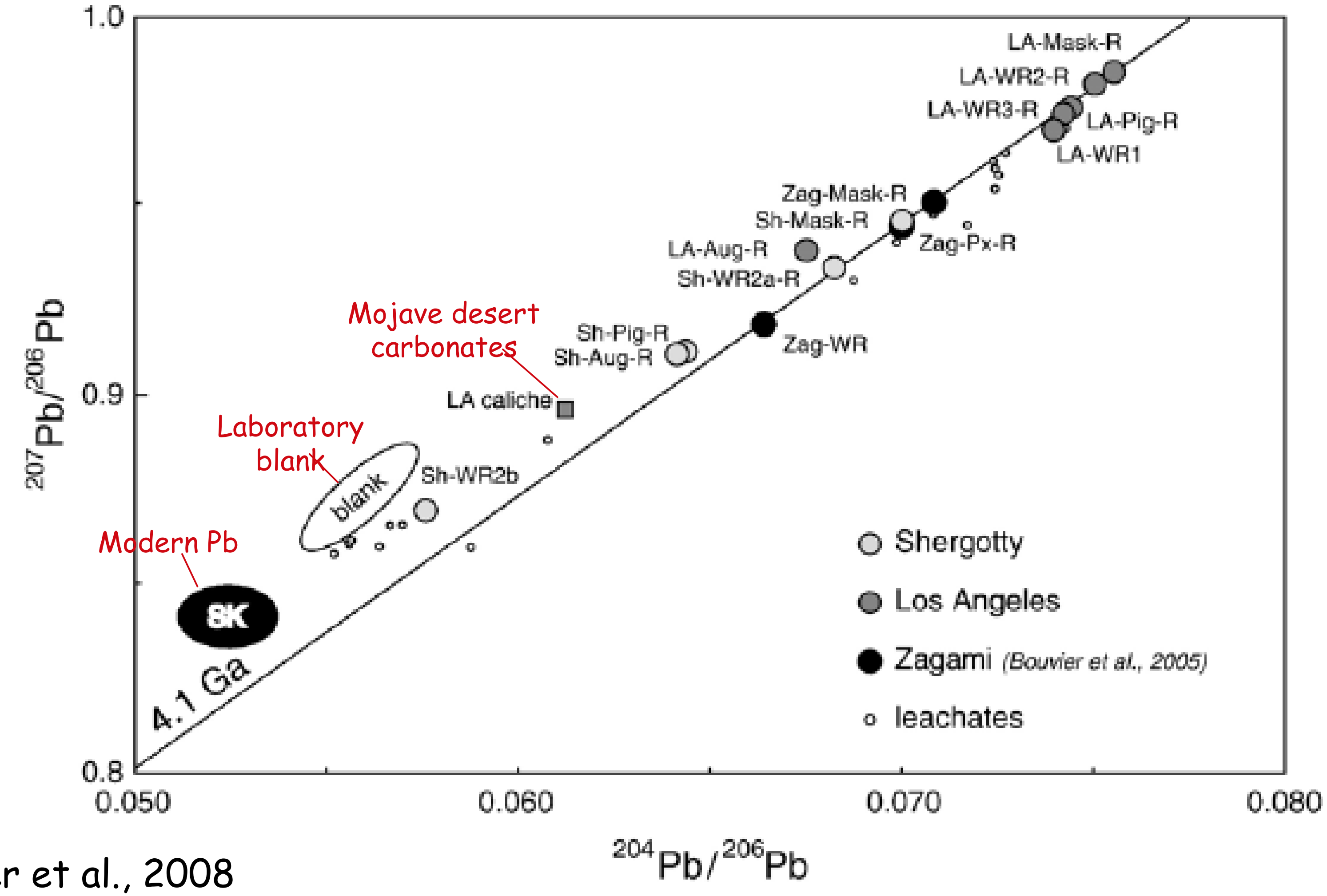
Bouvier et al., 2008



Bouvier et al., 2008

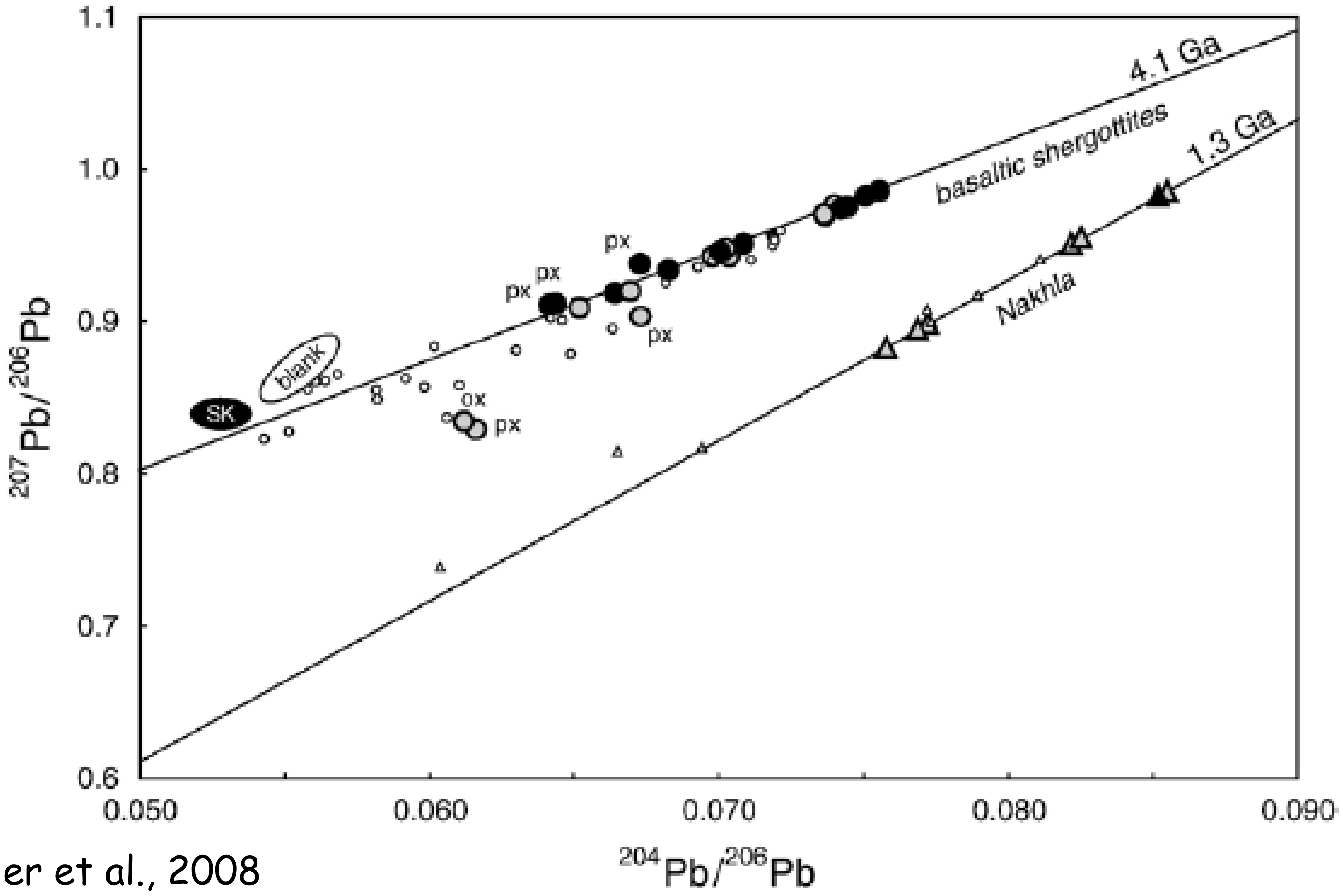
But it is also clear the the whole rock samples are heterogeneous : they contain different components with different isotopic compositions

All the leaching residues (whole rock, maskelynite and pyroxene) of the three shergotittes define a Pb-Pb line giving an age of 4.05 ± 0.7 Ga (except some augites with too low Pb concentrations)



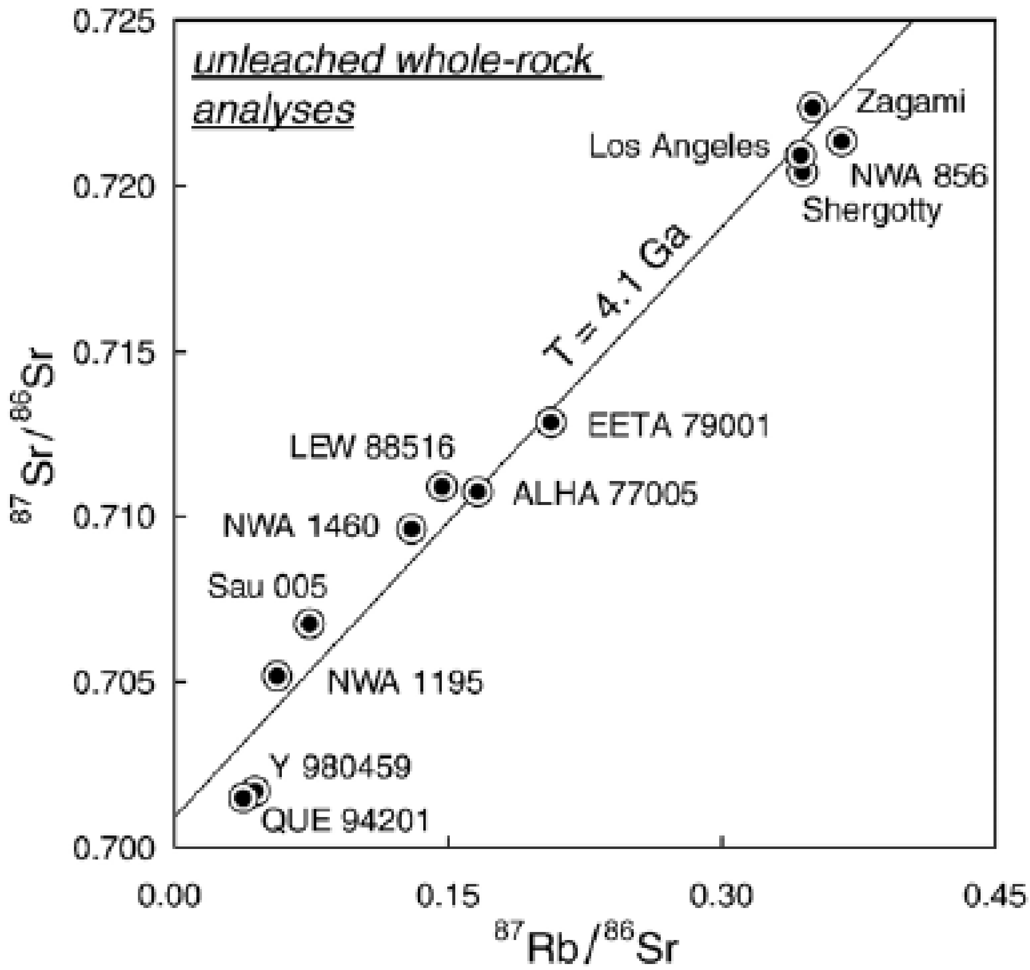
Bouvier et al., 2008

Nakhla, which is poorer in Pb, is not affected by any contamination or mixing with another component



Bouvier et al., 2008

A magmatic age of 4.1 Ga would also make sense with whole rock Rb-Sr data of all shergottites



The fact that the crystallization ages of martian meteorites is old is further suggested by rare gas systematic

- Xe has 9 isotopes, some being produced by extinct and extant radioactivities :

  $^{129}I \rightarrow {}^{129}Xe^*$ (16 Ma)

  $^{244}Pu \rightarrow {}^{131\text{-}136}Xe_f$ (82 Ma)

  $^{238}U \rightarrow {}^{131\text{-}136}Xe_f$ (4556 Ma)

- I : incompatible, volatile
- Pu, U : incompatible, refractory

The low $(^{129}Xe/^{136}Xe)^*$ ratios in the martian mantle imply early and short differentiation and degassing of I

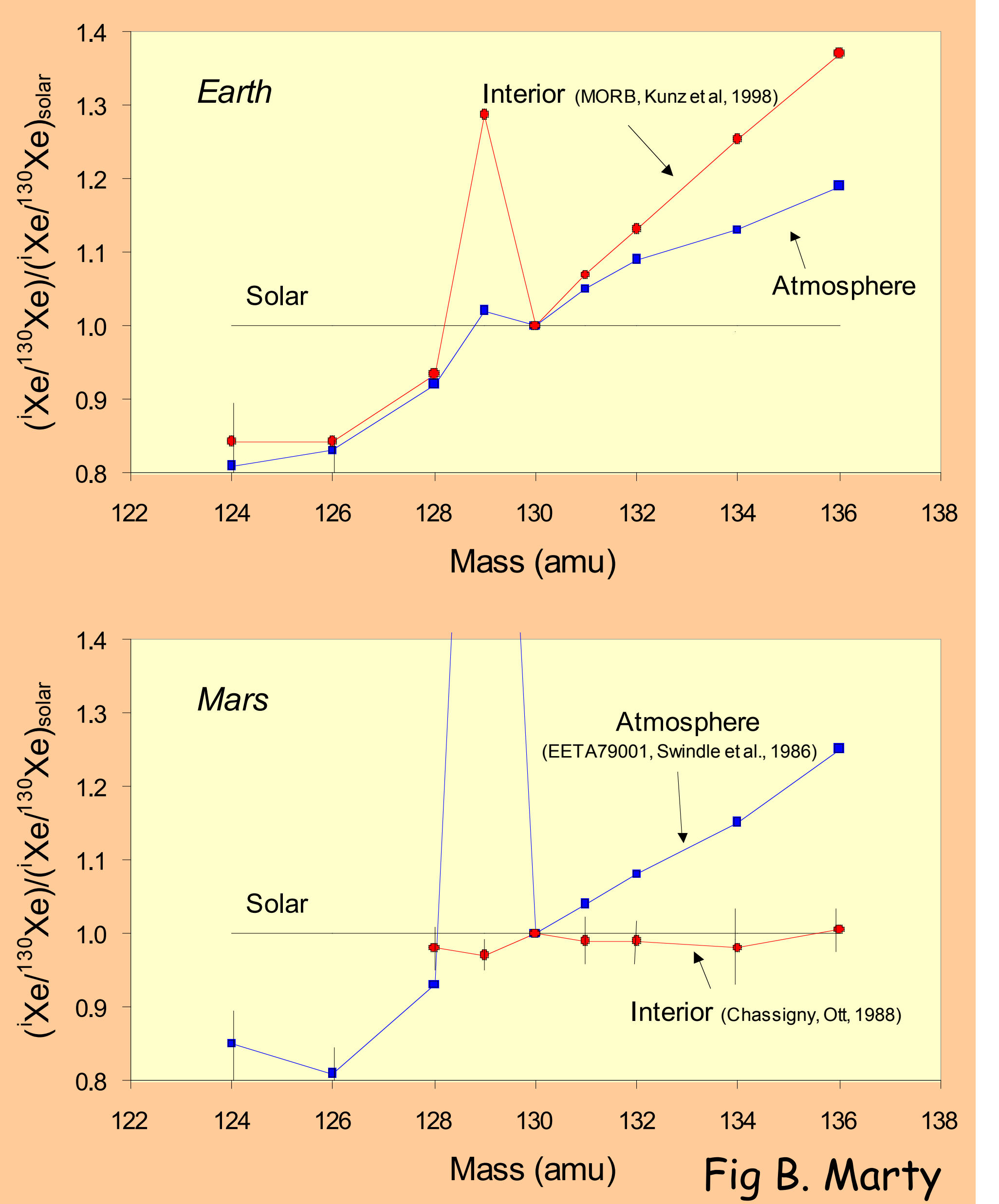
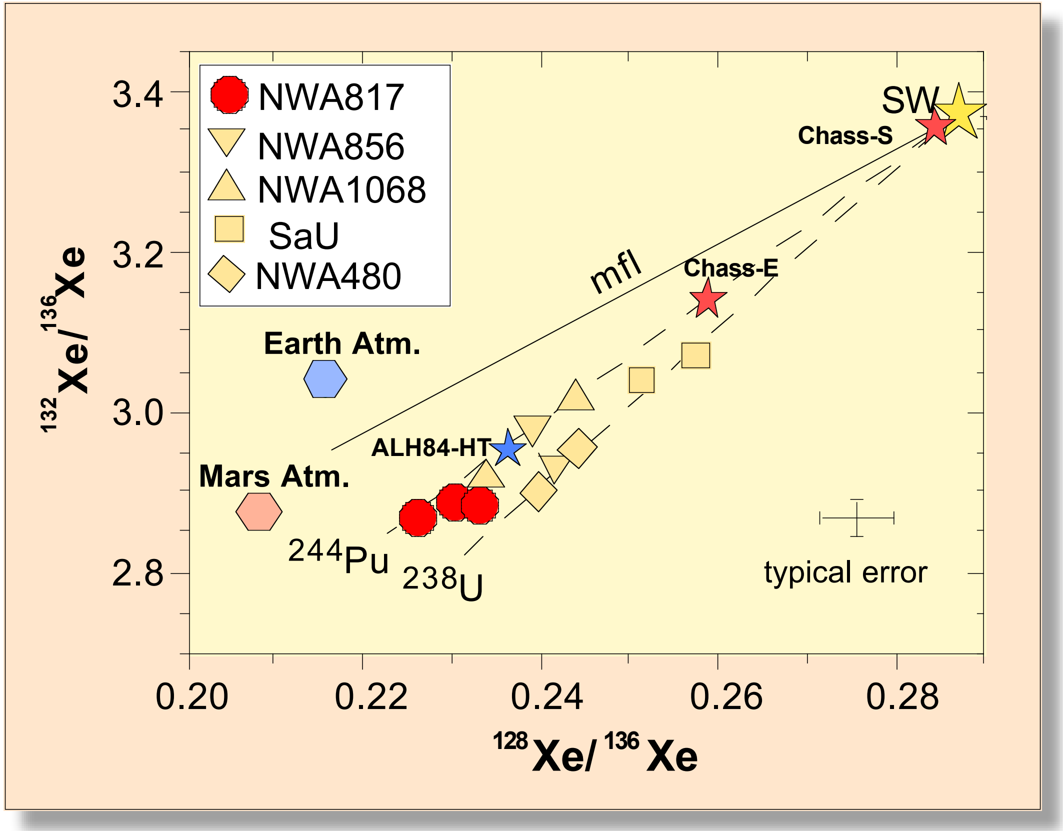


Fig B. Marty

The fact that the crystallization ages of martian meteorites is old is further suggested by rare gas systematic

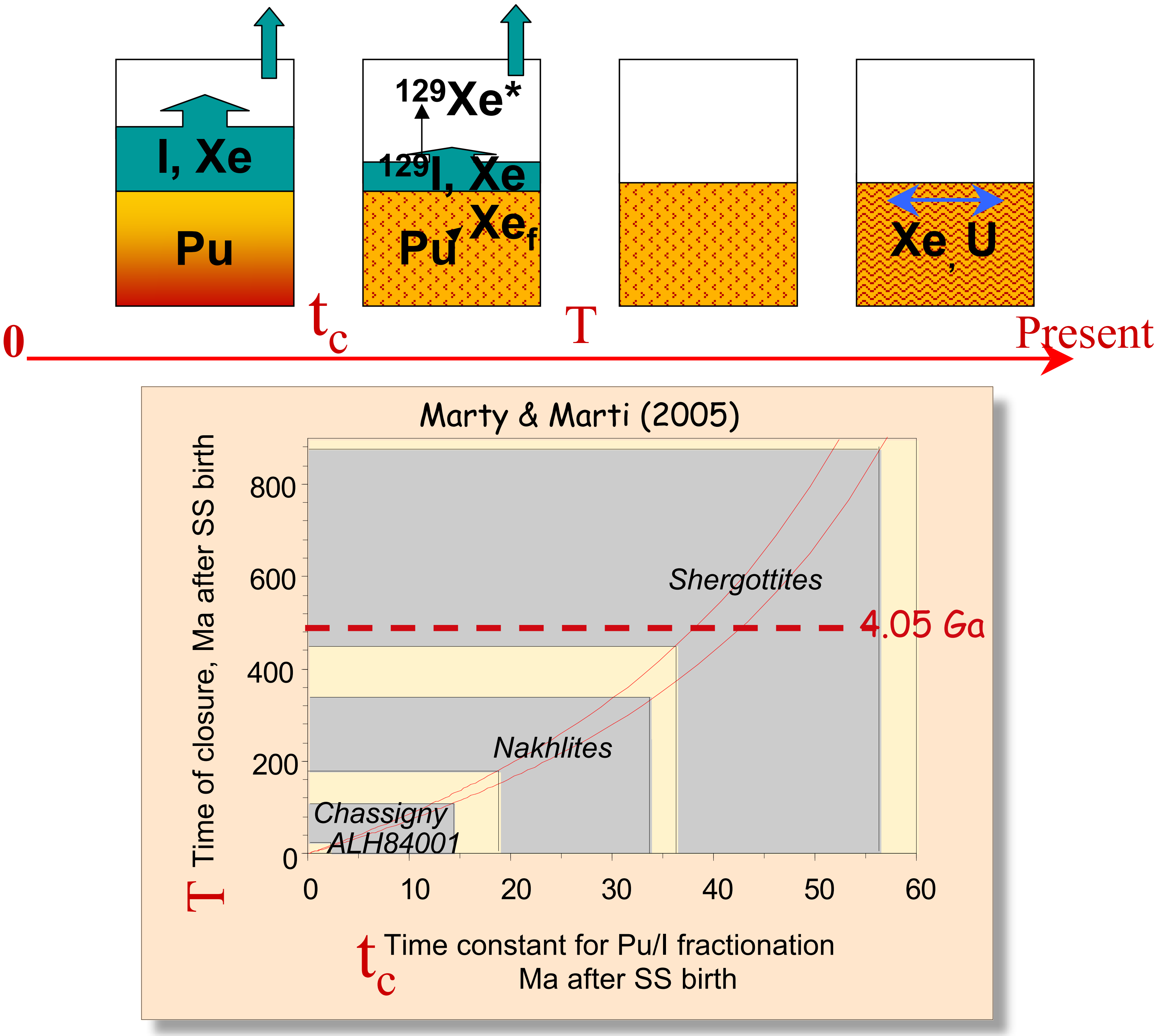
- Xe has 9 isotopes, some being produced by extinct and extant radioactivities :
  - $^{129}I \rightarrow {}^{129}Xe^*$ (16 Ma)
  - $^{244}Pu \rightarrow {}^{131-136}Xe_f$ (82 Ma)
  - $^{238}U \rightarrow {}^{131-136}Xe_f$ (4556 Ma)
- I : incompatible, volatile
- Pu, U : incompatible, refractory



Marty & Marti (2005)

Xe_f is dominated by $^{244}Pu_f$ (7 to 40 times $^{238}U_f$)

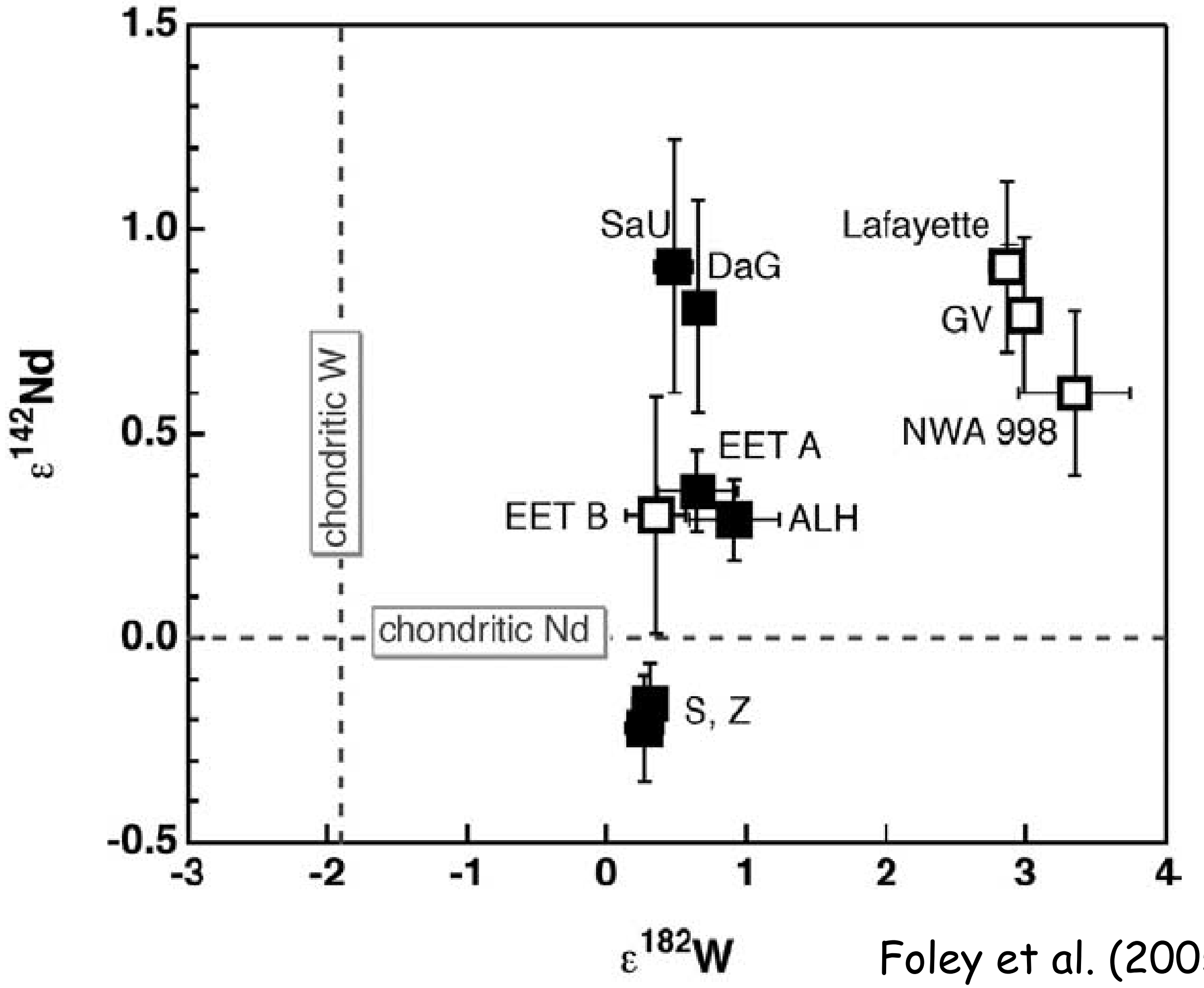
Xe is extracted from the meteorites by heating at 900°C



I, Xe
Pu
$^{129}Xe^*$
^{129}I, Xe
Pu
Xe_f
Xe, U
0
t_c
T
Present
Marty & Marti (2005)
Time of closure, Ma after SS birth
T
0
200
400
600
800
Shergottites
4.05 Ga
Nakhlites
Chassigny
ALH84001
0
10
20
30
40
50
60
t_c
Time constant for Pu/I fractionation
Ma after SS birth

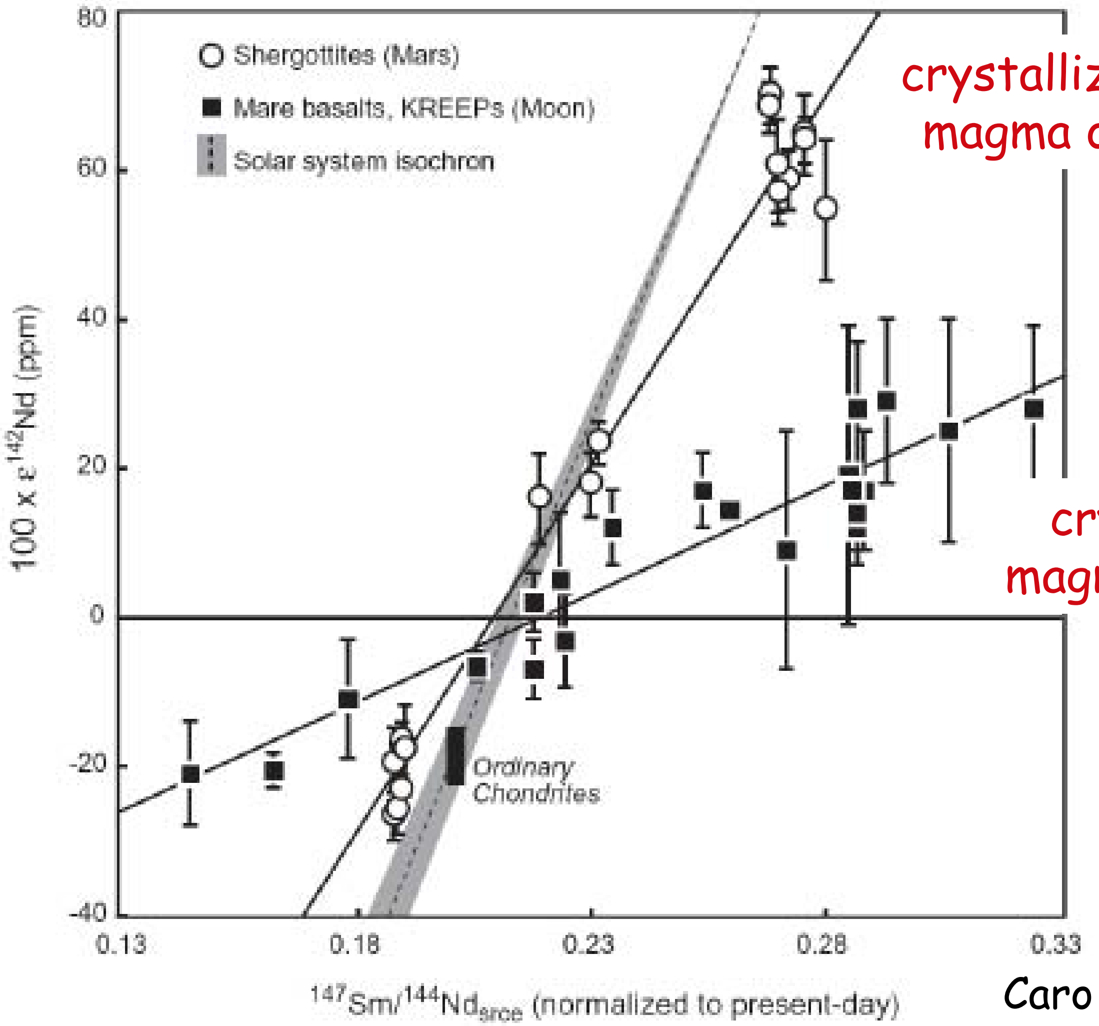
The very early differentiation of Mars (formation of the a metallic core and crystallization of a magma ocean) is indicated by excesses of:

- ^{182}W (decay of ^{182}Hf $T_{1/2}$= 9 Ma) ⟶ core at ≈ 12 Ma
- ^{142}Nd (decay of ^{142}Sm $T_{1/2}$= 103 Ma) ⟶ crystallization of magma ocean at 40 ± 20 Ma



Foley et al. (2005)

Mars, the Earth and Moon may have accreted from material with a non chondritic Sm/Nd ratio (5% difference, role of impacts ?)

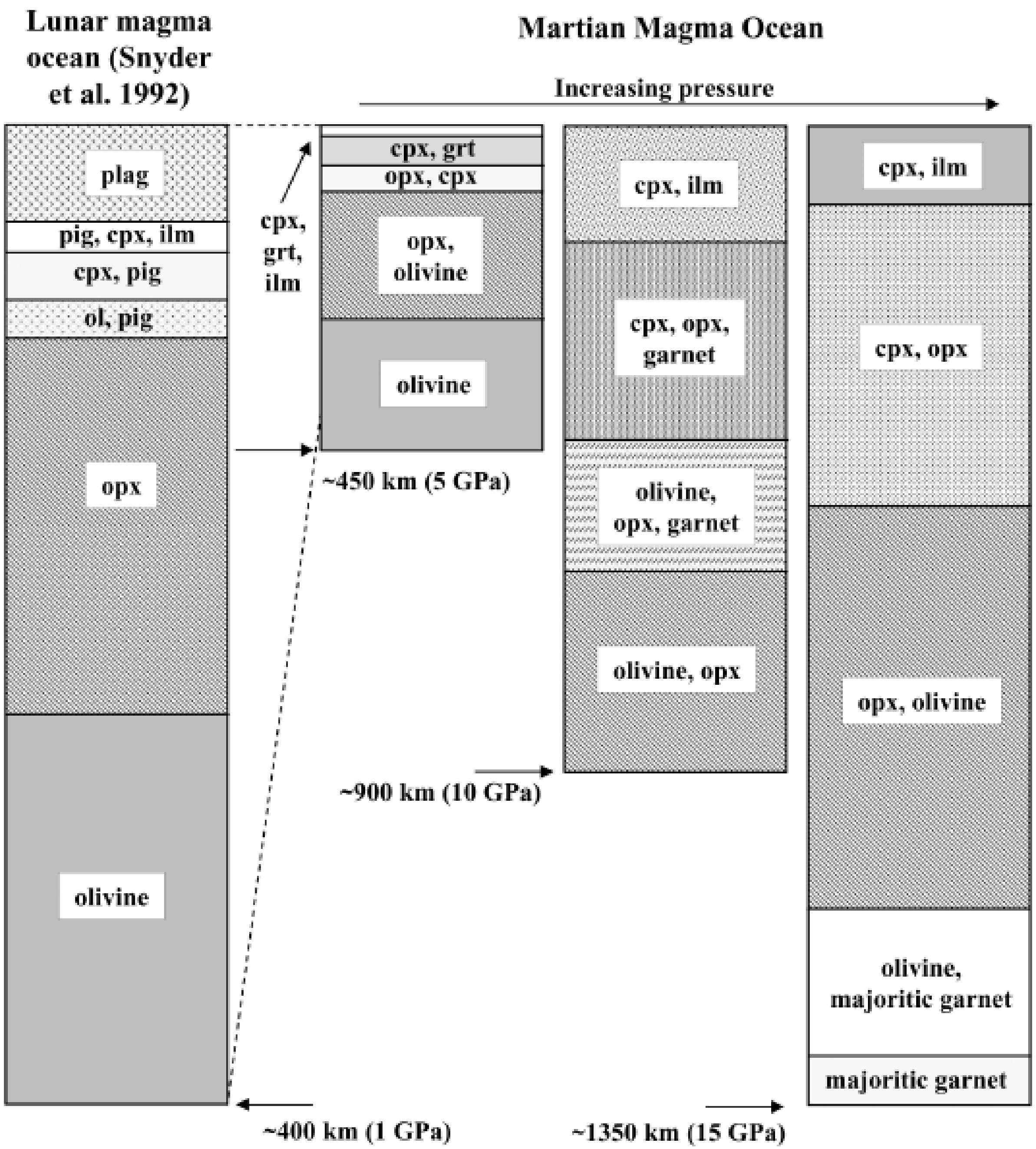


crystallization of the martian magma ocean at 40 ± 20 Ma

crystallization of the lunar magma ocean at ≈ 240 ± 40 Ma

Caro & Bourdon 2010

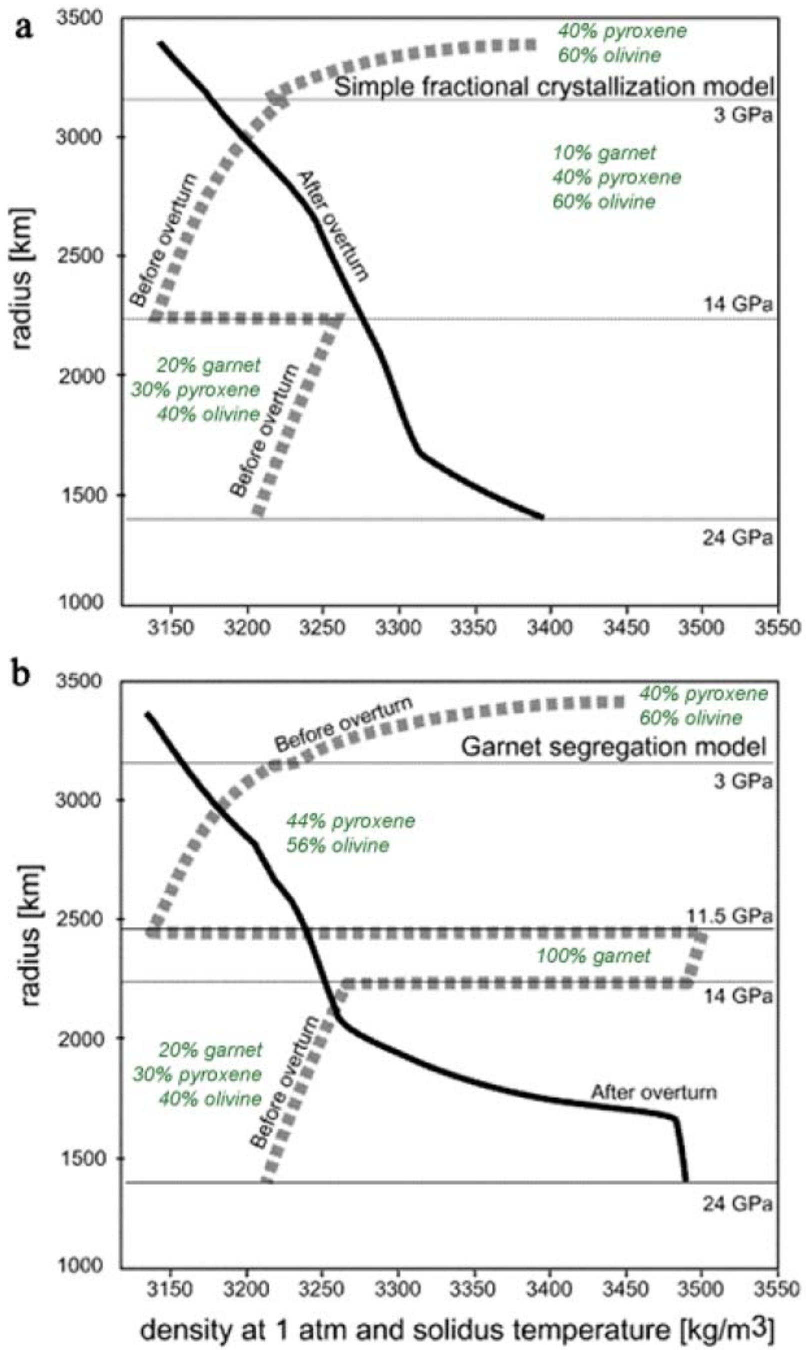
(data Debaille et al., 2007 ; Caro et al., 2008 ; Nyquist et al., 1995 ; Brandon et al. 2009 ; Boyet & Carlson 2007 ; Touboul et al. 2007)



Major difference with the Moon in the crystallization of the magma ocean: pressure

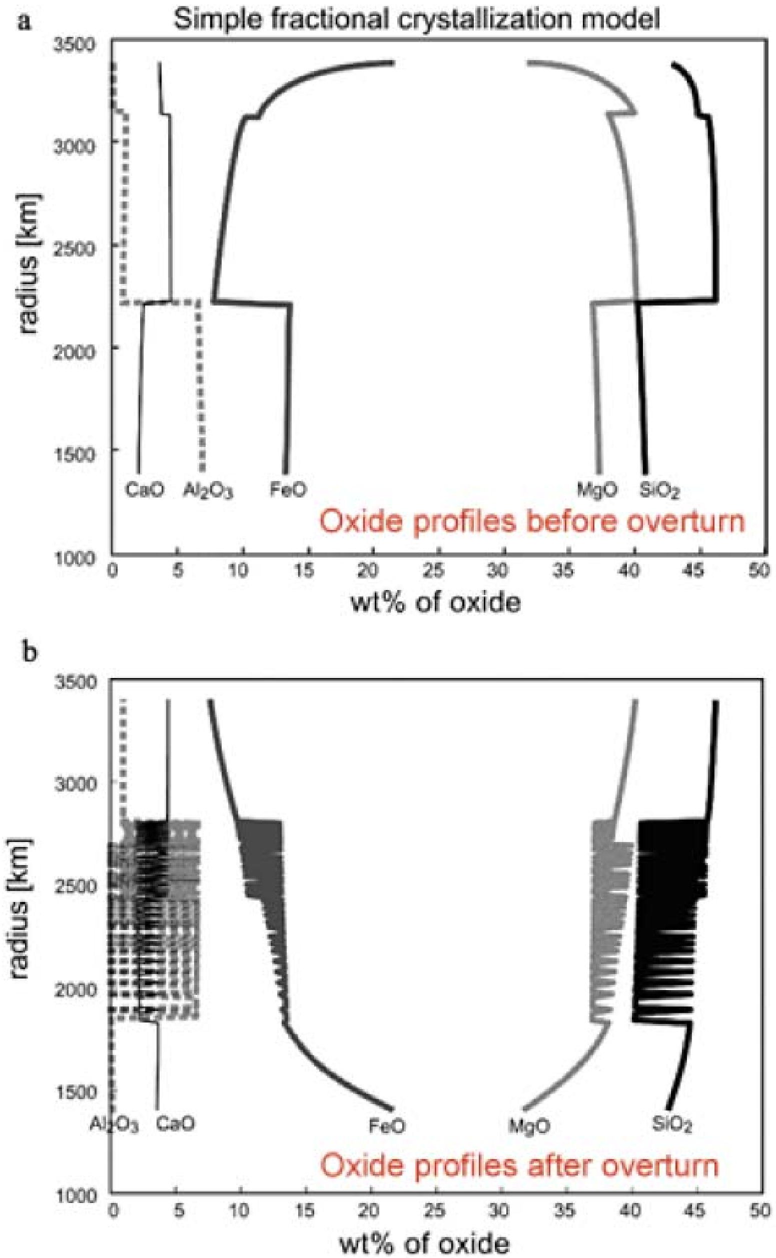
- garnet is a liquidus phase (high CaO/Al_2O_3 mantle)
- depleted nature of the martian mantle in agreement with sources inferred for Shergottites (+ late stage trapped liquids)

Borg & Draper, 2003



Different models for the crystallization of the magma ocean and the possible overturn in the mantle

Elkins-Tanton et al., 2003



Elkins-Tanton et al., 2003

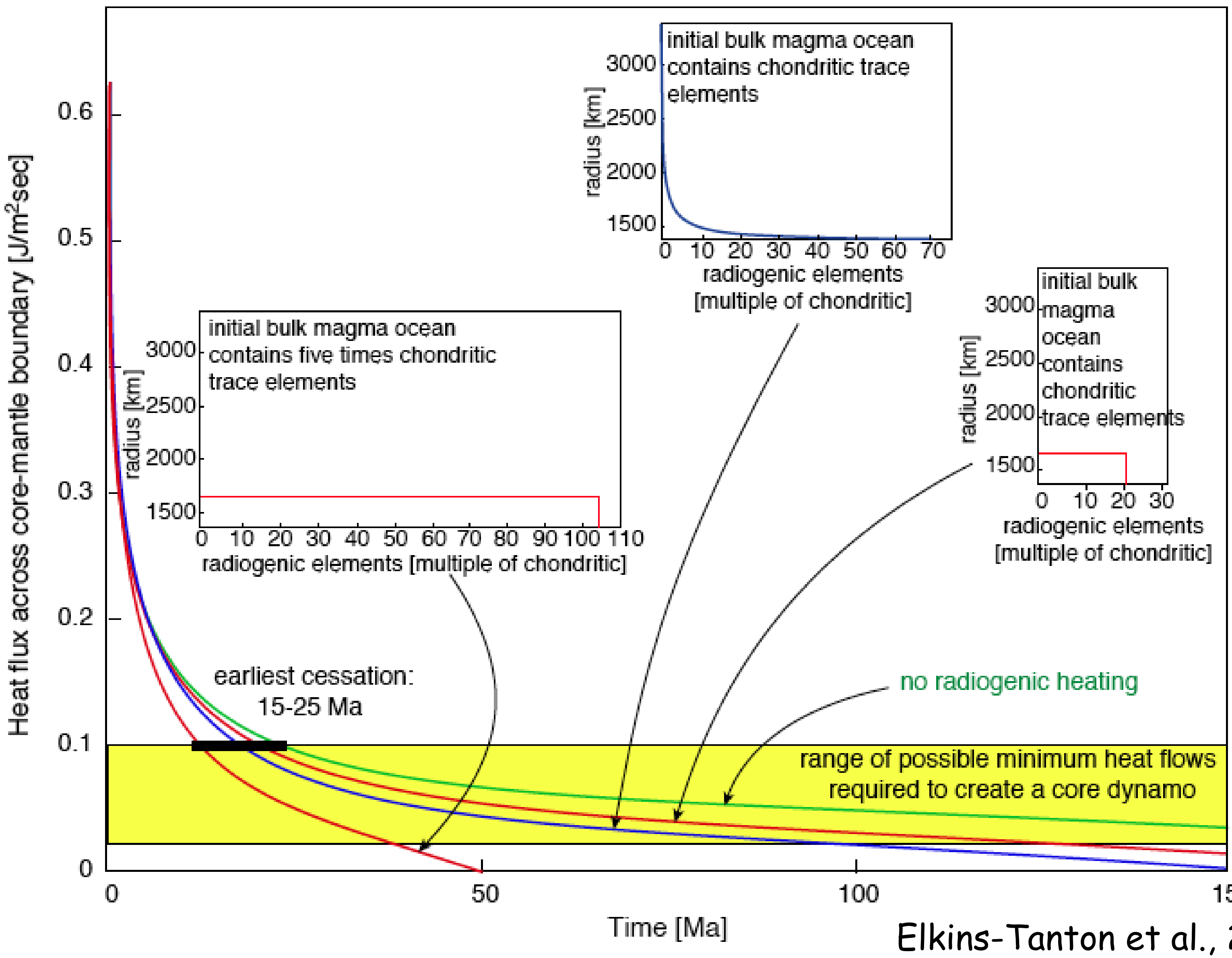
density

caracteristic time
1 to 10 Ma

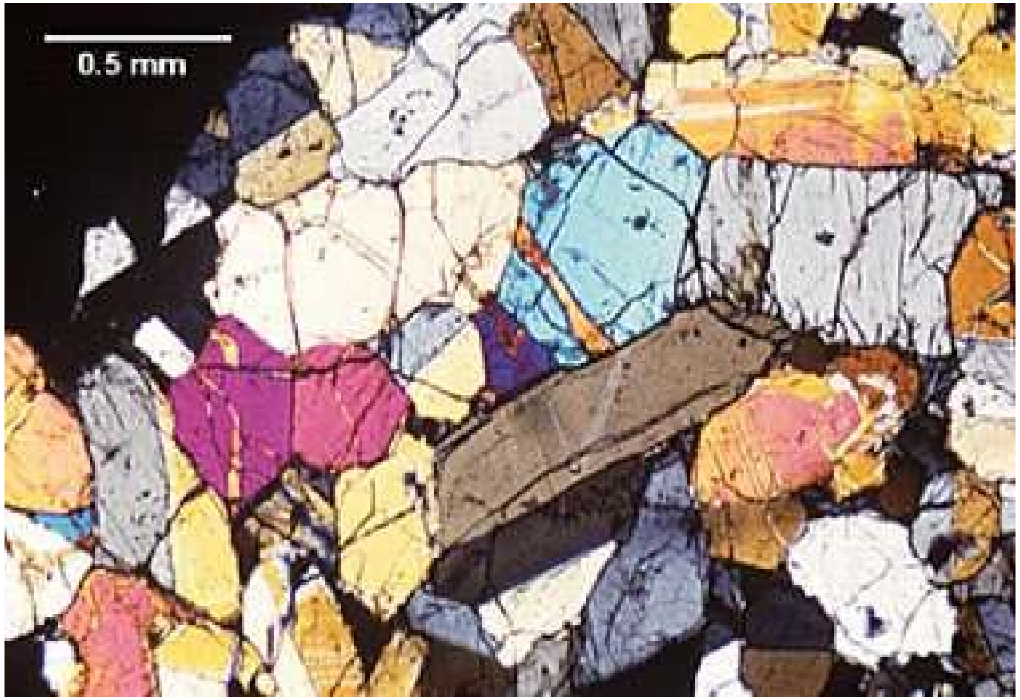
Initial depth

Elkins-Tanton et al., 2005

The overturn of the mantle may explain the rapid initiation and cessation of the magnetic field



Elkins-Tanton et al., 2005


0.5 mm