Thermal and Dynamic History of Planets

Planetary Volcanism and Crustal Evolution

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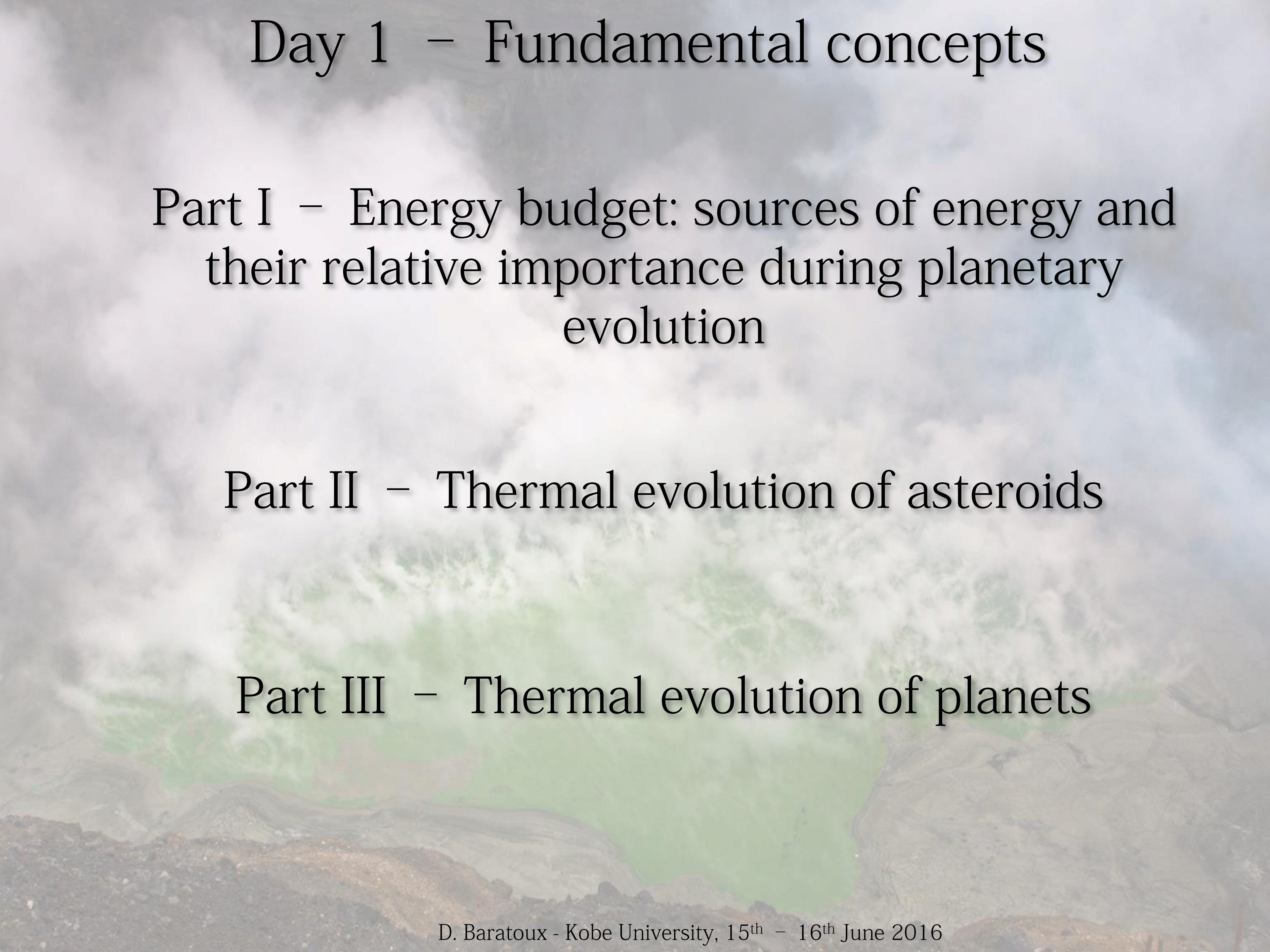
Institut Fondamental d'Afrique Noire

Day 1 – Fundamental concepts



Part I – Energy budget: sources of energy and their relative importance during planetary evolution

Part II – Thermal evolution of asteroids

Part III – Thermal evolution of planets

A few words about me…

1. Geoscience Environnement Toulouse
University of Toulouse

Planetary Evolution
Surface processes
Igneous processes
Impact cratering

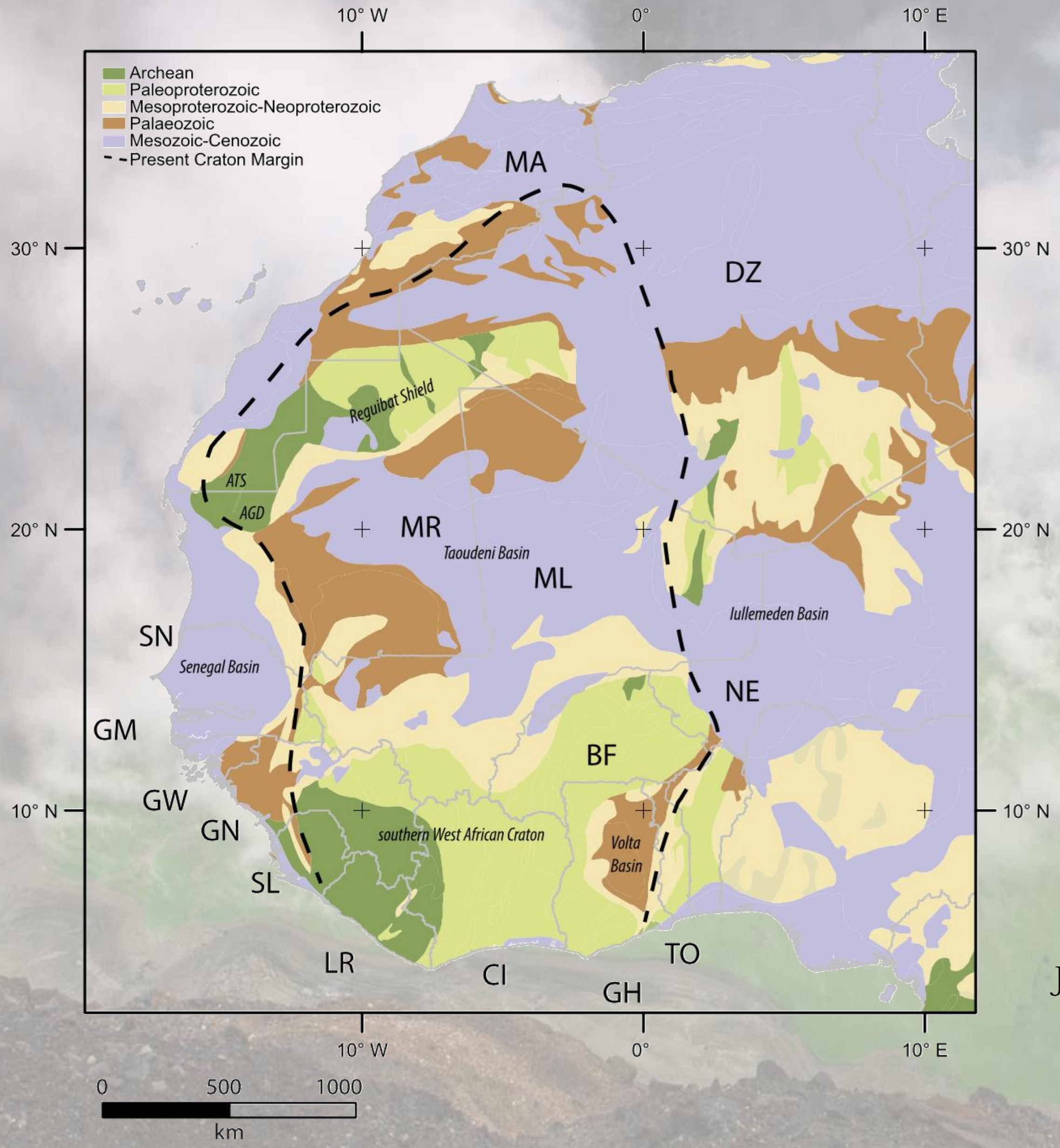
Mars Exploration
Mars Express

2. Institute of Research for Development
Institut Fondamental d'Afrique Noire, Dakar
Senegal

Why in West Africa ?

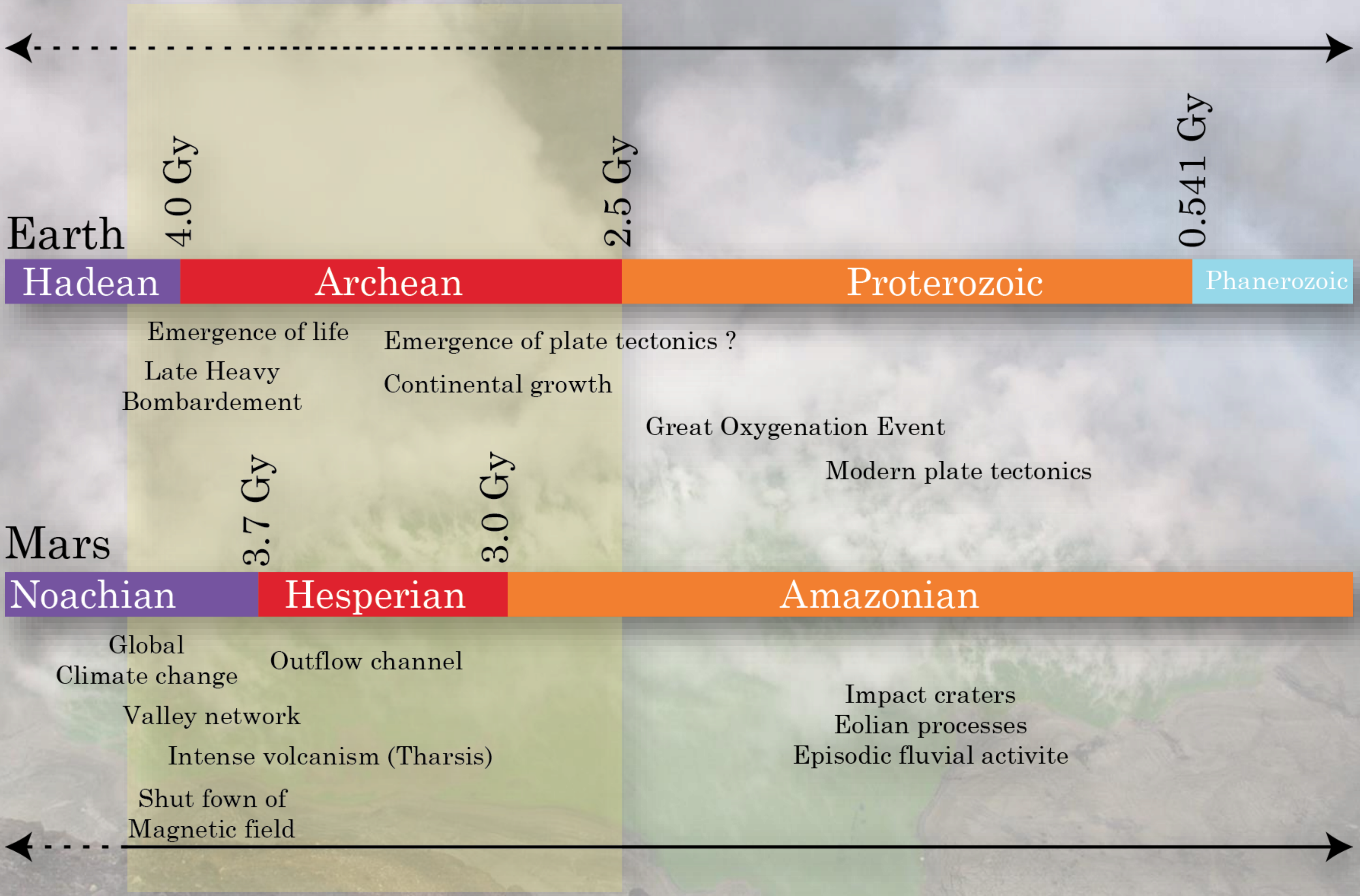
Because there are many fun things to do and nice beaches…

Because planetary scientists need to learn about ancient Earth



Jessell et al. 2015

Comparing Mars and West Africa



Earth

4.0 Gy

2.5 Gy

0.541 Gy

Hadean

Archean

Proterozoic

Phanerozoic

Emergence of life

Late Heavy
Bombardement

Emergence of plate tectonics ?

Continental growth

Great Oxygenation Event

Modern plate tectonics

Mars

3.7 Gy

3.0 Gy

Noachian

Hesperian

Amazonian

Global
Climate change

Outflow channel

Valley network

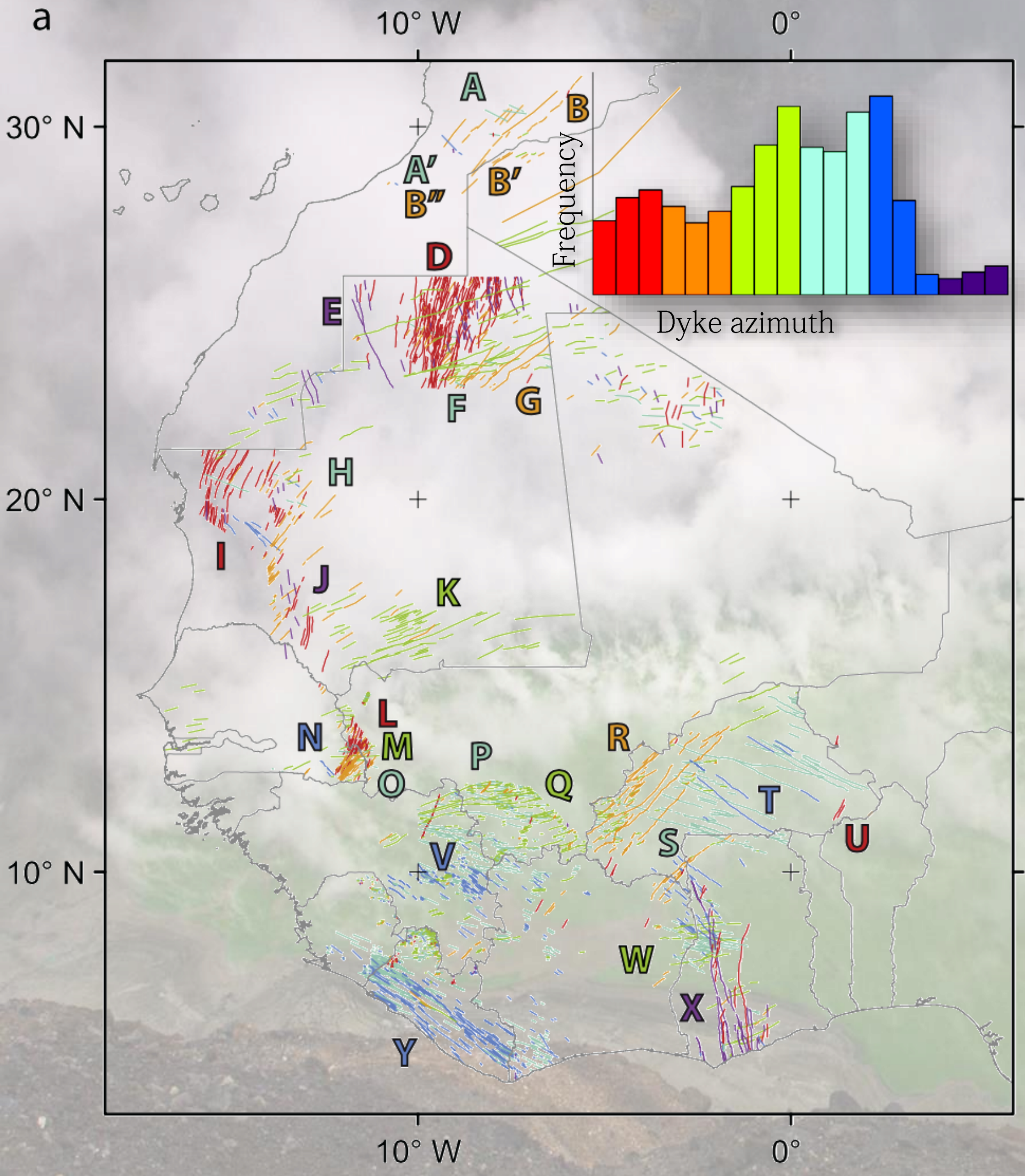
Intense volcanism (Tharsis)

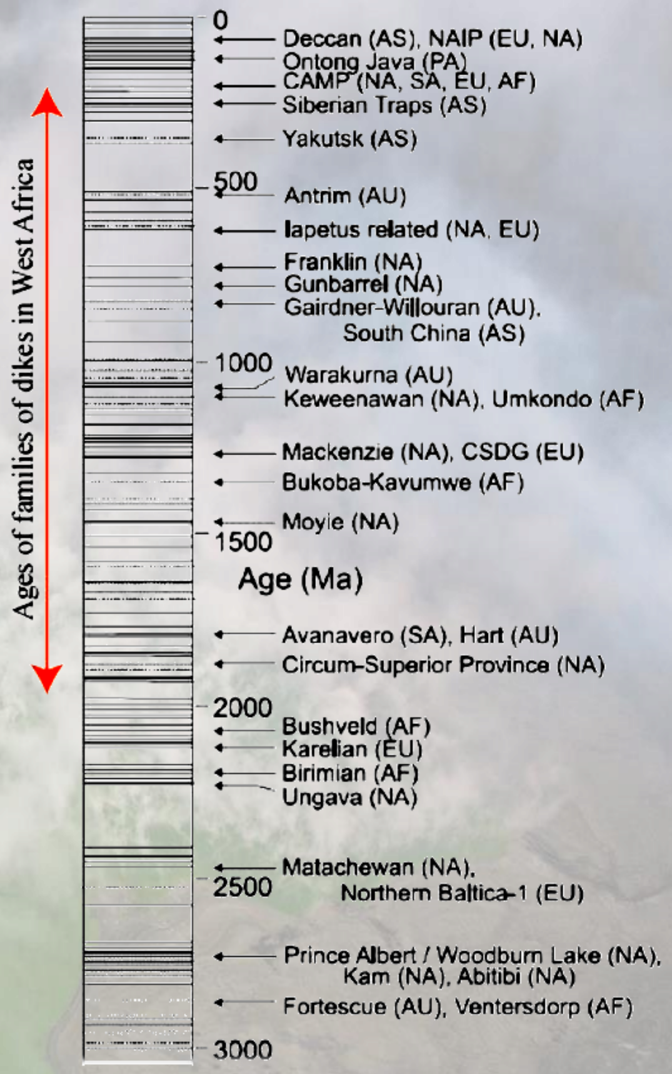
Shut fown of
Magnetic field

Impact craters
Eolian processes
Episodic fluvial activite

2 billions of years of magmatic history

Mantle evolution with time





Jessell et al. 2015

… and because there is plenty of gold

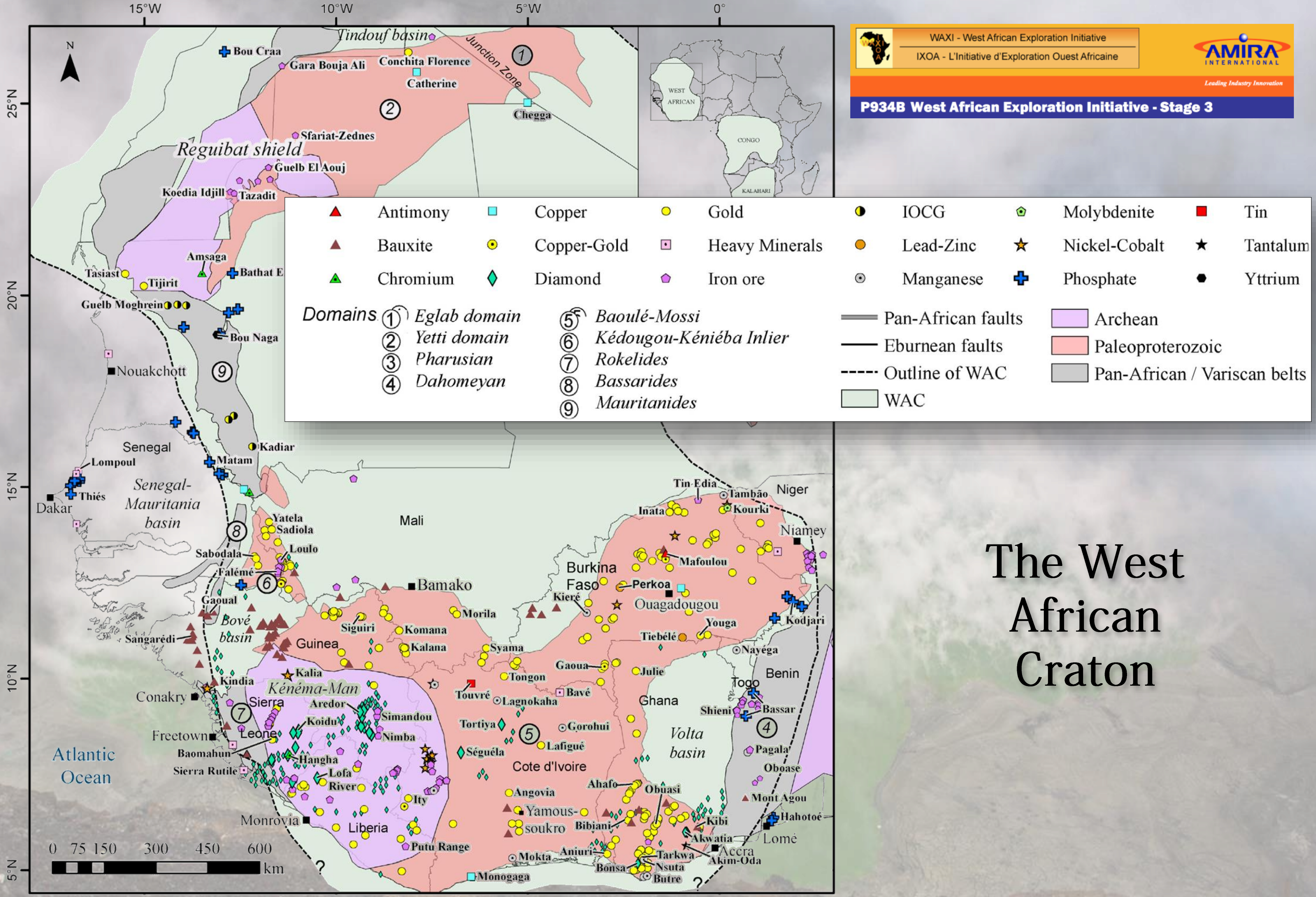
WAXI - West African Exploration Initiative

IXOA - L'Initiative d'Exploration Ouest Africaine

AMIRA INTERNATIONAL

Leading Industry Innovation

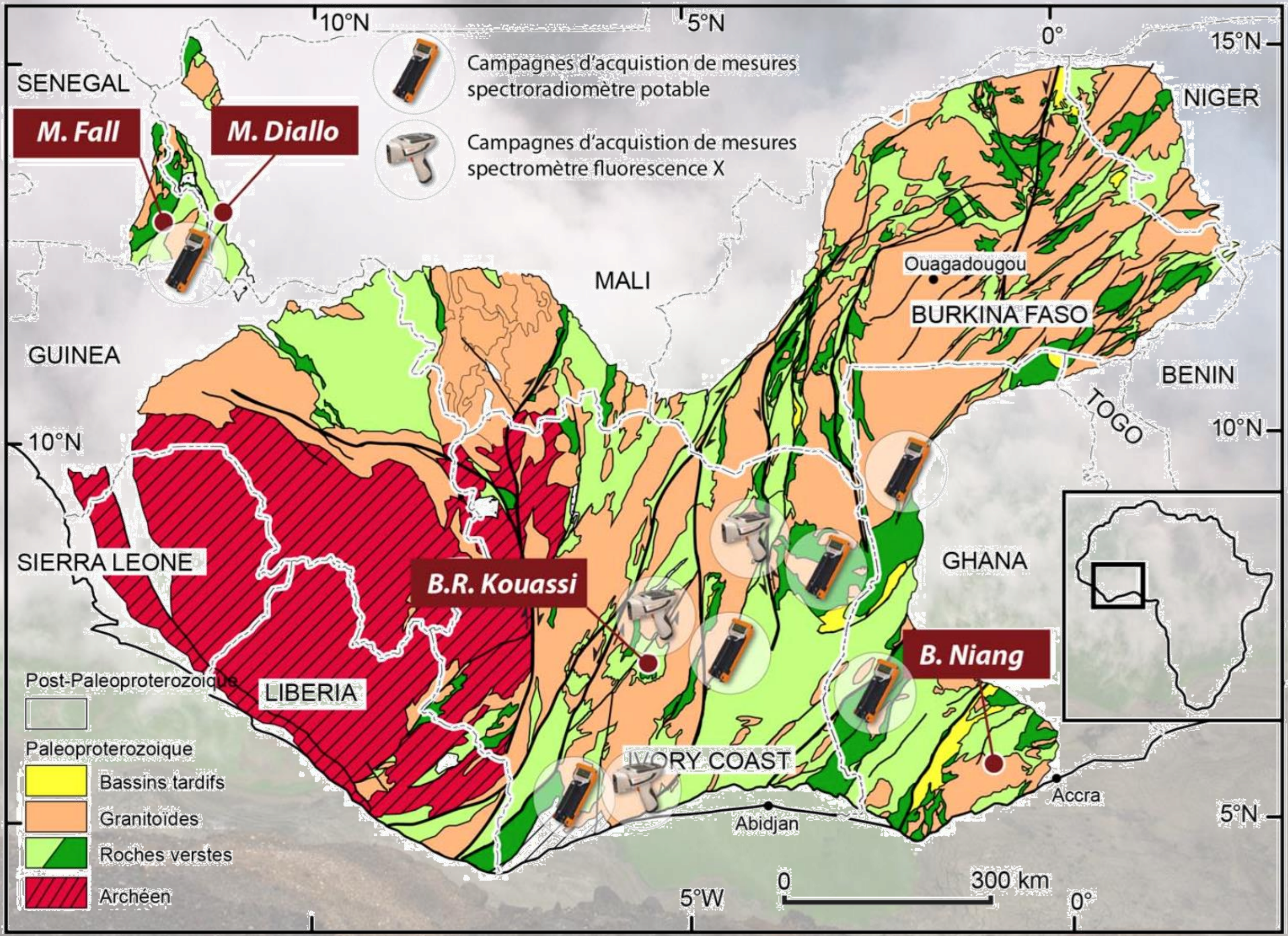
P934B West African Exploration Initiative - Stage 3



The West African Craton

Chemical mapping of metals with portable instruments

REE, Au, K, Th, U

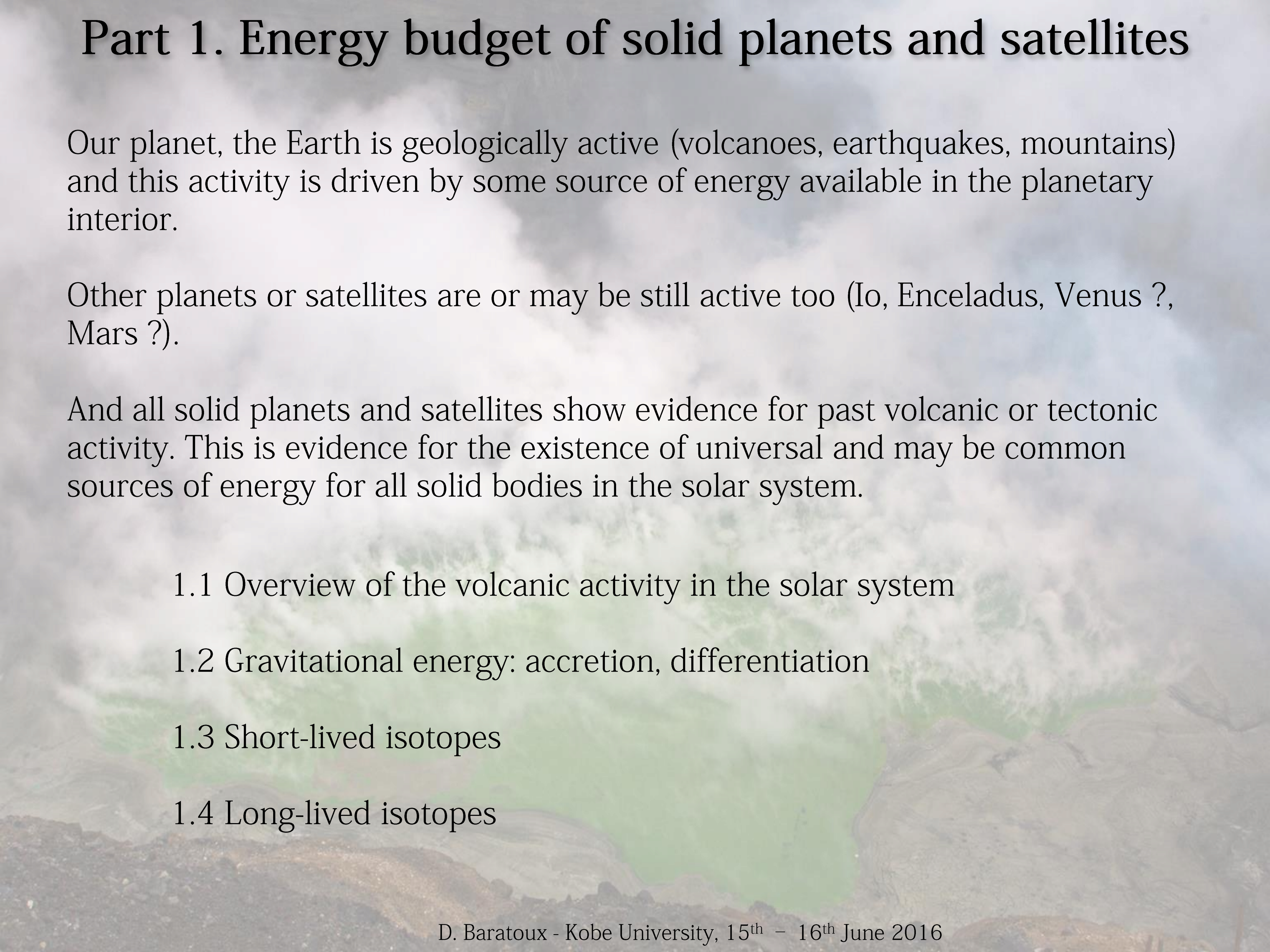


Chemical mapping with portable instruments

Measuring the spatial distribution of K – U – Th
The heat-producing elements (source of energy for the Earth)

Thermal and Dynamic History of Planets

Part 1. Energy budget of solid planets and satellites



Our planet, the Earth is geologically active (volcanoes, earthquakes, mountains) and this activity is driven by some source of energy available in the planetary interior.

Other planets or satellites are or may be still active too (Io, Enceladus, Venus ?, Mars ?).

And all solid planets and satellites show evidence for past volcanic or tectonic activity. This is evidence for the existence of universal and may be common sources of energy for all solid bodies in the solar system.

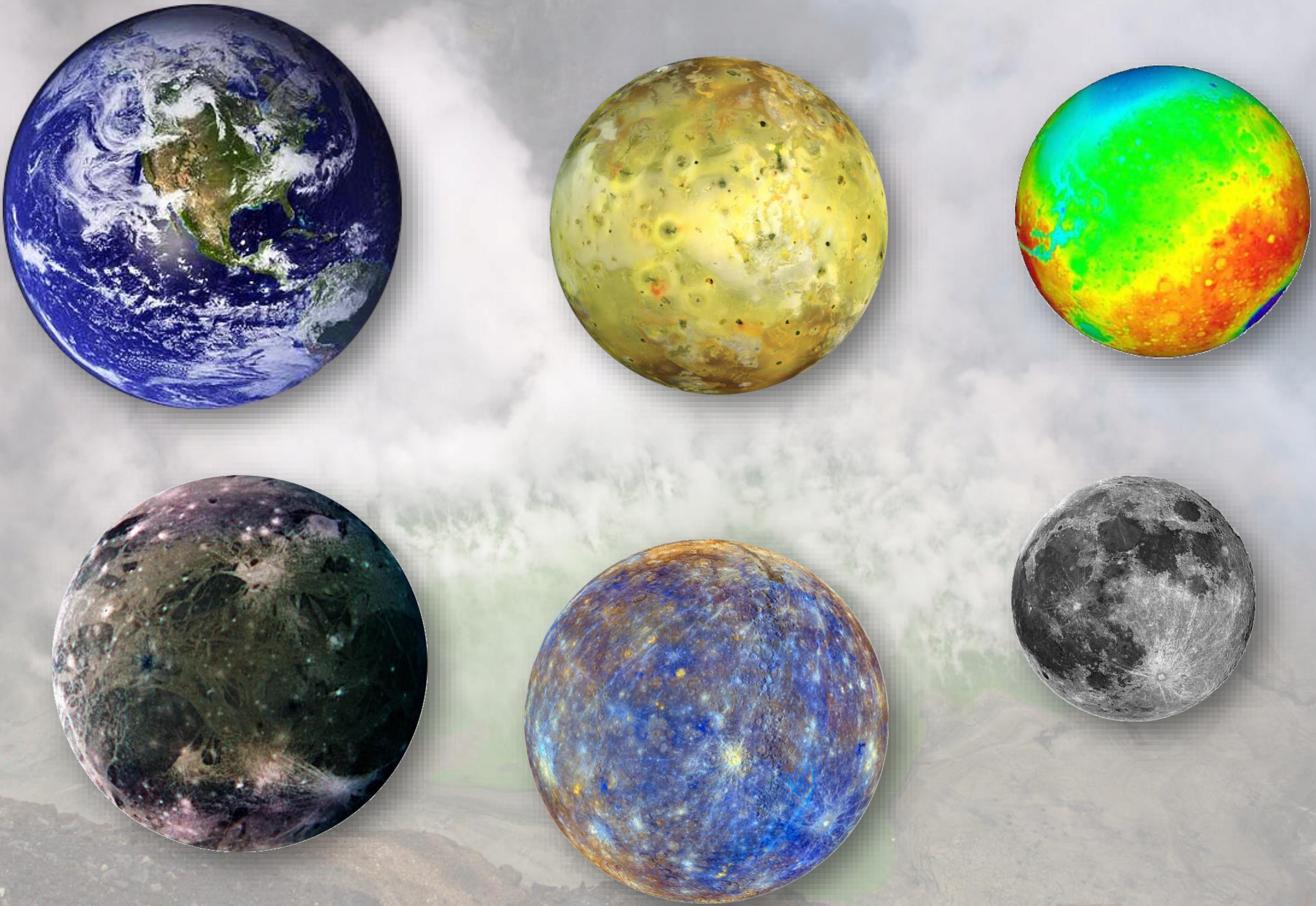
1.1 Overview of the volcanic activity in the solar system

1.2 Gravitational energy: accretion, differentiation

1.3 Short-lived isotopes

1.4 Long-lived isotopes

1.1 Overview of the volcanic activity in the solar system



1.1 Overview of the volcanic activity in the solar system

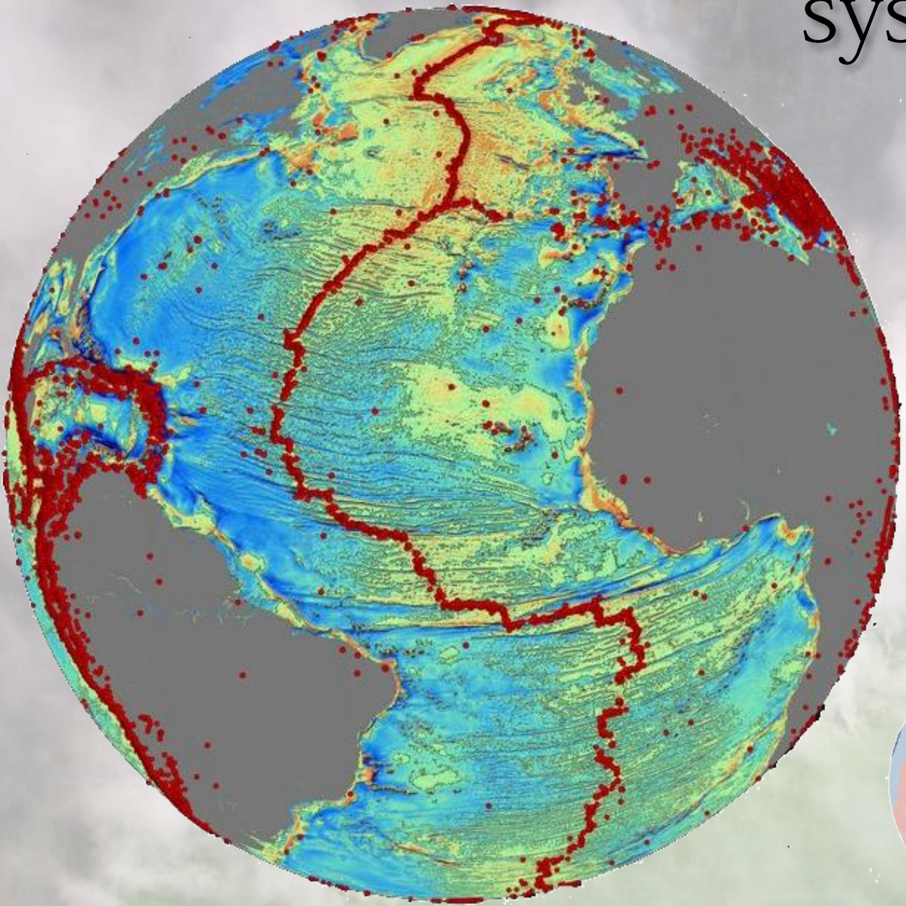
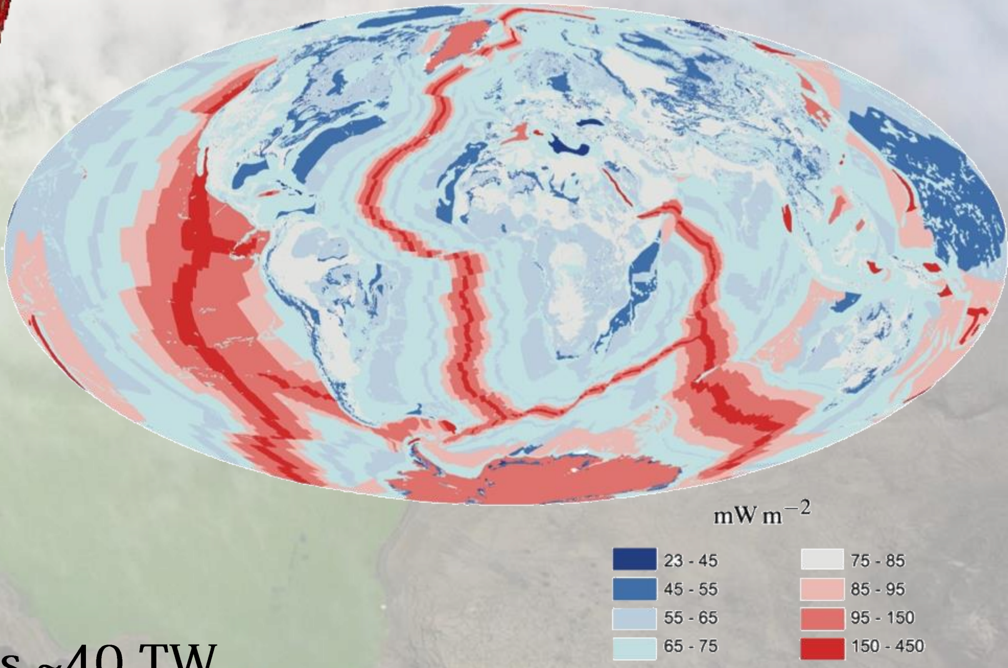


Plate tectonics – may be the most important thing that has happened to the Earth

Volcanic (and tectonic) activity along plate boundaries



Earth heat loss ~40 TW

1.1 Overview of the volcanic activity in the solar system

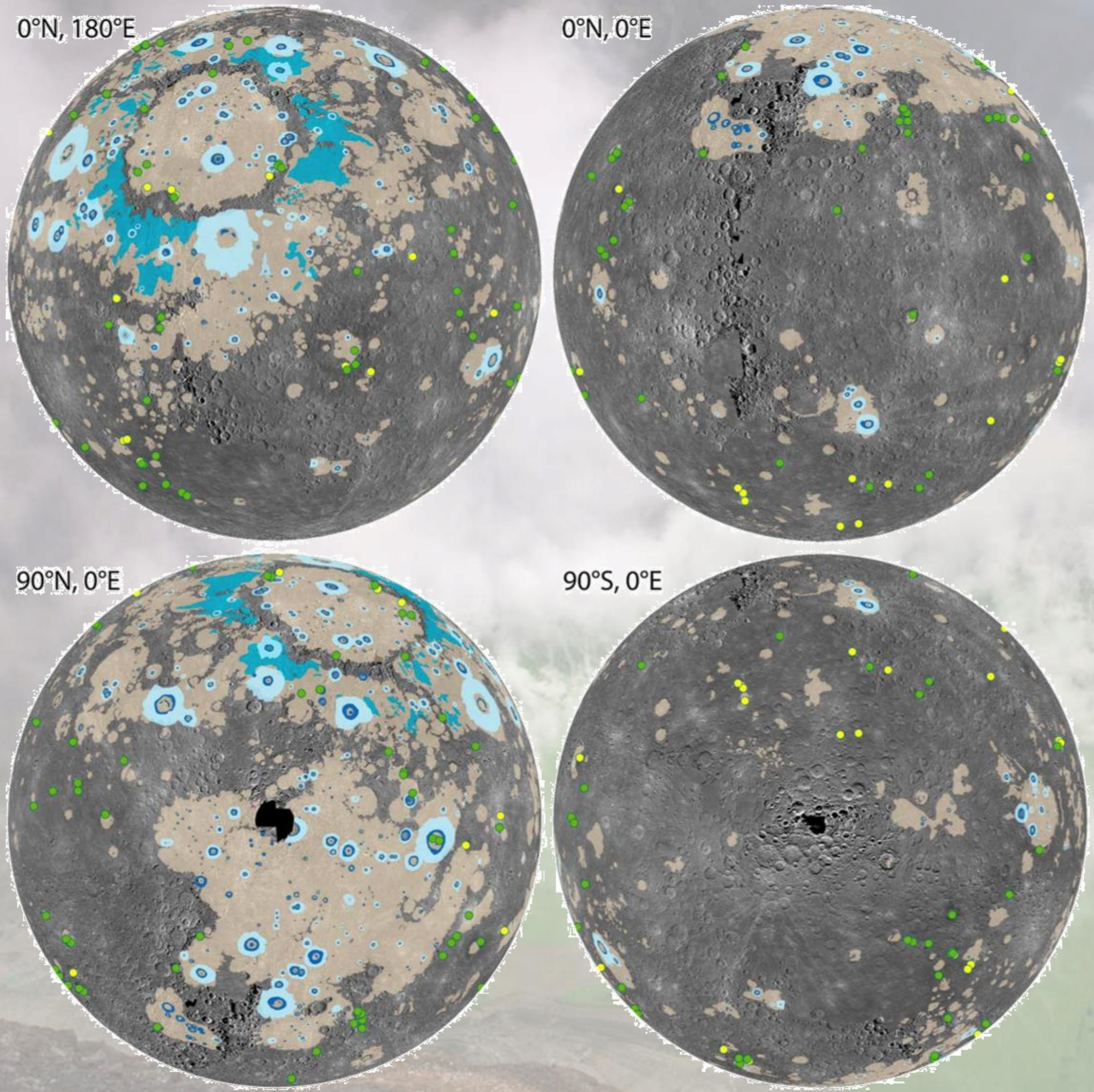
A paradigm for the volcanic history of terrestrial planets

It takes more time for bigger objects to cool than for smaller objects

Large terrestrial planets (Earth, Venus) are still active, whereas smaller terrestrial planets or satellites (Mercury, Mars, Moon) are now extinct

Is it really true ?

Mercury – Plains volcanism



Smooth plains - effusive volcanism

Model ages obtained for widespread plains-forming lava flows range from ~4.1 to 3.55 Ga

- 🟫 Smooth plains
- 🟦 Odin-type plains (Caloris basin)
- 🟦 Crater materials
- ⬜ Ejecta deposits
- 🟢 Volcanic vents
- 🟡 Probable volcanic vents

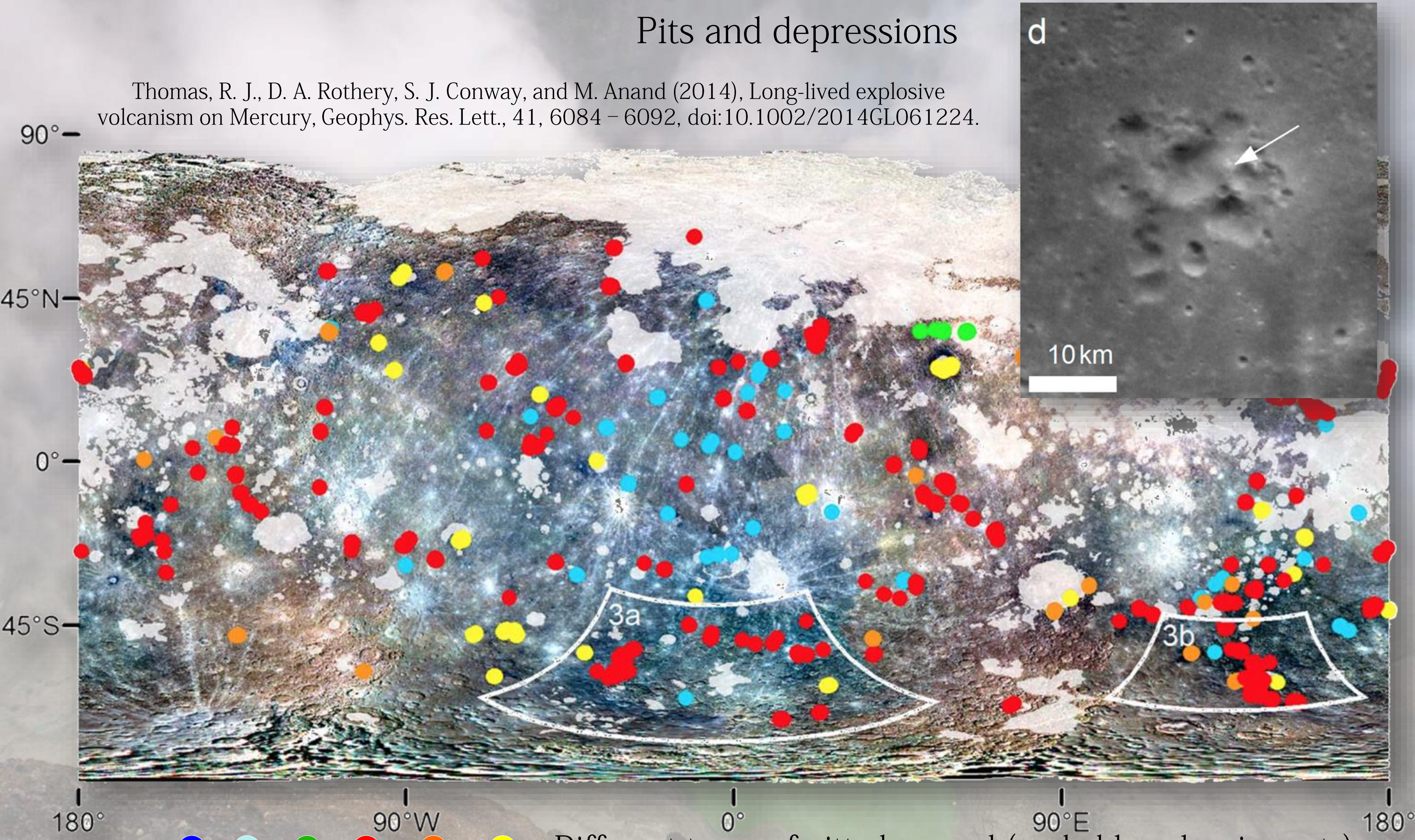
Denevi, B. W., et al. (2013), The distribution and origin of smooth plains on Mercury, J. Geophys. Res. Planets, 118, doi:10.1002/jgre.20075.

Mercury

More recent explosive volcanism ?

Pits and depressions

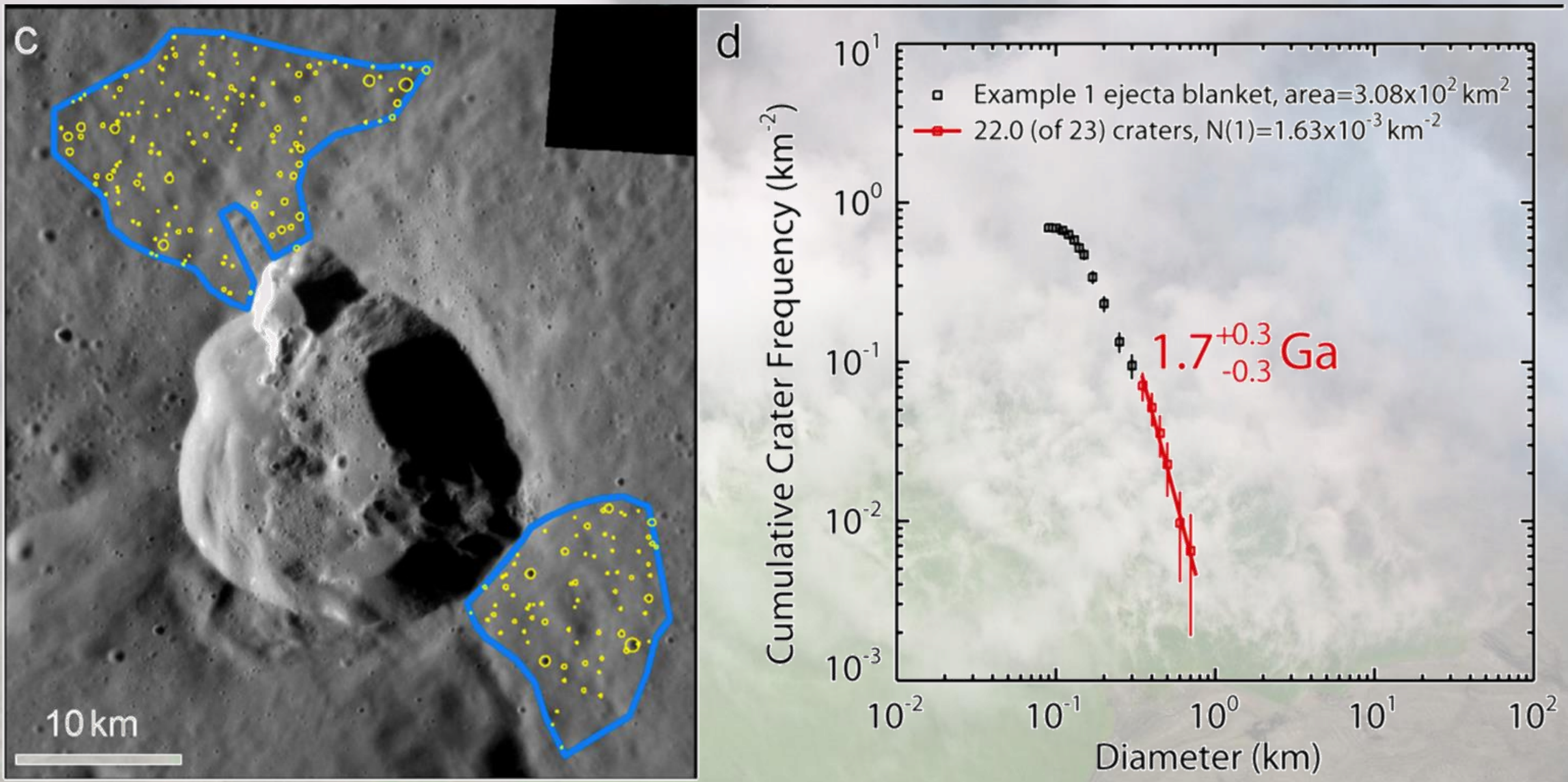
Thomas, R. J., D. A. Rothery, S. J. Conway, and M. Anand (2014), Long-lived explosive volcanism on Mercury, Geophys. Res. Lett., 41, 6084 – 6092, doi:10.1002/2014GL061224.



● ● ● ● ● ● Different types of pitted ground (probable volcanic vents)

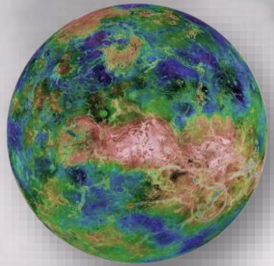
Mercury

More recent explosive volcanism ?

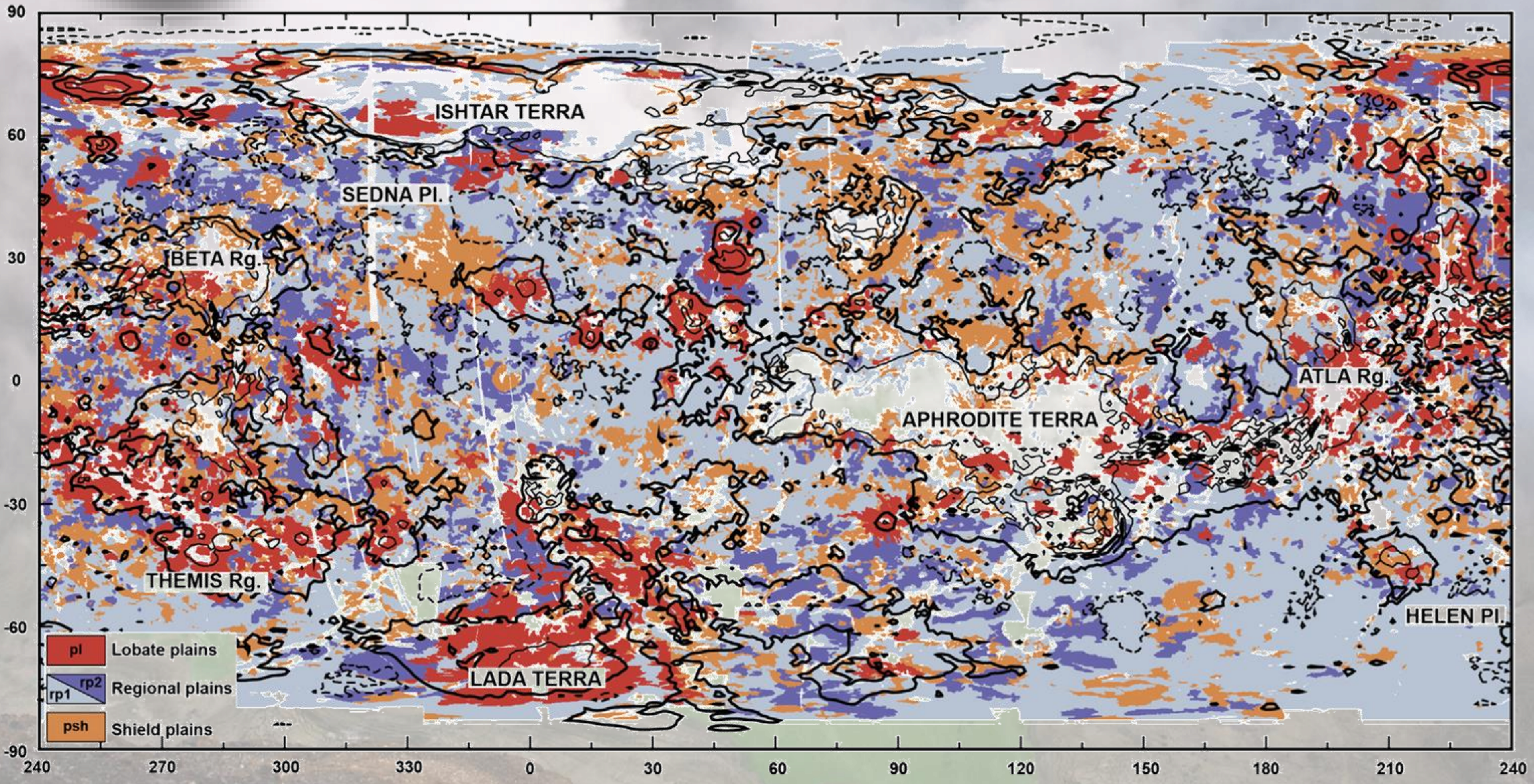


Thomas, R. J., D. A. Rothery, S. J. Conway, and M. Anand (2014), Long-lived explosive volcanism on Mercury, Geophys. Res. Lett., 41, 6084 – 6092, doi:10.1002/2014GL061224.

Venus



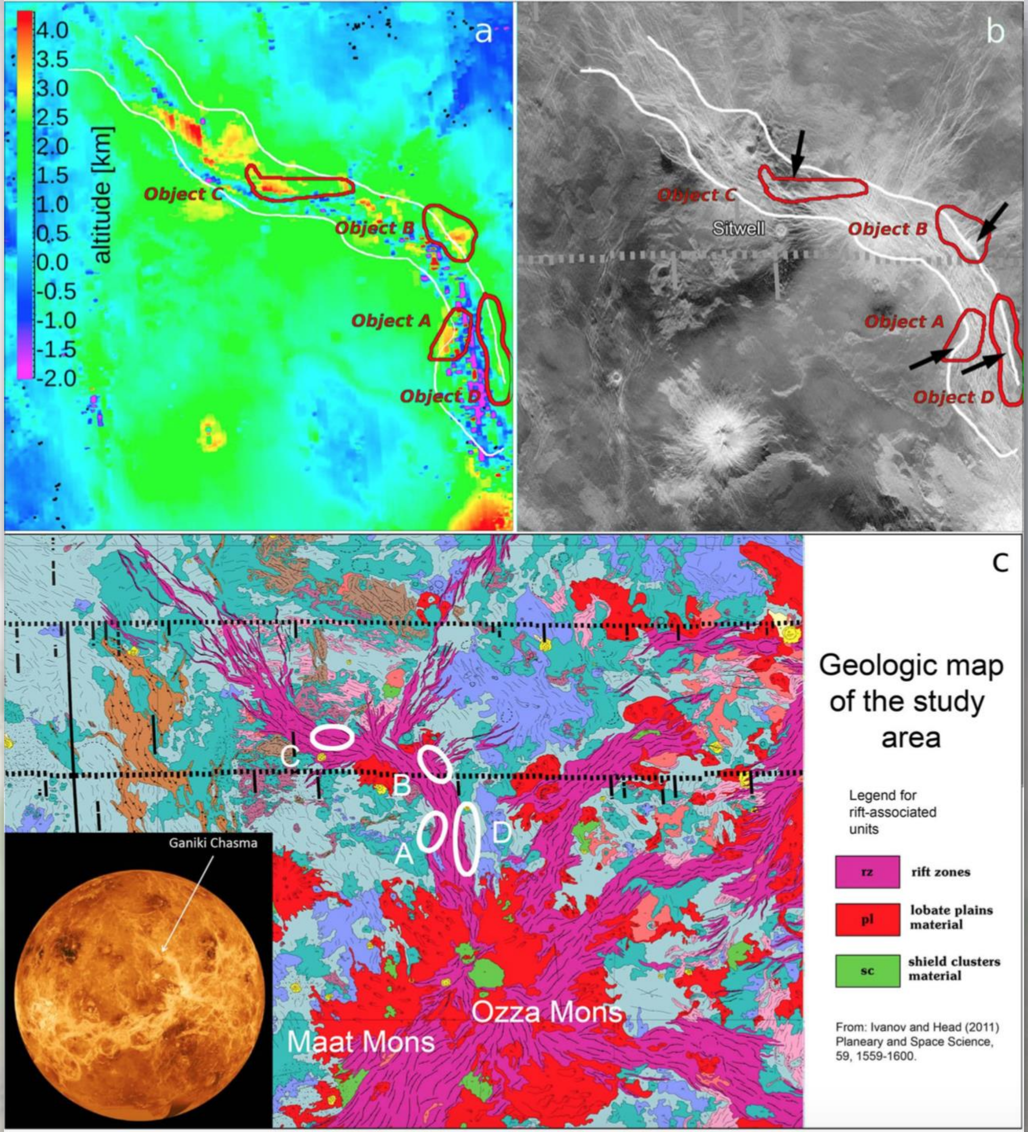
Venus is known to have been volcanically resurfaced in the last third of solar system history and to have undergone a significant decrease in volcanic activity a few hundred million years ago



M.A. Ivanov, J. W. Head (2013) The history of volcanism on Venus – Planetary and Space Science, 84, 66-92

Venus

Ganiki Chasma*

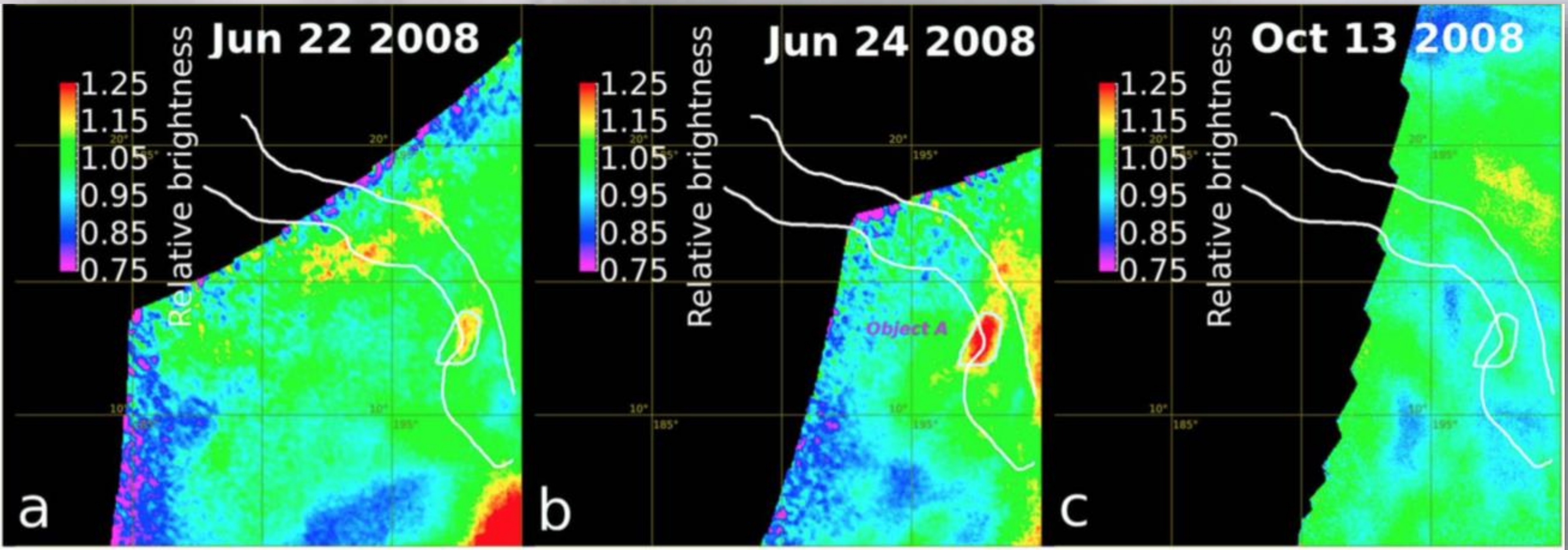


From: Ivanov and Head (2011) Planeary and Space Science, 59, 1559-1600.

*Chasma: large valley, canyon

Shalygin, E. V., W. J. Markiewicz, A. T. Basilevsky, D. V. Titov, N. I. Ignatiev, and J. W. Head (2015), Active volcanism on Venus in the Ganiki Chasma rift zone, *Geophys. Res. Lett.*, *42*, 4762 – 4769, doi:10.1002/2015GL064088.

Venus



Venus Monitoring Camera (VMC) in UV-VIS-NEAR was able to sound Venus surface through the atmosphere transparency window

Transient bright phenomena were observed in the Ganiki Chasma zone
They are consistent with hypothesis of lava lakes on the surface.

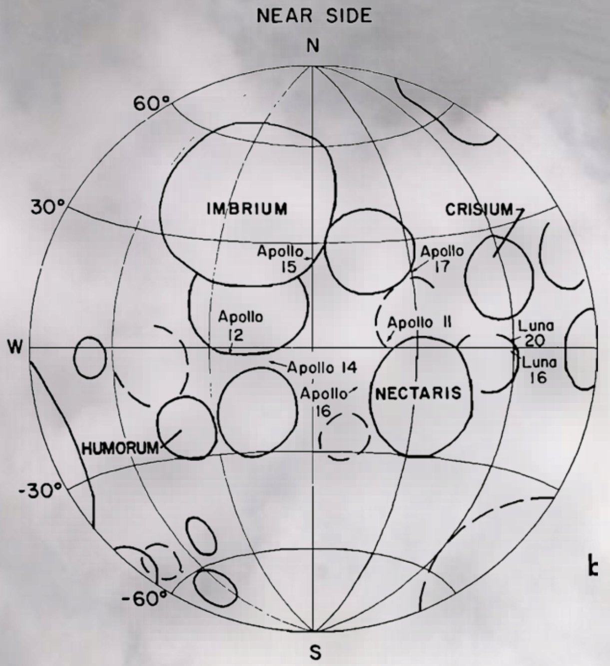
Other pieces of evidence (emissivity anomalies) for very recent volcanism (2.5 millions – 250 000 years)
Smrekar et al. 2010 Science.

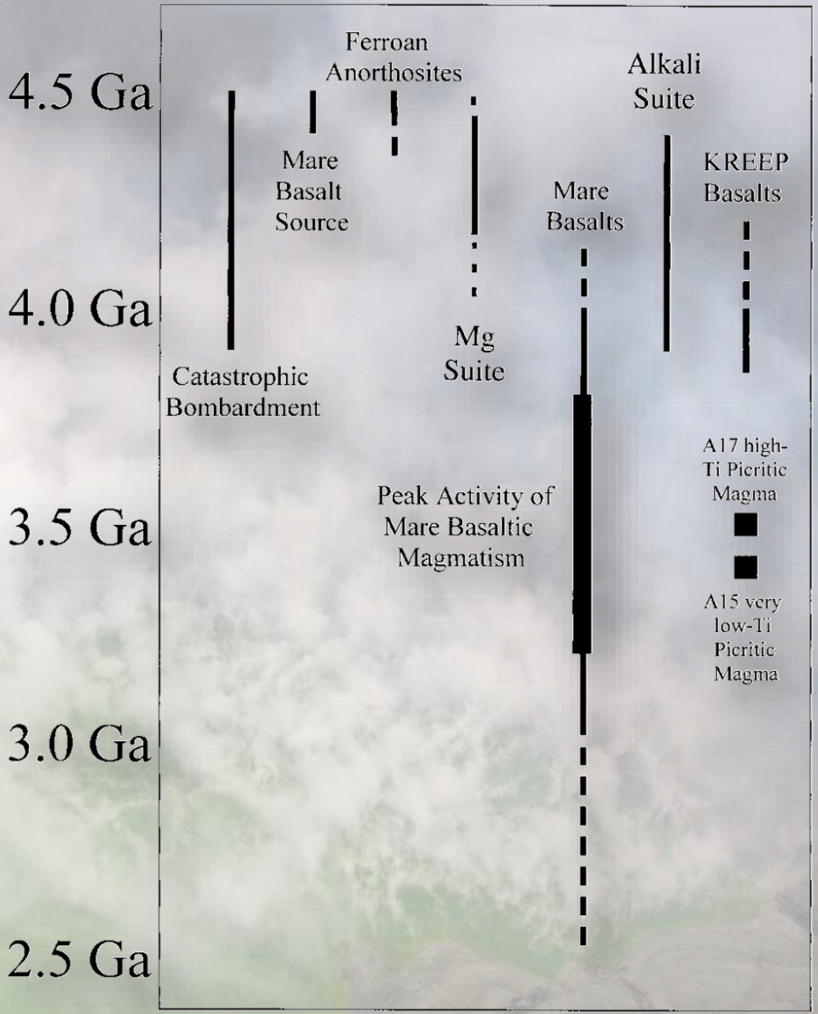
Shalygin, E. V., W. J. Markiewicz, A. T. Basilevsky, D. V. Titov, N. I. Ignatiev, and J. W. Head (2015), Active volcanism on Venus in the Ganiki Chasma rift zone, *Geophys. Res. Lett.*, *42*, 4762 – 4769, doi:10.1002/2015GL064088.

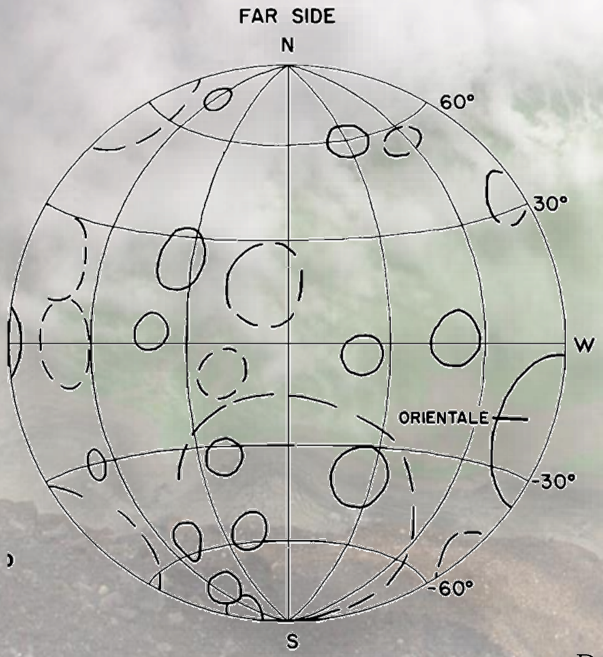
The Moon

Head, J.W 1976 – Reviews of Geophysics and Space Physics, 14, 265 - 301

The Moon







Shear, C.K., Papike, J.J, 1999. Magmatic evolution of the Moon. American Mineralogist. 84, 1469-1494.

Head, J.W 1976 – Reviews of Geophysics and Space Physics, 14, 265 - 301

The Moon

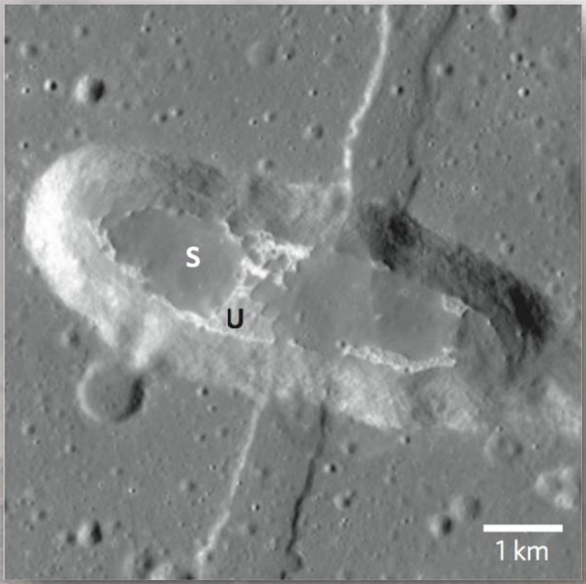
nature geoscience

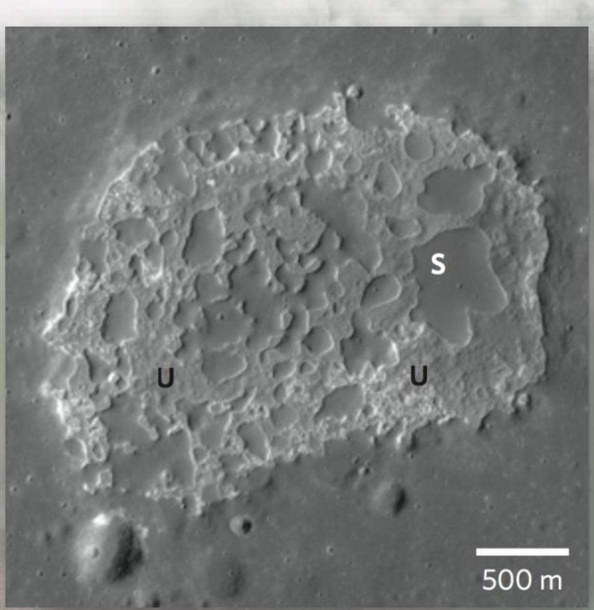
LETTERS

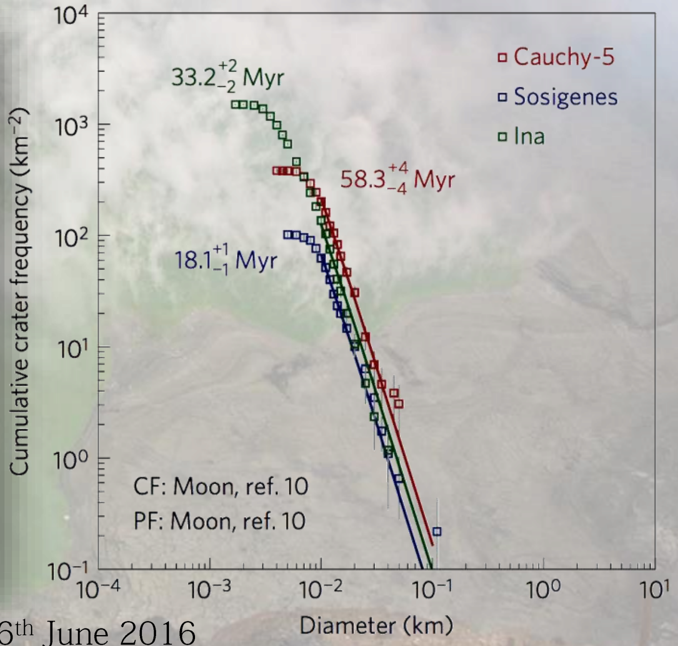
PUBLISHED ONLINE: 12 OCTOBER 2014 | DOI: 10.1038/NGEO2252

Evidence for basaltic volcanism on the Moon within the past 100 million years

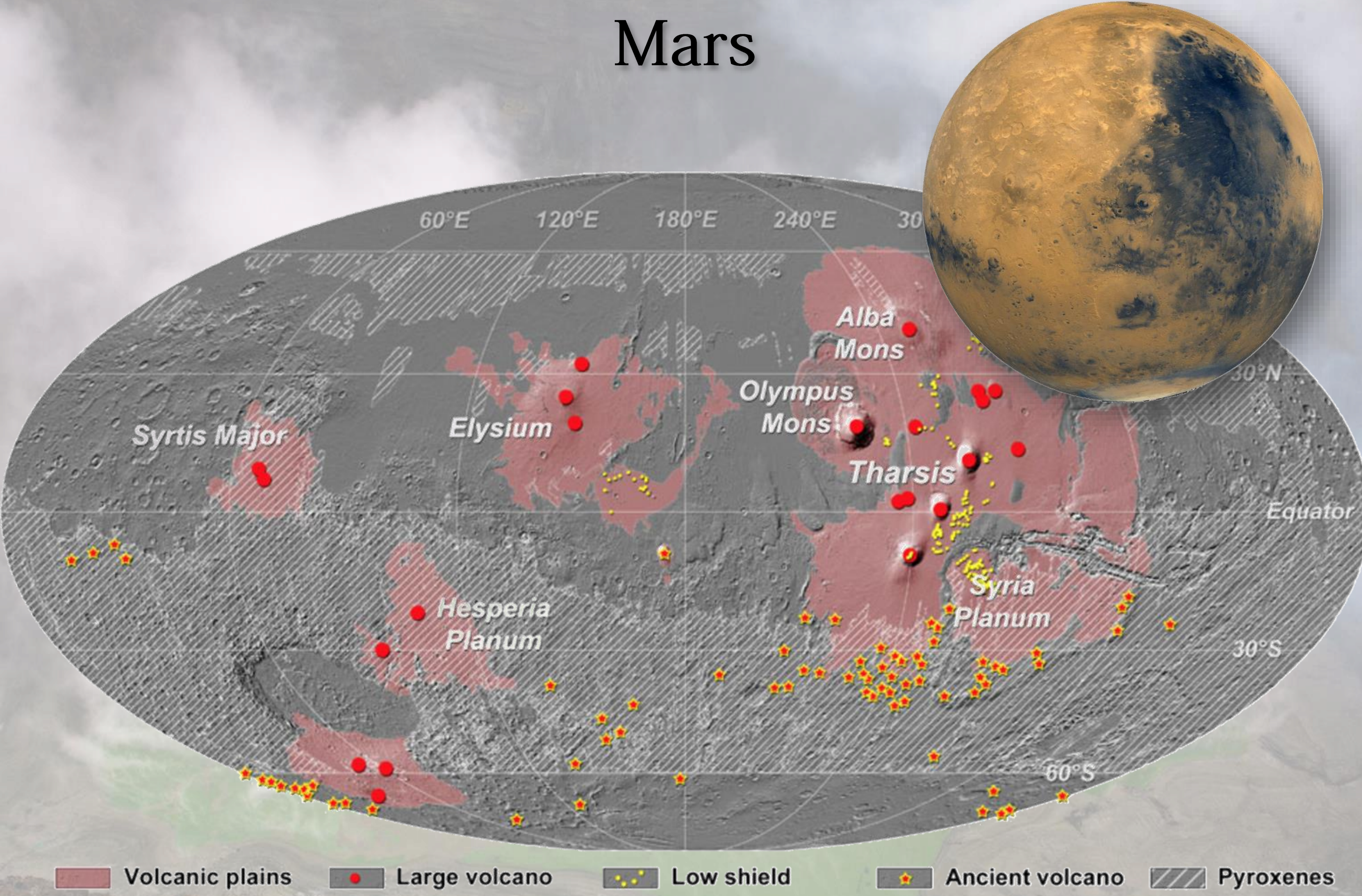
S. E. Braden[1]*, J. D. Stopar[1], M. S. Robinson[1], S. J. Lawrence[1], C. H. van der Bogert[2] and H. Hiesinger[2]





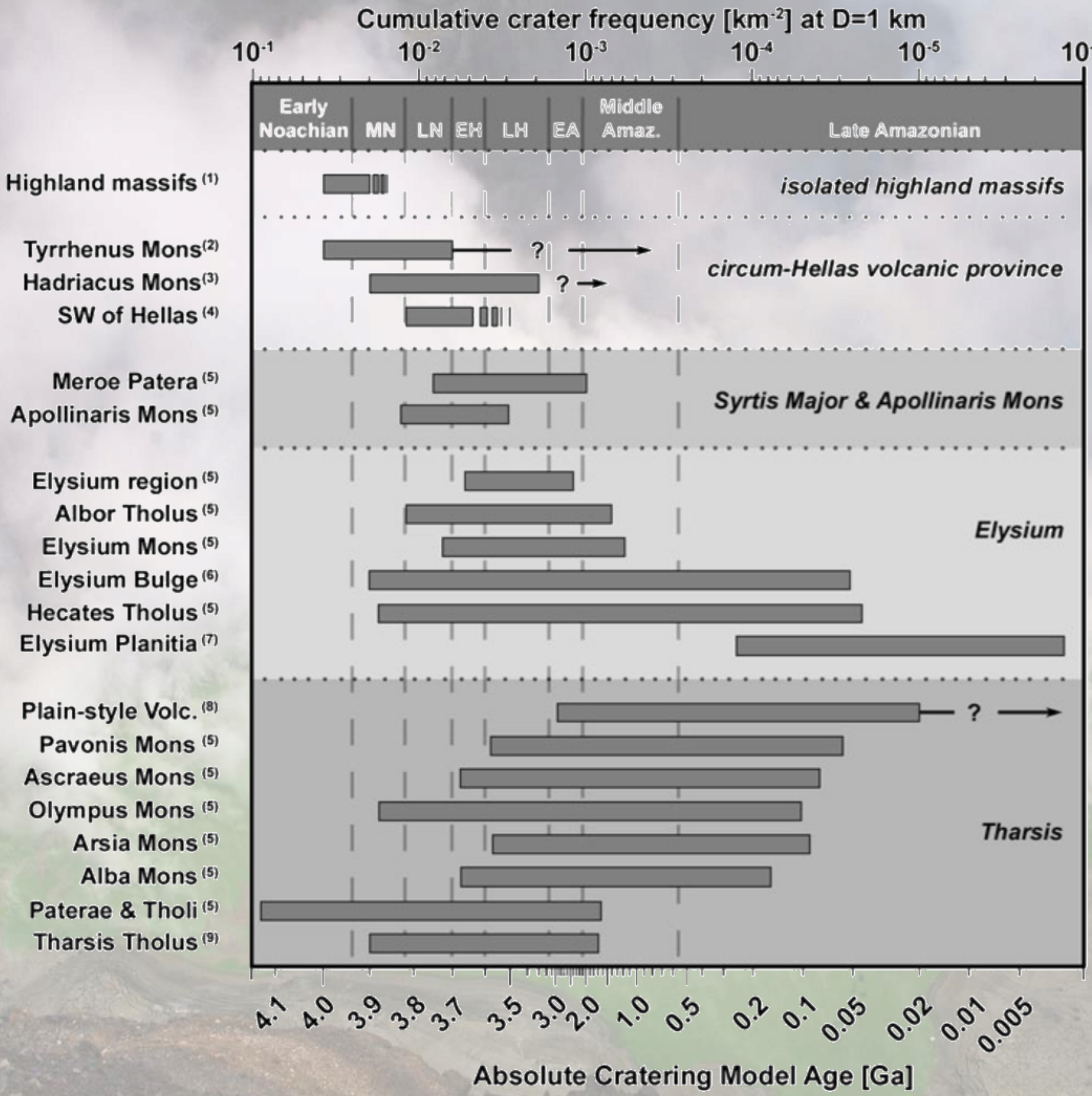


Mars



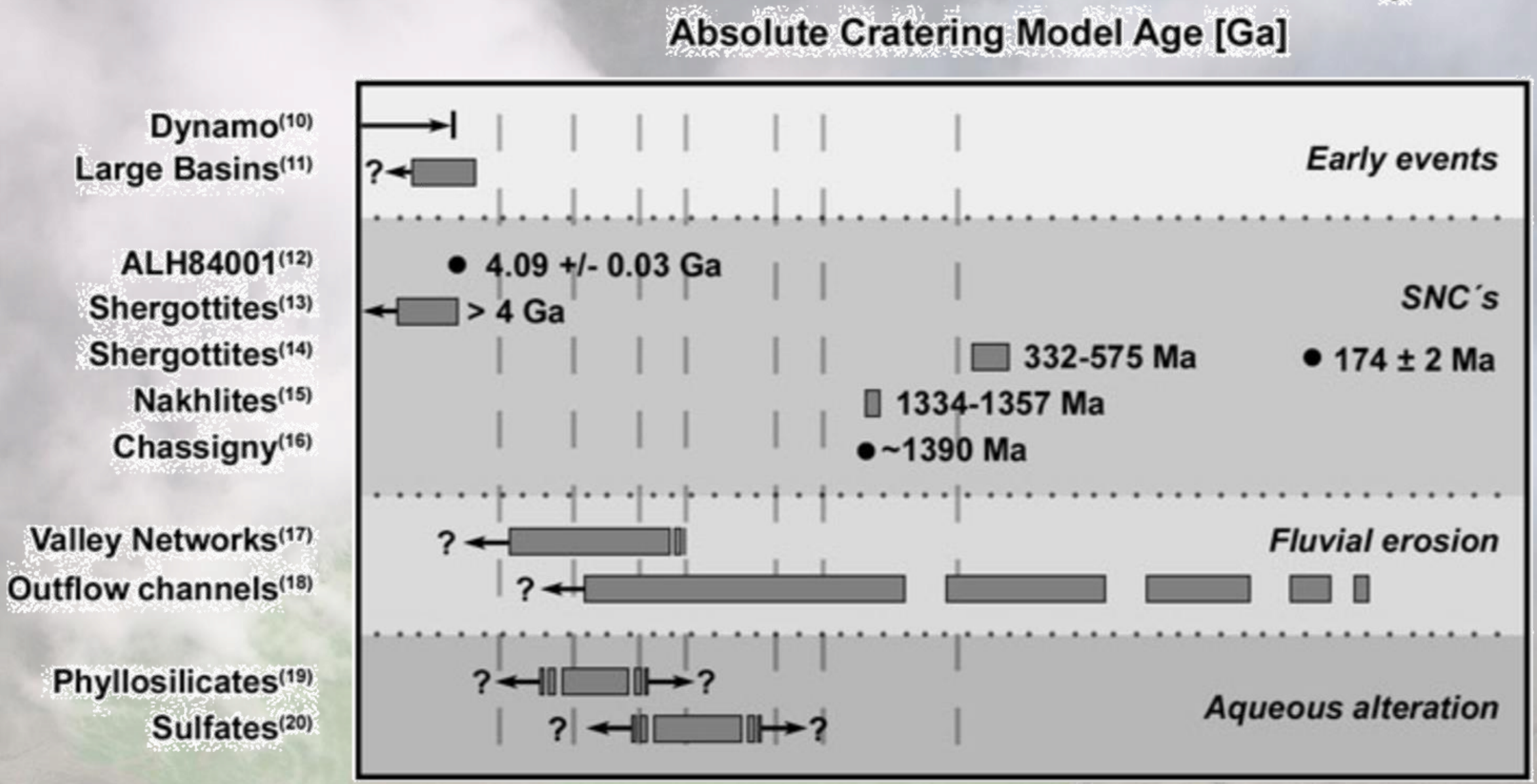
Grott et al. 2013 – Space Science Reviews, 174, 49-111.

Mars



Grott et al. 2013 –
Space Science Reviews,
174, 49-111.

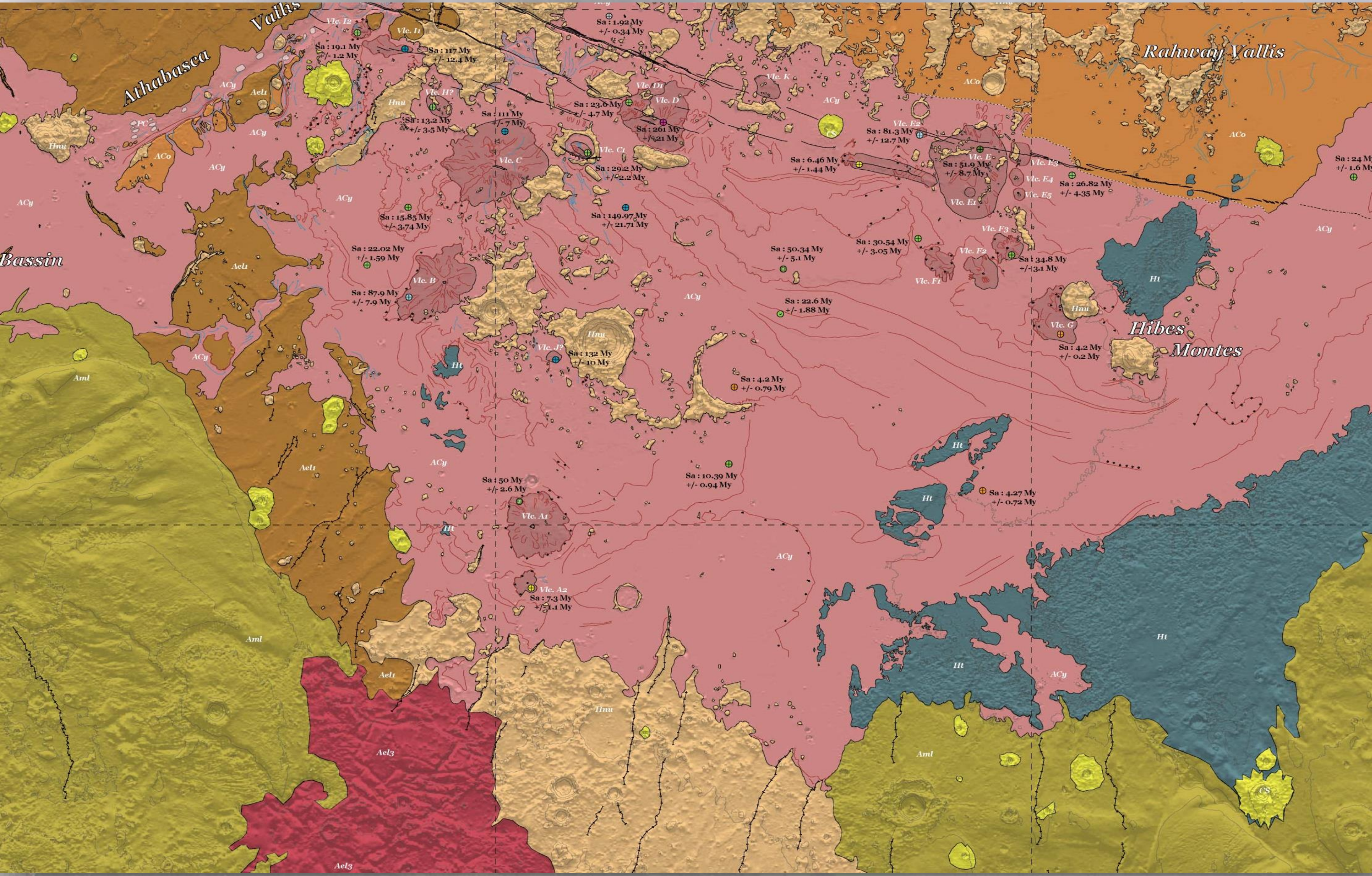
Mars



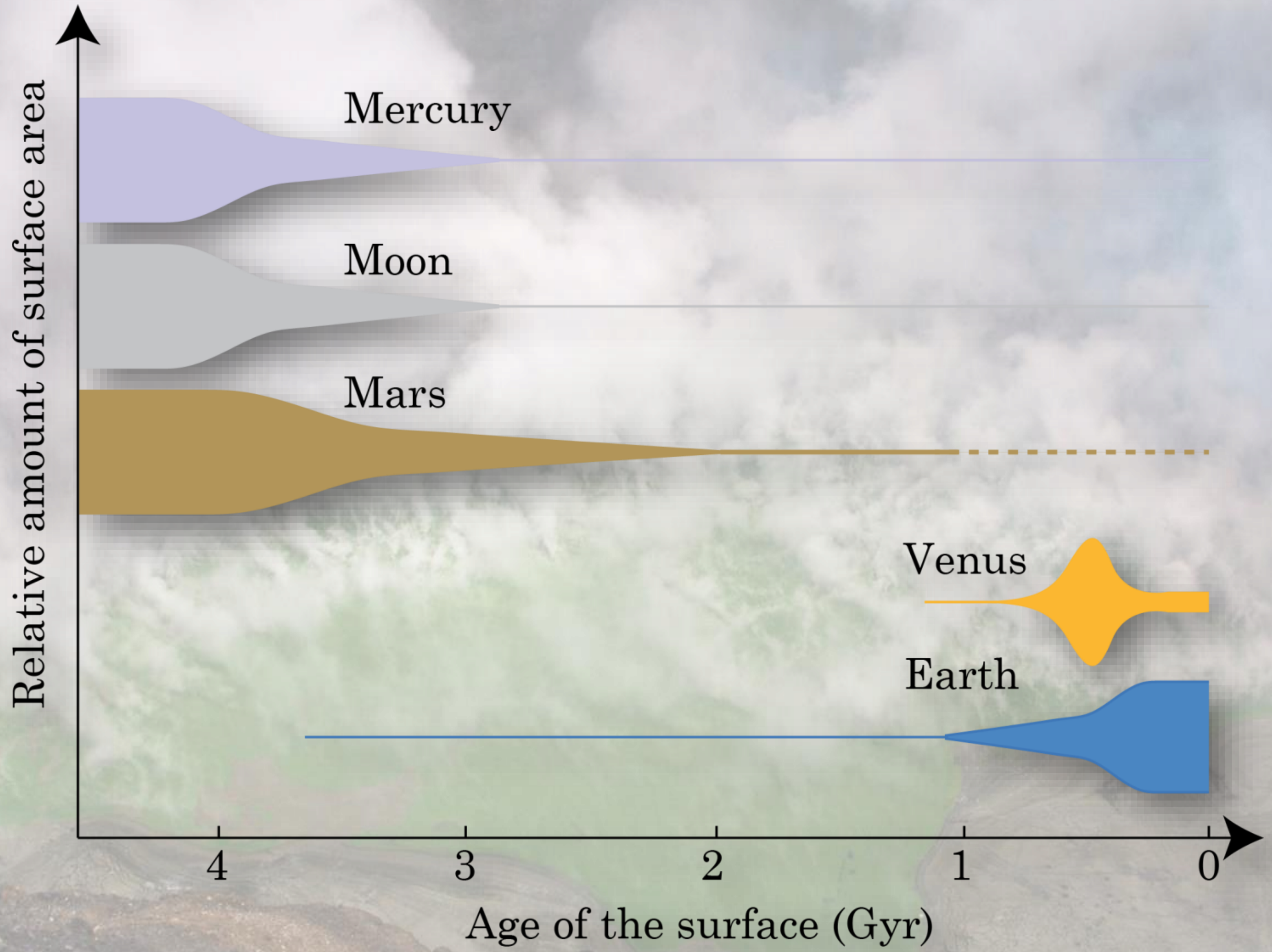
Grott et al. 2013 – Space Science Reviews, 174, 49-111.

Vaucher et al. 2009 - Icarus

Mars

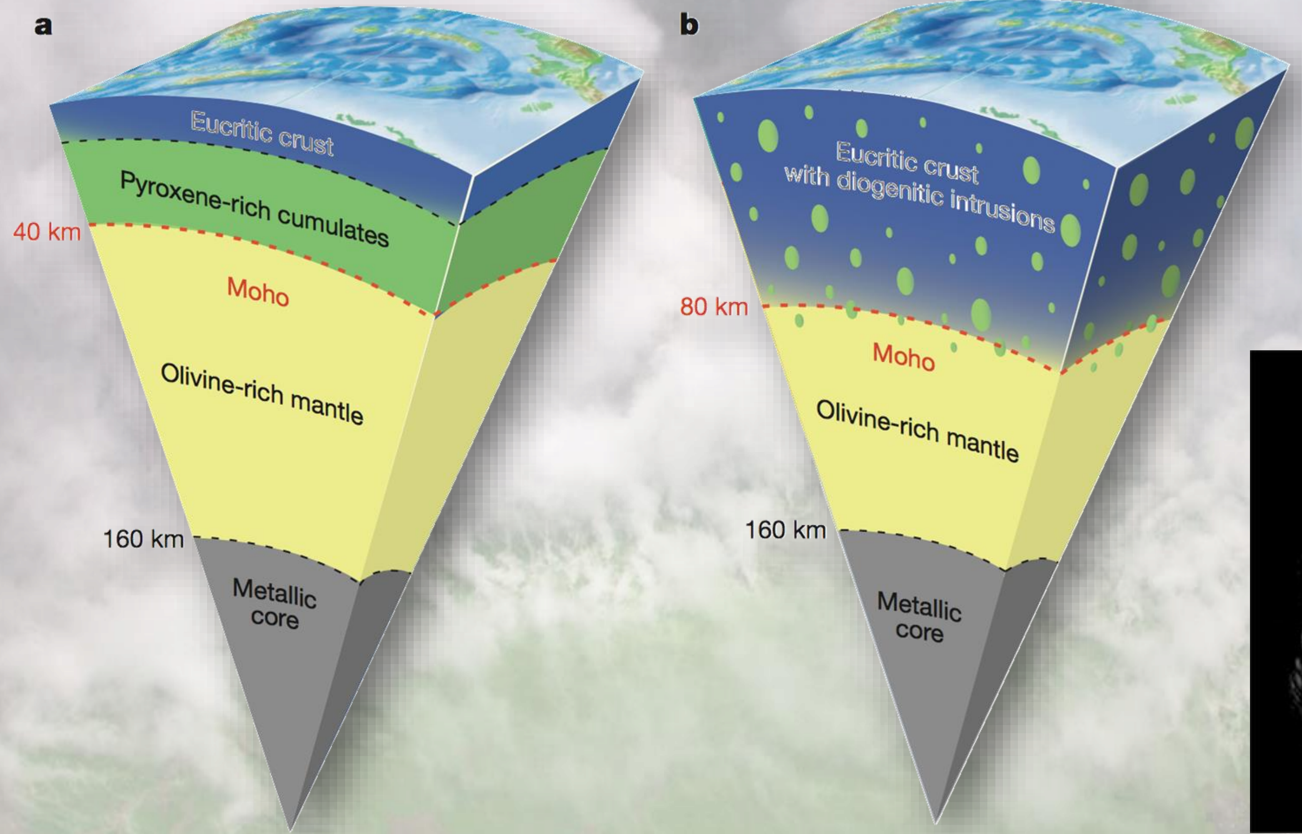


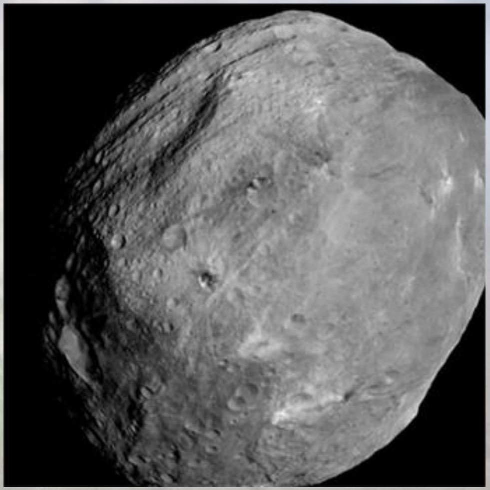
Recent volcanic activity of terrestrial planets – change of paradigm ?



Vesta

The ~ 500 km asteroid has a > 80 km thick crust





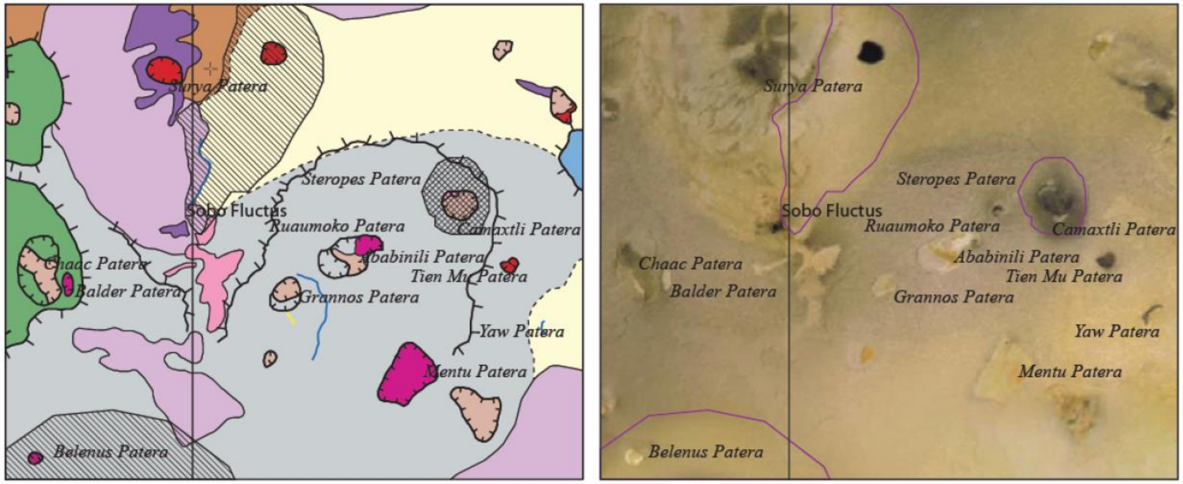
Howardite – eucrite – diogenite (HED) meteorites origin- ating from Vesta (basaltic and ultramafic rocks)

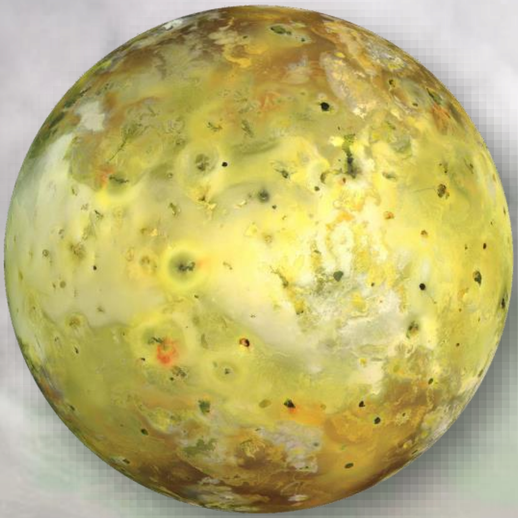
Clenet al. 2014 – Nature

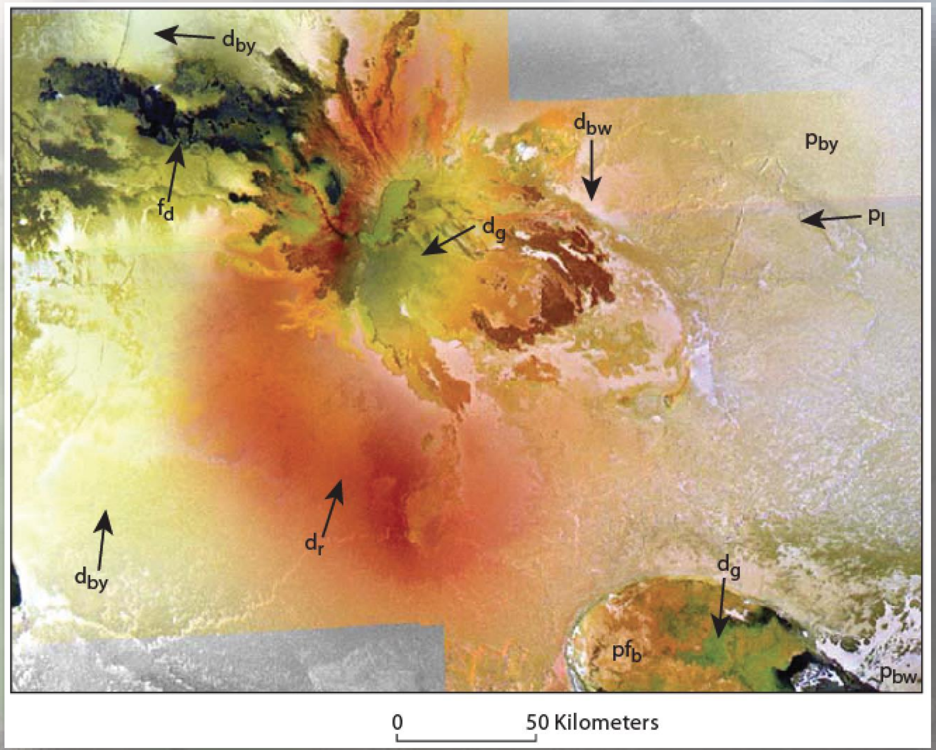
1.1 Overview of the volcanic activity in the solar system

Io

A portion of the global geologic map covering the Chaac-Camaxtli Patera region f the antijovian hemisphere + color mosaic.



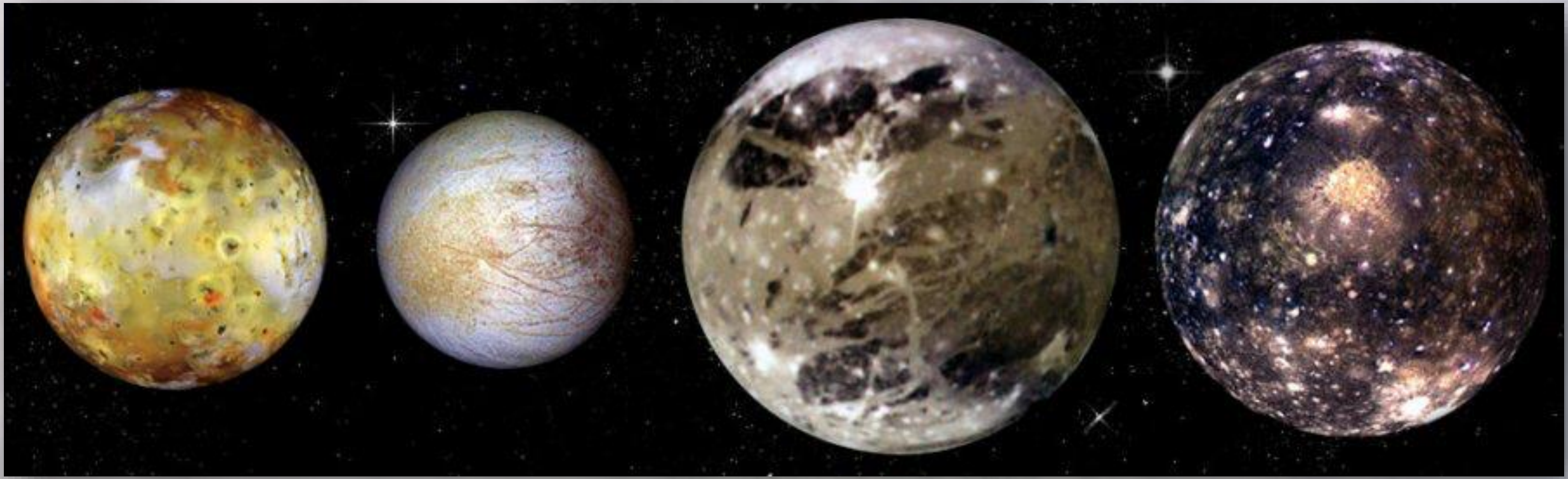


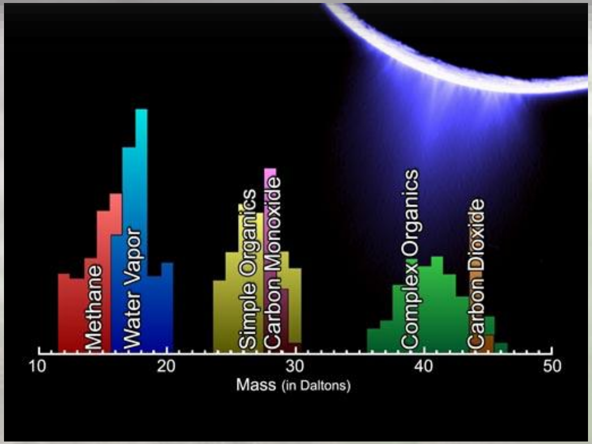


Culann Patera (center) and northern Tohil Patera.
Galileo SSI-GRN-VIS color mosaic (200 m/pixel)

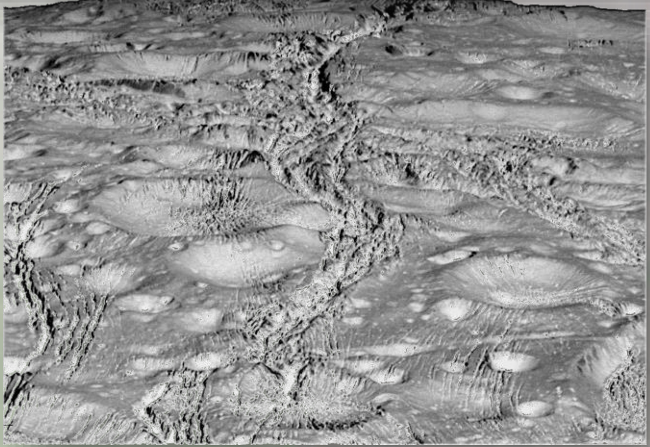
1.1 Overview of volcanism in the solar system

Satellites of the giant planets





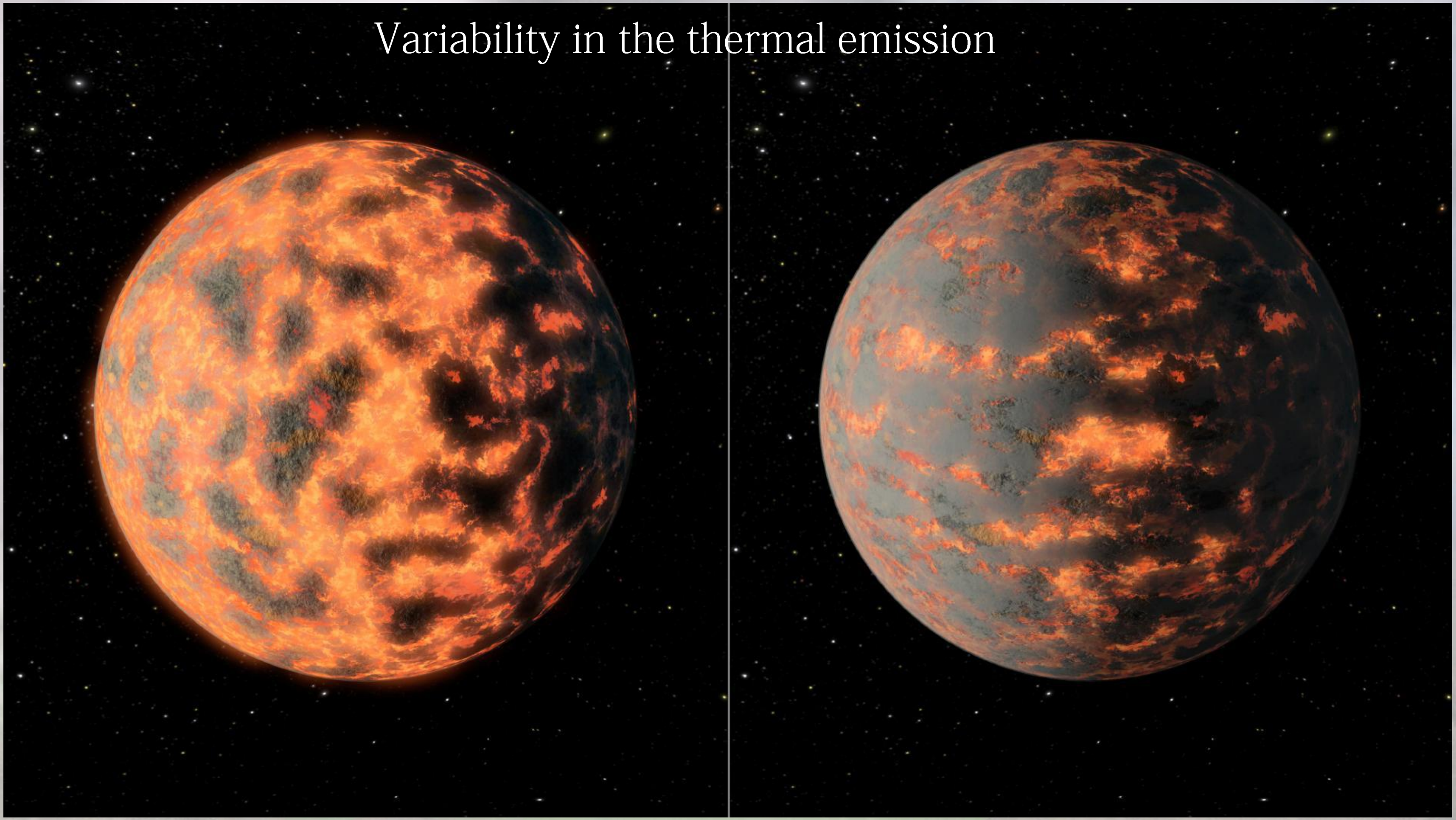
Enceladus: vapor plumes, fresh surface ices and resurfacing



Enceladus: vapor plumes, fresh surface ices and resurfacing

1.1 Overview of volcanism in the solar system

… and even beyond

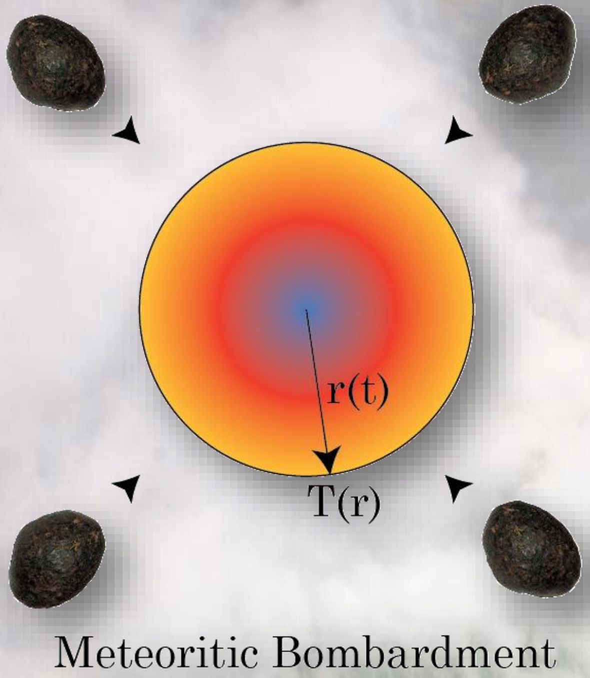


55 Cancri e, just 40 light-years from Earth, might be volcanically active
Demory et al. 2016 MNRAS, doi: 10.1093/mnras/stv2239

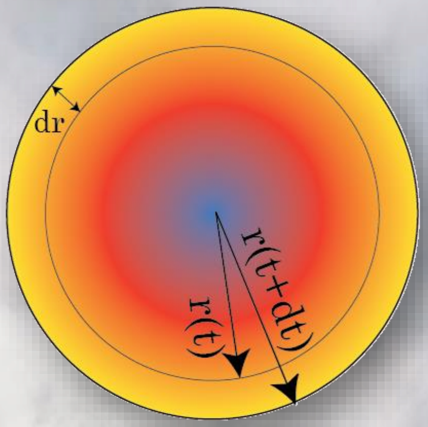
Where does come from the heat of all solid planets ?

1.2 Gravitational energy (accretion, differentiation)

1.2 Gravitational energy - accretion



Protoplanet at time t

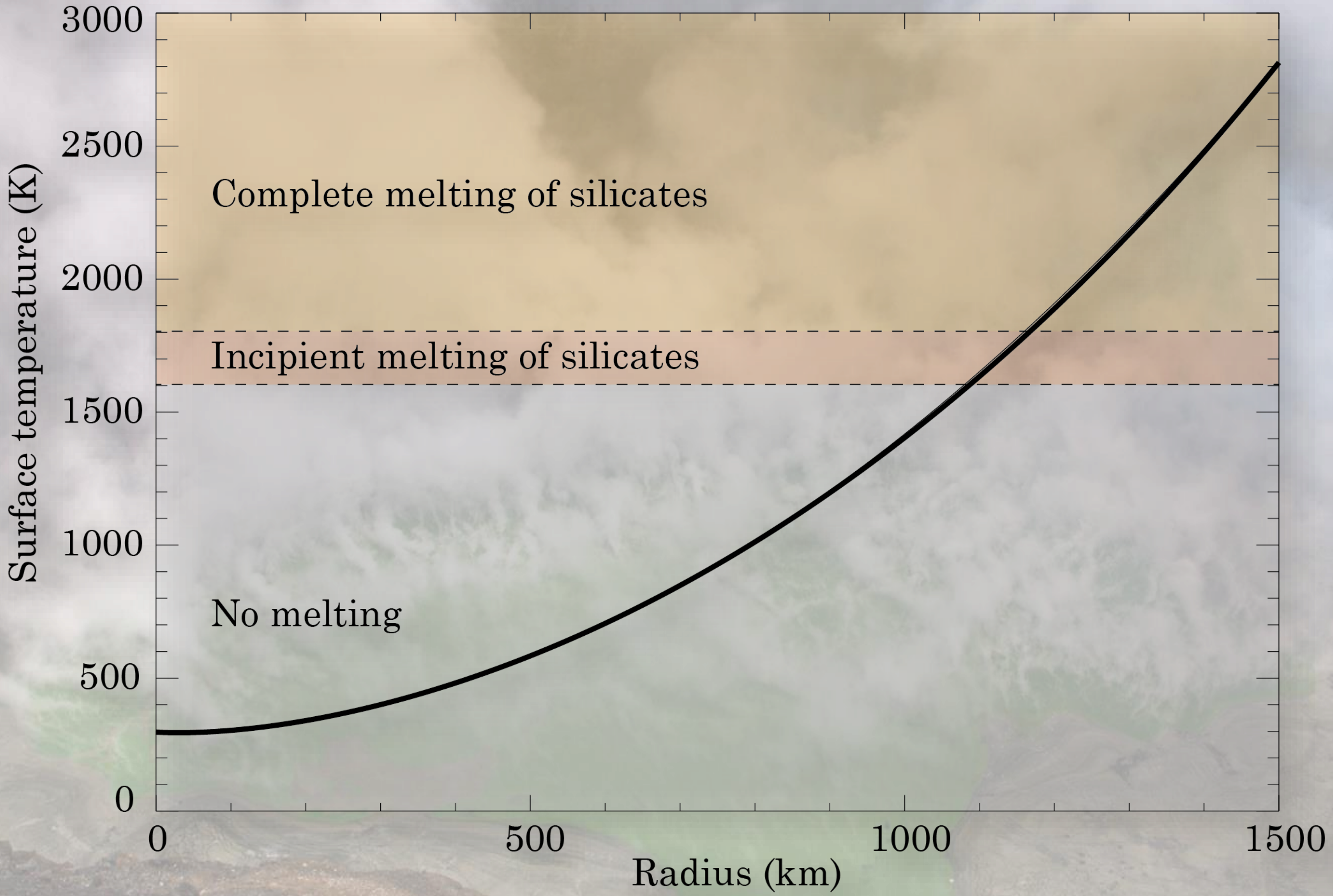


Protoplanet at time t + dt

$$4\pi R^2 dR C_p \rho (T - T_n) = \frac{4}{3}\pi R^3 \rho * \frac{4\pi R^2 dR G}{R}\rho$$

$$\rightarrow \quad T_s = \frac{4}{3}\frac{\pi R^2 G \rho^2}{C_p} + T_n$$

1.2 Gravitational energy - accretion



Heat from the decay of naturally radioactive isotopes or elements

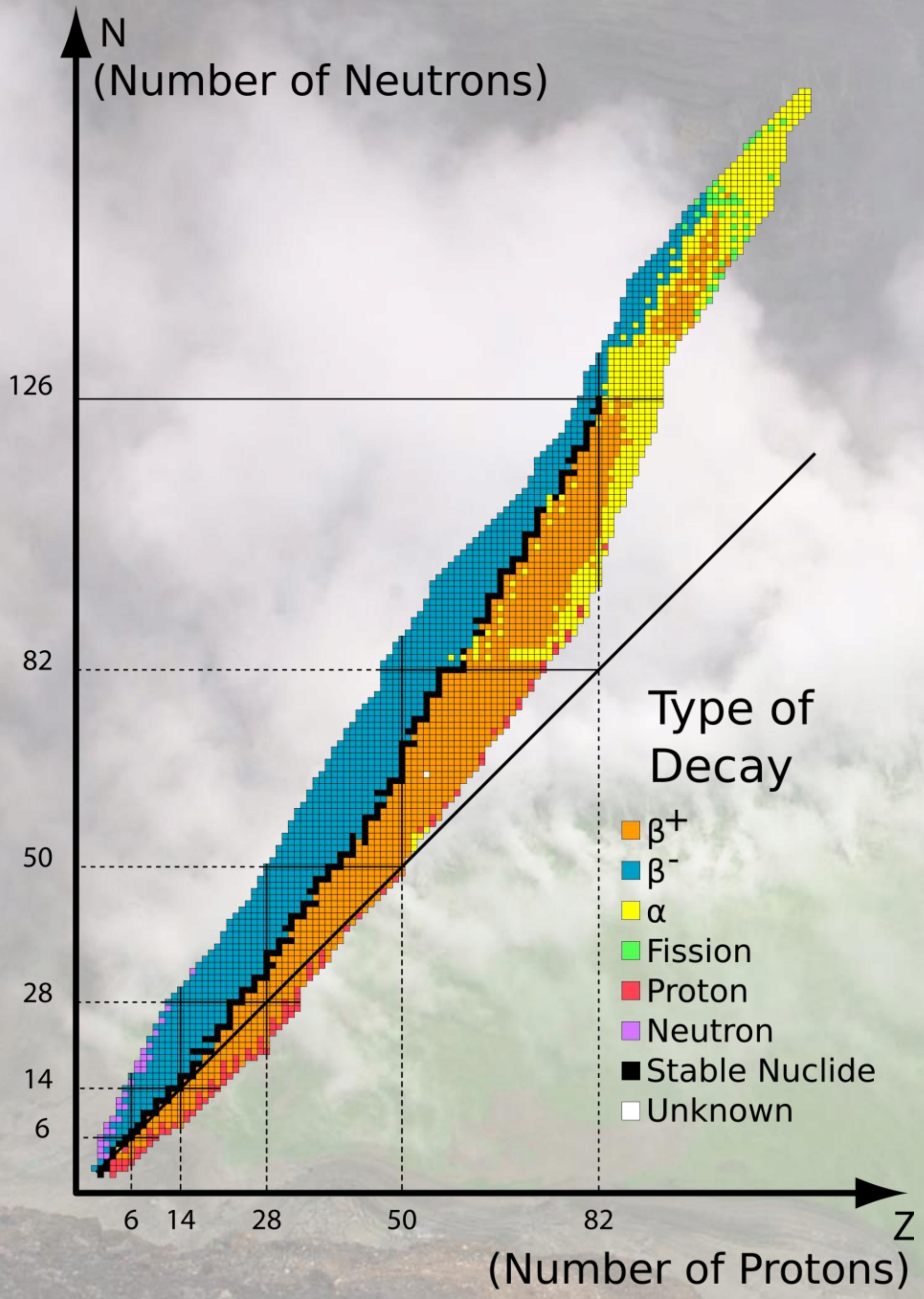
Which elements can heat solid (metal-silicate) planets ?

Elements concentrated in rocky planets
Elements present in mantle (silicates) and core (metal)
Refractory and moderately volatile elements

Concentration
Elements with sufficient concentration elements with unstable isotope(s) of sufficient concentration

Half-time
short – large of amount of energy released in a short amount of time
long – the energy is released progressively and can feed continuously the engine for planetary evolution.

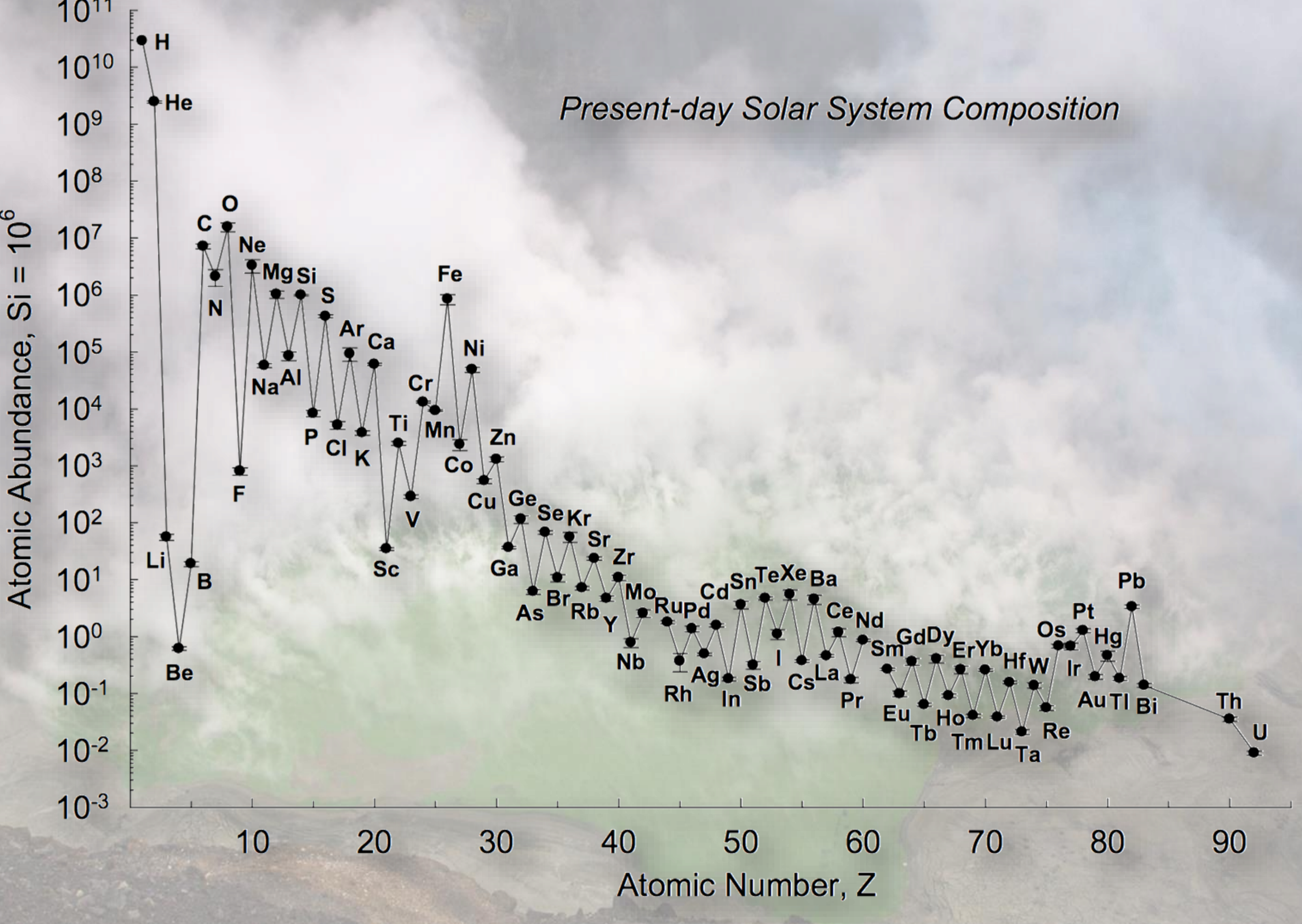
The Belt of Stability



A source of heat should have the following properties:

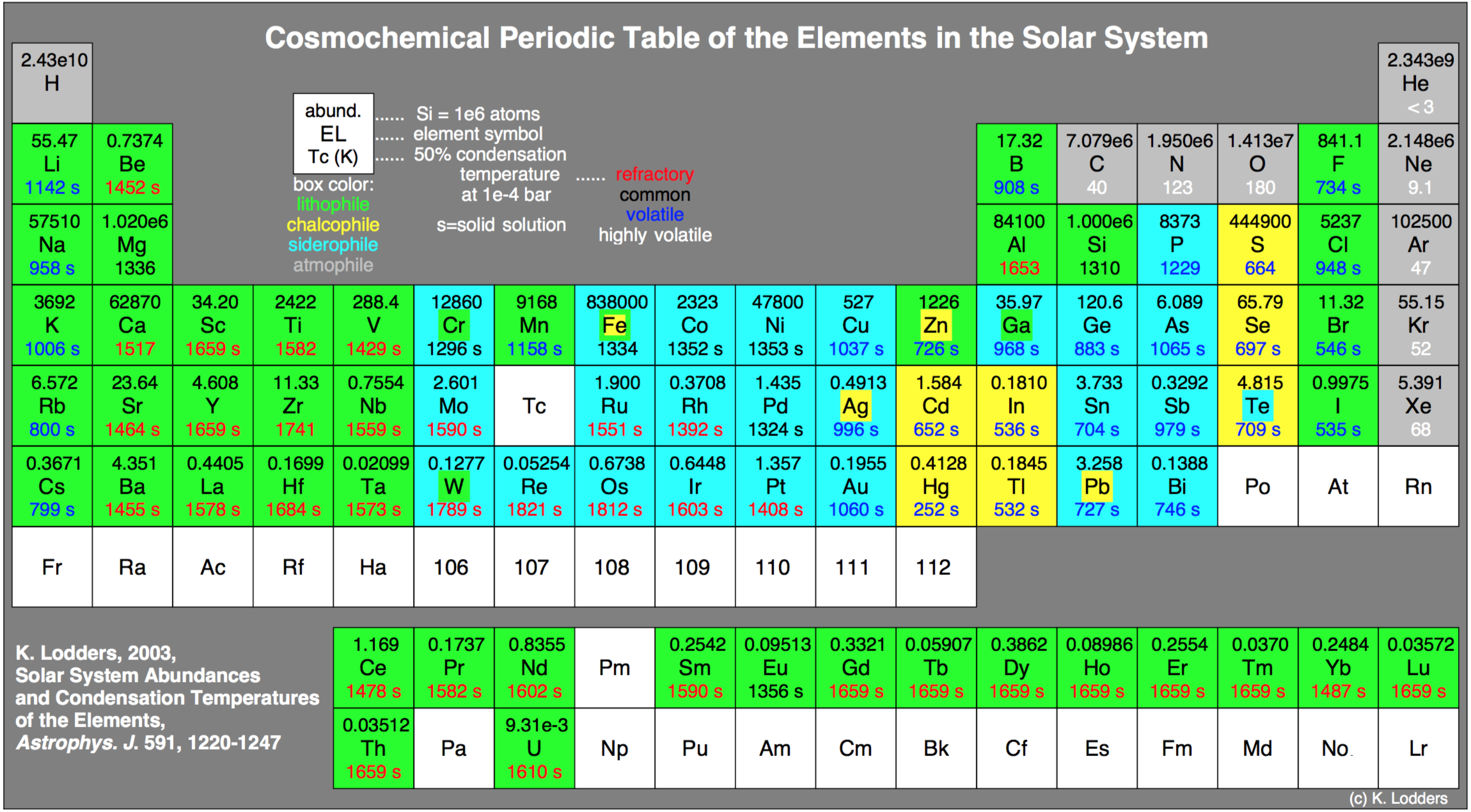
- Sufficient abundance of the chemical element
- Sufficient abundance of the radioisotope in natural material (naturally occurring nuclide)
- Decay time not too short (to be available for long-term evolution), but not too long (to be a significant source of energy)

Naturally occurring radioactive material



Present-day Solar System Composition

Naturally occurring radioactive material



Cosmochemical Periodic Table of the Elements in the Solar System

abund. ...... Si = 1e6 atoms
EL ...... element symbol
Tc (K) ...... 50% condensation temperature at 1e-4 bar ...... refractory
common
volatile
highly volatile

box color:
lithophile
chalcophile
siderophile
atmophile

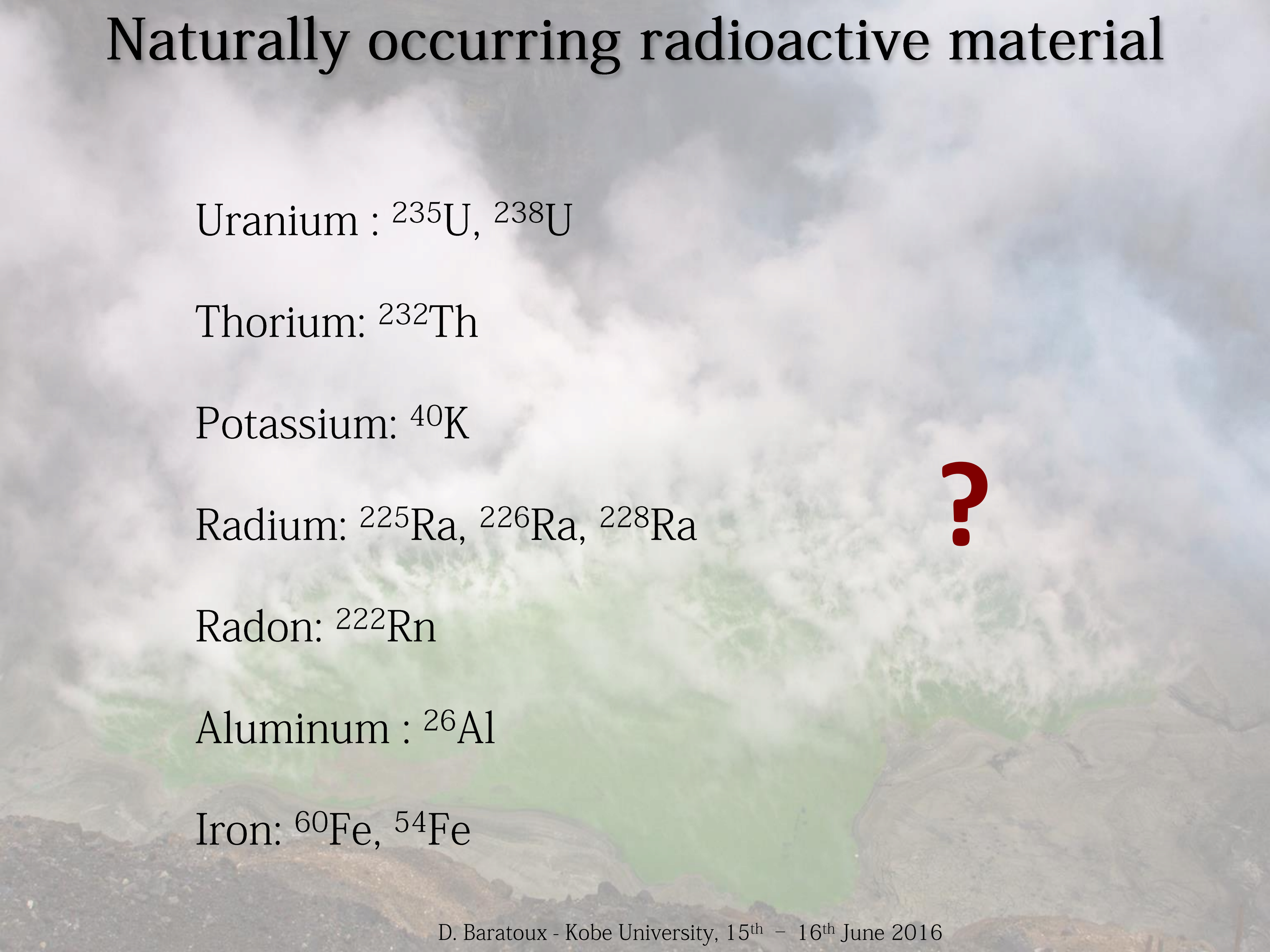
s=solid solution

2.43e10 H																	2.343e9 He < 3
55.47 Li 1142 s	0.7374 Be 1452 s											17.32 B 908 s	7.079e6 C 40	1.950e6 N 123	1.413e7 O 180	841.1 F 734 s	2.148e6 Ne 9.1
57510 Na 958 s	1.020e6 Mg 1336											84100 Al 1653	1.000e6 Si 1310	8373 P 1229	444900 S 664	5237 Cl 948 s	102500 Ar 47
3692 K 1006 s	62870 Ca 1517	34.20 Sc 1659 s	2422 Ti 1582	288.4 V 1429 s	12860 Cr 1296 s	9168 Mn 1158 s	838000 Fe 1334	2323 Co 1352 s	47800 Ni 1353 s	527 Cu 1037 s	1226 Zn 726 s	35.97 Ga 968 s	120.6 Ge 883 s	6.089 As 1065 s	65.79 Se 697 s	11.32 Br 546 s	55.15 Kr 52
6.572 Rb 800 s	23.64 Sr 1464 s	4.608 Y 1659 s	11.33 Zr 1741	0.7554 Nb 1559 s	2.601 Mo 1590 s	Tc	1.900 Ru 1551 s	0.3708 Rh 1392 s	1.435 Pd 1324 s	0.4913 Ag 996 s	1.584 Cd 652 s	0.1810 In 536 s	3.733 Sn 704 s	0.3292 Sb 979 s	4.815 Te 709 s	0.9975 I 535 s	5.391 Xe 68
0.3671 Cs 799 s	4.351 Ba 1455 s	0.4405 La 1578 s	0.1699 Hf 1684 s	0.02099 Ta 1573 s	0.1277 W 1789 s	0.05254 Re 1821 s	0.6738 Os 1812 s	0.6448 Ir 1603 s	1.357 Pt 1408 s	0.1955 Au 1060 s	0.4128 Hg 252 s	0.1845 Tl 532 s	3.258 Pb 727 s	0.1388 Bi 746 s	Po	At	Rn
Fr	Ra	Ac	Rf	Ha	106	107	108	109	110	111	112						
				1.169 Ce 1478 s	0.1737 Pr 1582 s	0.8355 Nd 1602 s	Pm	0.2542 Sm 1590 s	0.09513 Eu 1356 s	0.3321 Gd 1659 s	0.05907 Tb 1659 s	0.3862 Dy 1659 s	0.08986 Ho 1659 s	0.2554 Er 1659 s	0.0370 Tm 1659 s	0.2484 Yb 1487 s	0.03572 Lu 1659 s
				0.03512 Th 1659 s	Pa	9.31e-3 U 1610 s	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

K. Lodders, 2003,
Solar System Abundances
and Condensation Temperatures
of the Elements,
***Astrophys. J.* 591, 1220-1247**

Controls the concentration of elements in terrestrial planets

Naturally occurring radioactive material



Uranium : ^{235}U, ^{238}U

Thorium: ^{232}Th

Potassium: ^{40}K

Radium: ^{225}Ra, ^{226}Ra, ^{228}Ra

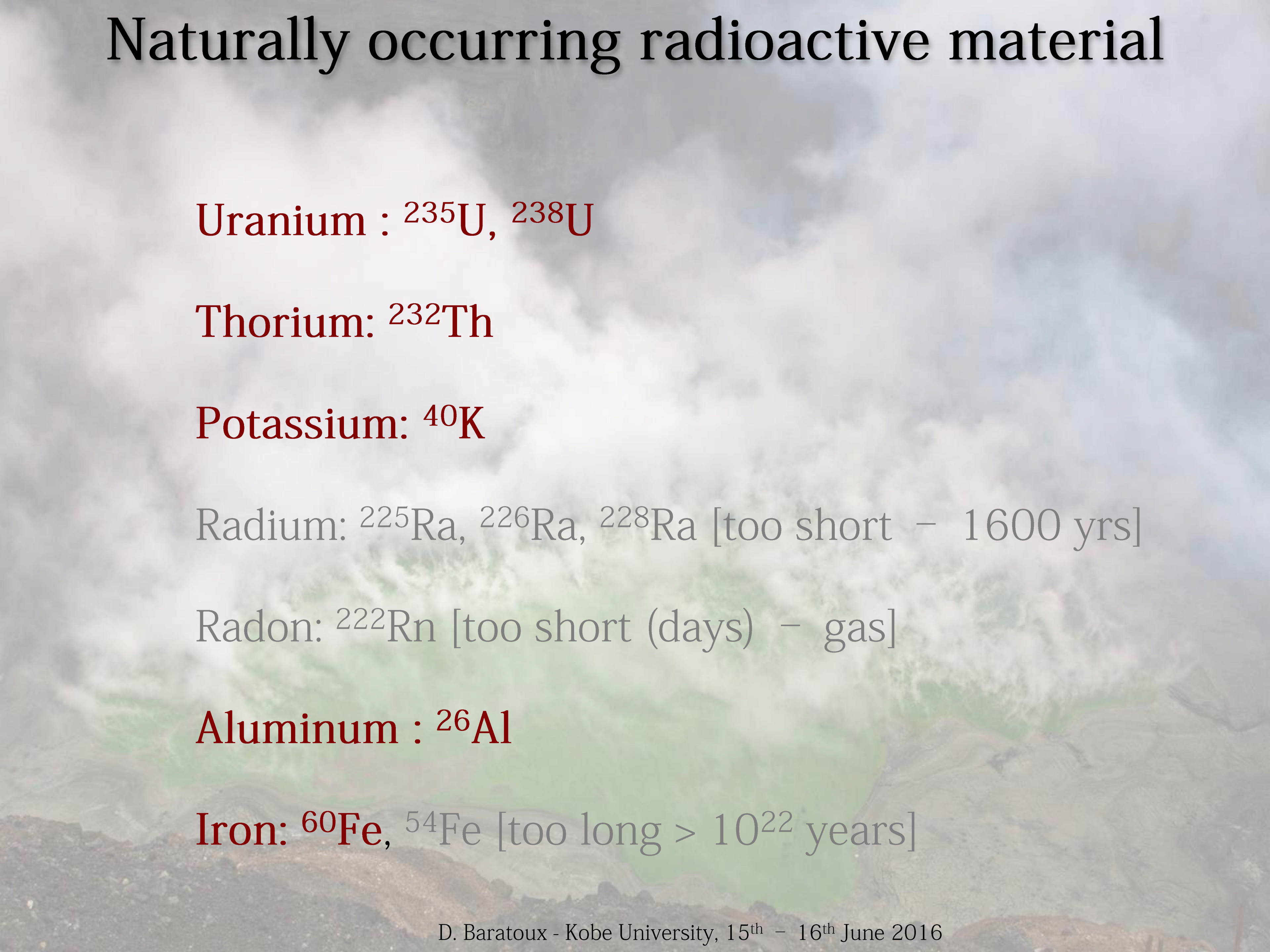
Radon: ^{222}Rn

Aluminum : ^{26}Al

Iron: ^{60}Fe, ^{54}Fe

?

Naturally occurring radioactive material



Uranium : ^{235}U, ^{238}U

Thorium: ^{232}Th

Potassium: ^{40}K

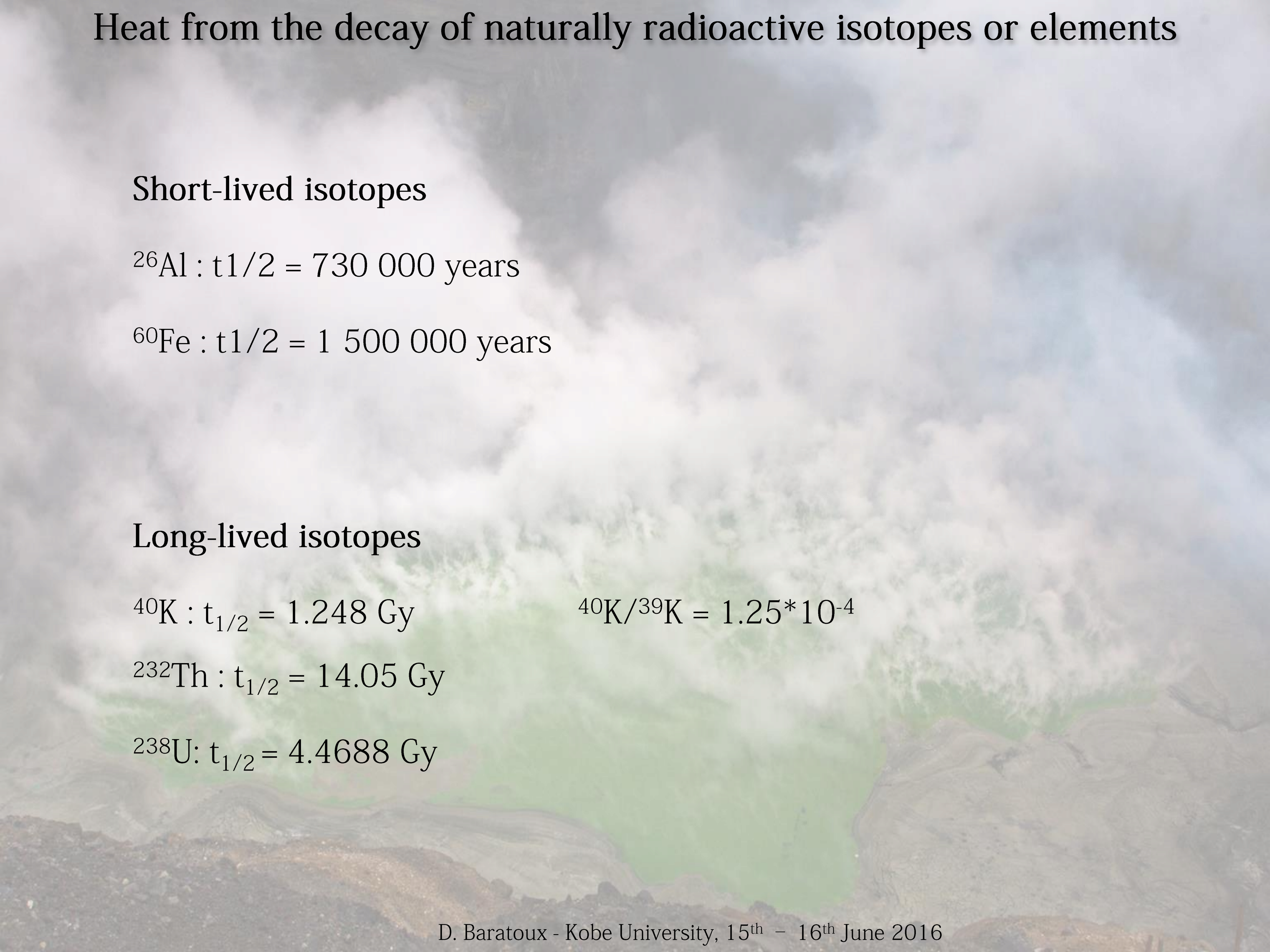
Radium: ^{225}Ra, ^{226}Ra, ^{228}Ra [too short – 1600 yrs]

Radon: ^{222}Rn [too short (days) – gas]

Aluminum : ^{26}Al

Iron: ^{60}Fe, ^{54}Fe [too long > 10^{22} years]

Heat from the decay of naturally radioactive isotopes or elements



Short-lived isotopes

^{26}Al : t1/2 = 730 000 years

^{60}Fe : t1/2 = 1 500 000 years

Long-lived isotopes

^{40}K : $t_{1/2}$ = 1.248 Gy

^{40}K/^{39}K = 1.25*10^{-4}

^{232}Th : $t_{1/2}$ = 14.05 Gy

^{238}U: $t_{1/2}$ = 4.4688 Gy

1.3 Short-lived isotopes

$^{26}\mathrm{Al} \longrightarrow {}^{26}\mathrm{Mg}$

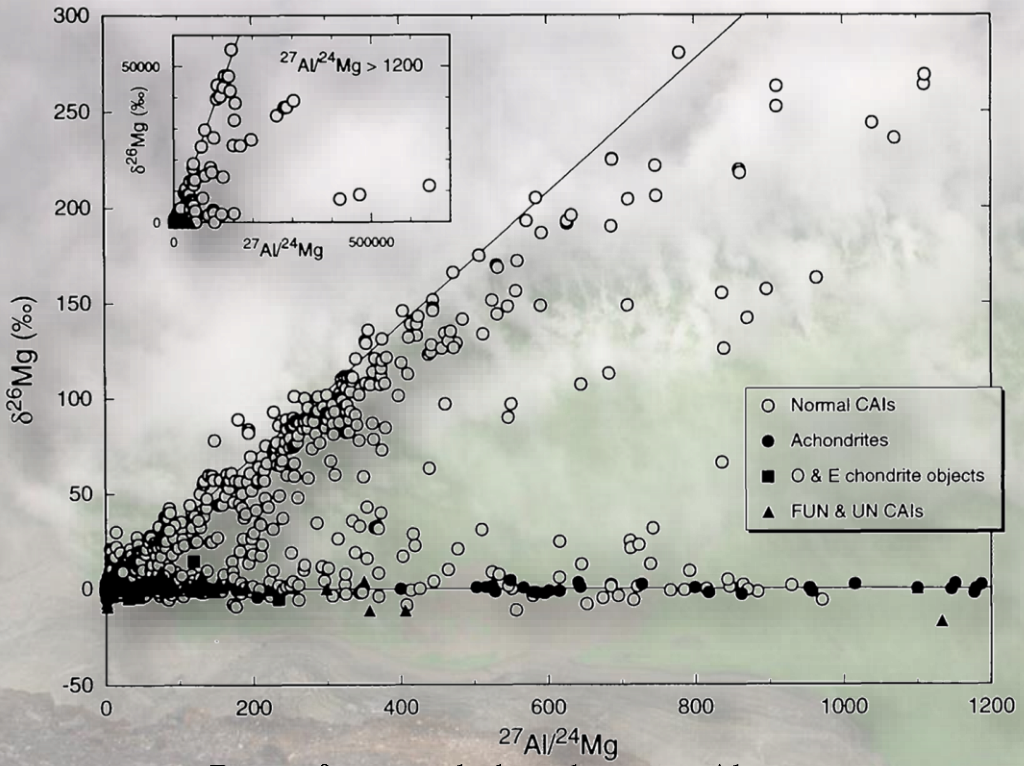
β+ or electron capture

Al: ^{26}Al – radioactive
^{27}Al – stable

Mg: ^{24}Mg – stable
^{25}Mg – stable
^{26}Mg – stable

Half-life: 730 000 years

MacPherson et al. 1995. Meteoritics



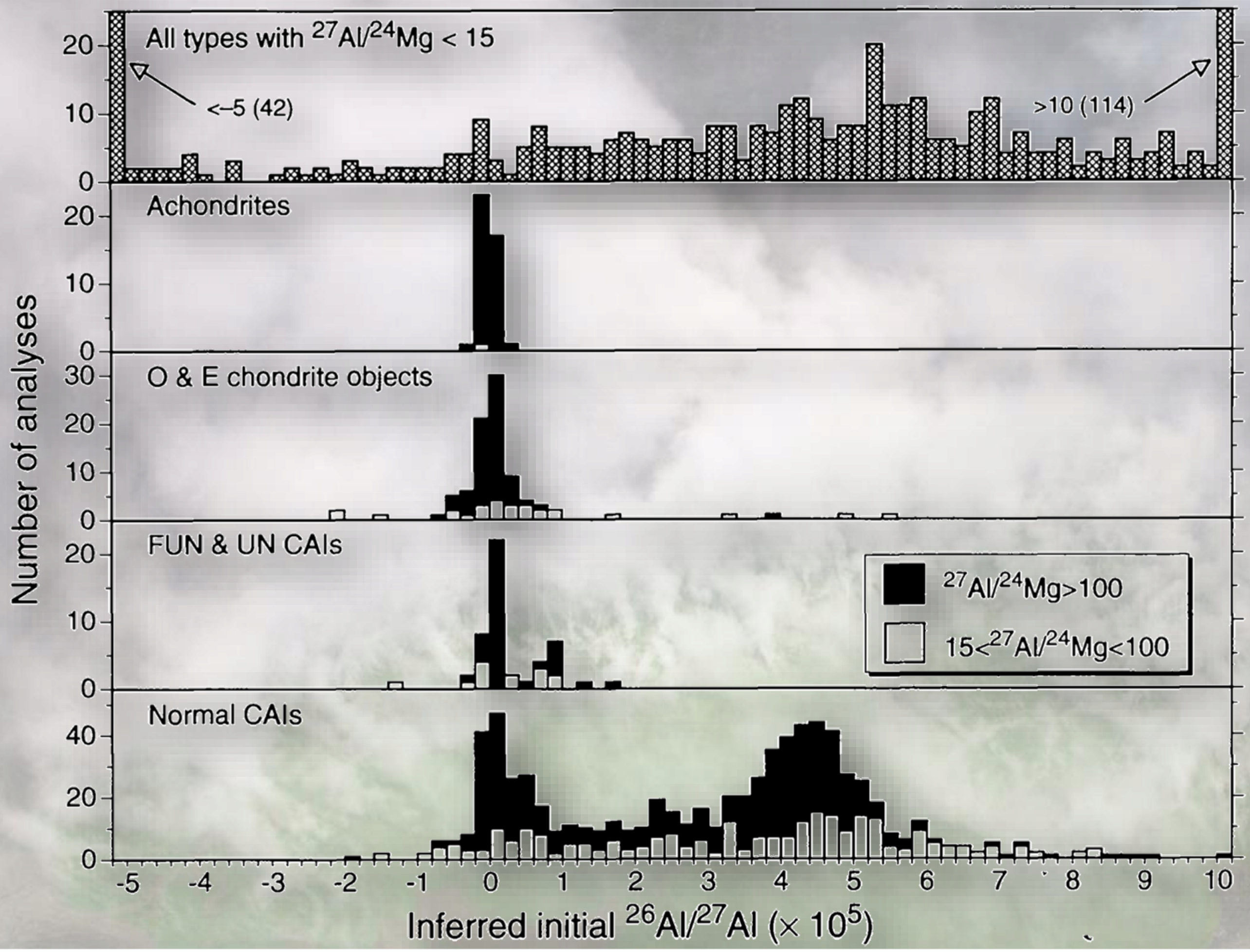
Measure of the excess of ^{26}Al

Proxy for initial abundance in Al

Compilation of over 1500 Mg-isotopic analyses of Al-rich material from primitive solar system matter (meteorites) shows that ^{26}Al existed in the early Solar System.

1.3 Short-lived isotopes

MacPherson et al. 1995. Meteoritics



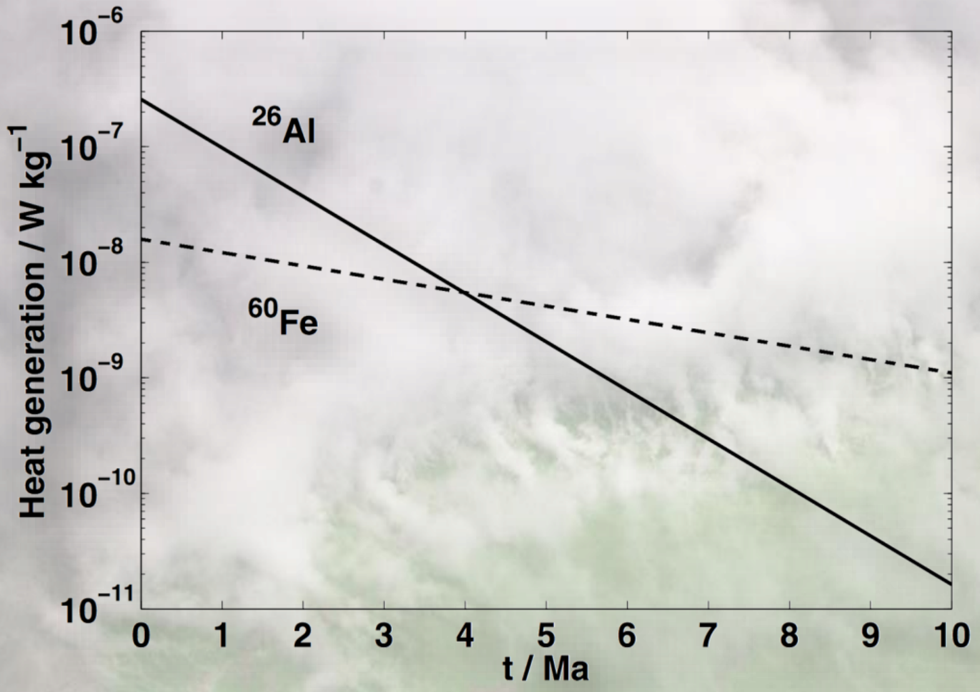
Compilation of over 1500 Mg-isotopic analyses of Al-rich material from primitive solar system matter (meteorites) shows that ^{26}Al existed in the early Solar System.

1.3 Short-lived isotopes

$^{60}Fe \xrightarrow[\beta^-]{} {}^{60}Co$

Fe: ^{56}Fe – stable
^{60}Fe – Radioactive

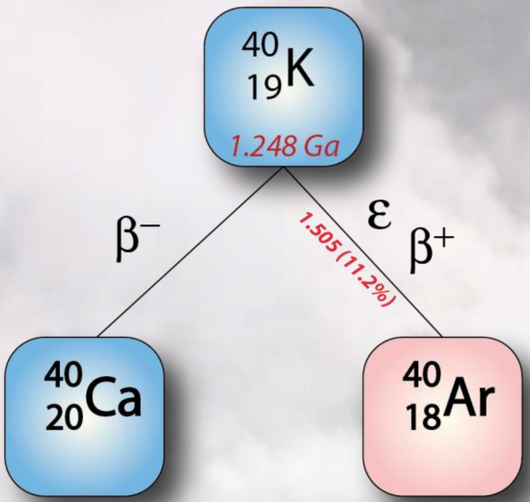
Half-life: 1 500 000 years



Neumann, W., Breuer, D., Spohn, T. (2012) Differentiation and core formation in accreting planetesimals.

Deciding whether ^{26}Al or ^{60}Fe were or were not the agent of heating that caused melting in the achondrite parent bodies hinges less on its widespread abundance in the nebula than it does on the timing of planetesimal accretion relative to the formation of the CAIs.

1.3 Long-lived isotopes



🟦 Actinides

🟧 Alkaline Earth Metals

🟥 Noble gases

🟩 Metalloids

⬜ Post-transition metals

🟧 Alkali Metals

🟫 Transition metals

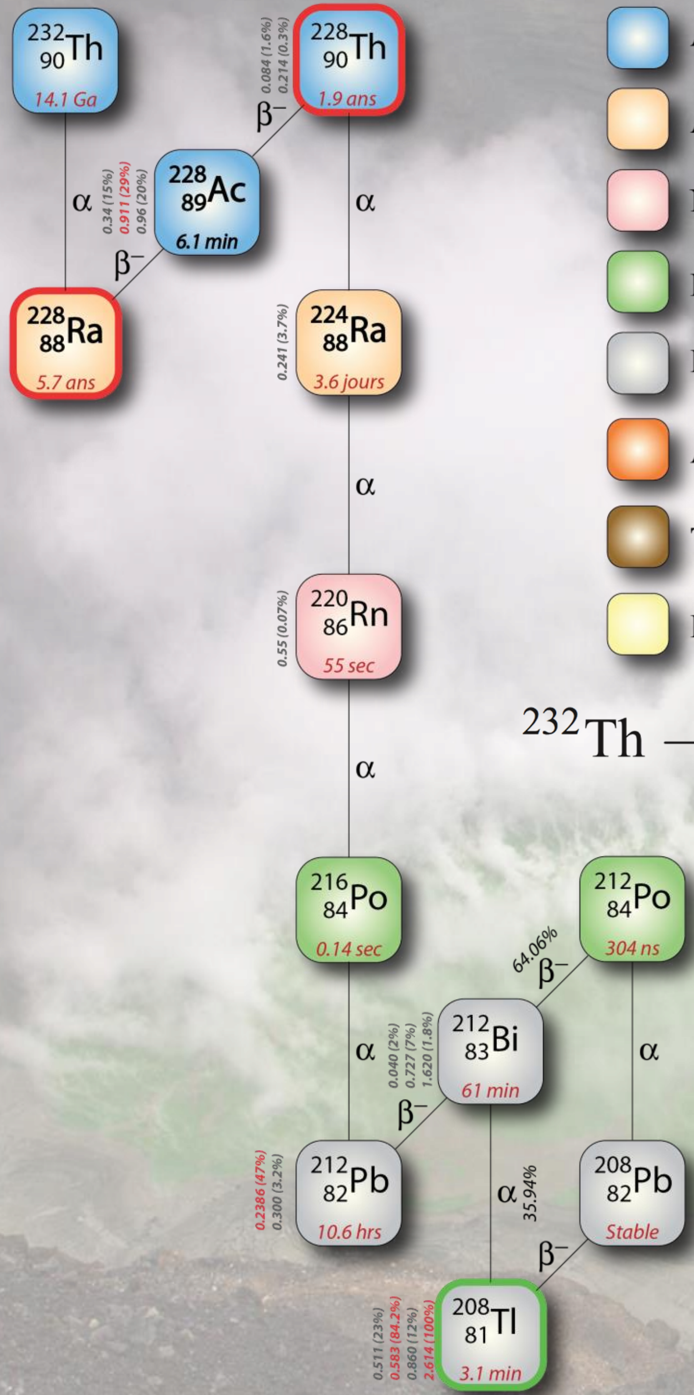
🟨 Halogens

^{232}K : $t_{1/2}$ = 1.248 Gy

$$^{40}\mathrm{K} \rightarrow {}^{40}\ \mathrm{Ca} + \mathrm{e}^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}$$

$$^{40}\mathrm{K} + \mathrm{e}^{-} \rightarrow {}^{40}\ \mathrm{Ar} + \nu_e + 1.51\ \mathrm{MeV}$$

1.3 Long-lived isotopes

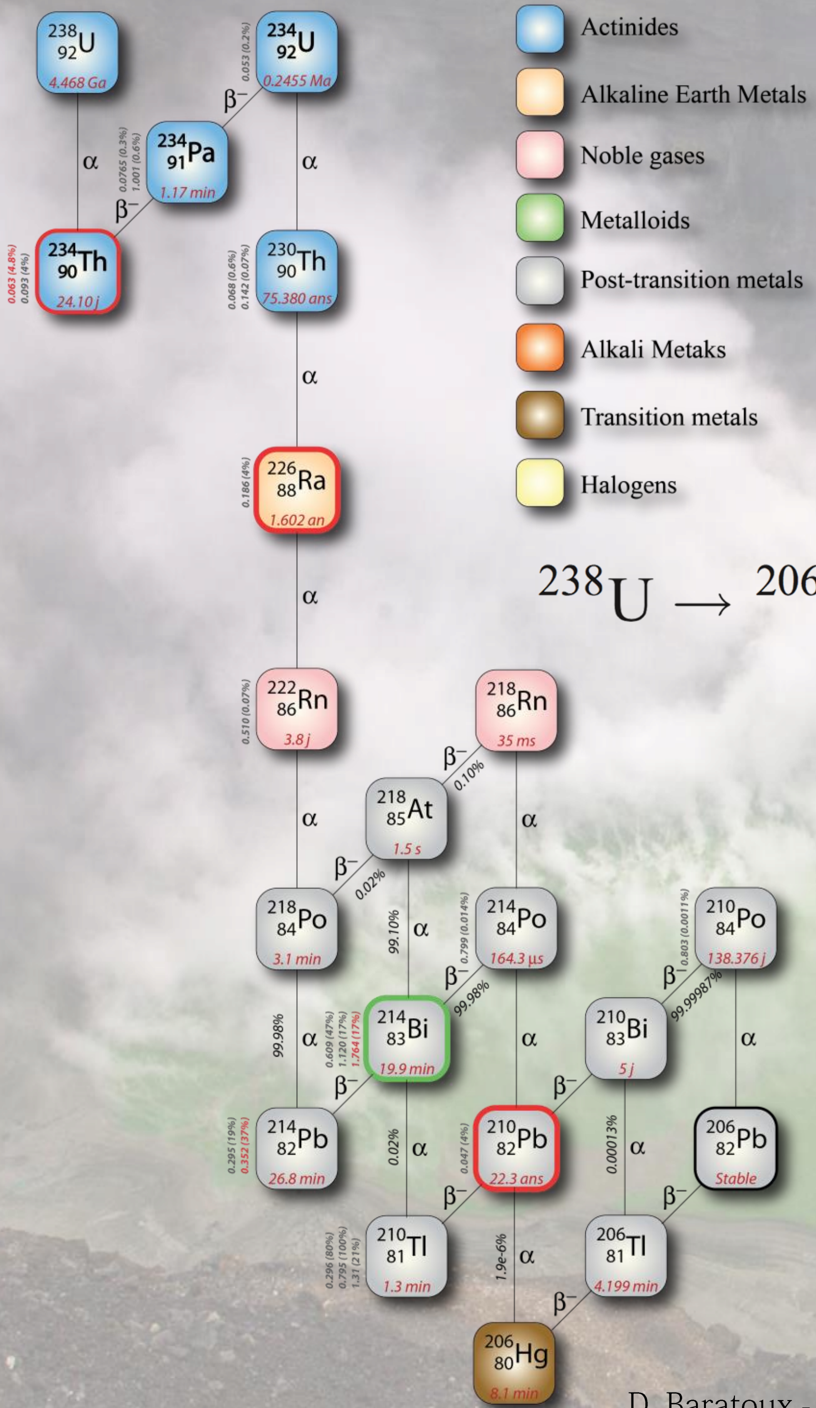


- 🟦 Actinides
- 🟧 Alkaline Earth Metals
- 🟥 Noble gases
- 🟩 Metalloids
- ⬜ Post-transition metals
- 🟧 Alkali Metals
- 🟫 Transition metals
- 🟨 Halogens

^{232}Th : $t_{1/2}$ = 14.05 Gy

$$^{232}\mathrm{Th} \rightarrow {}^{208}\ \mathrm{Pb} + 6^4\mathrm{He} + 4\mathrm{e}^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

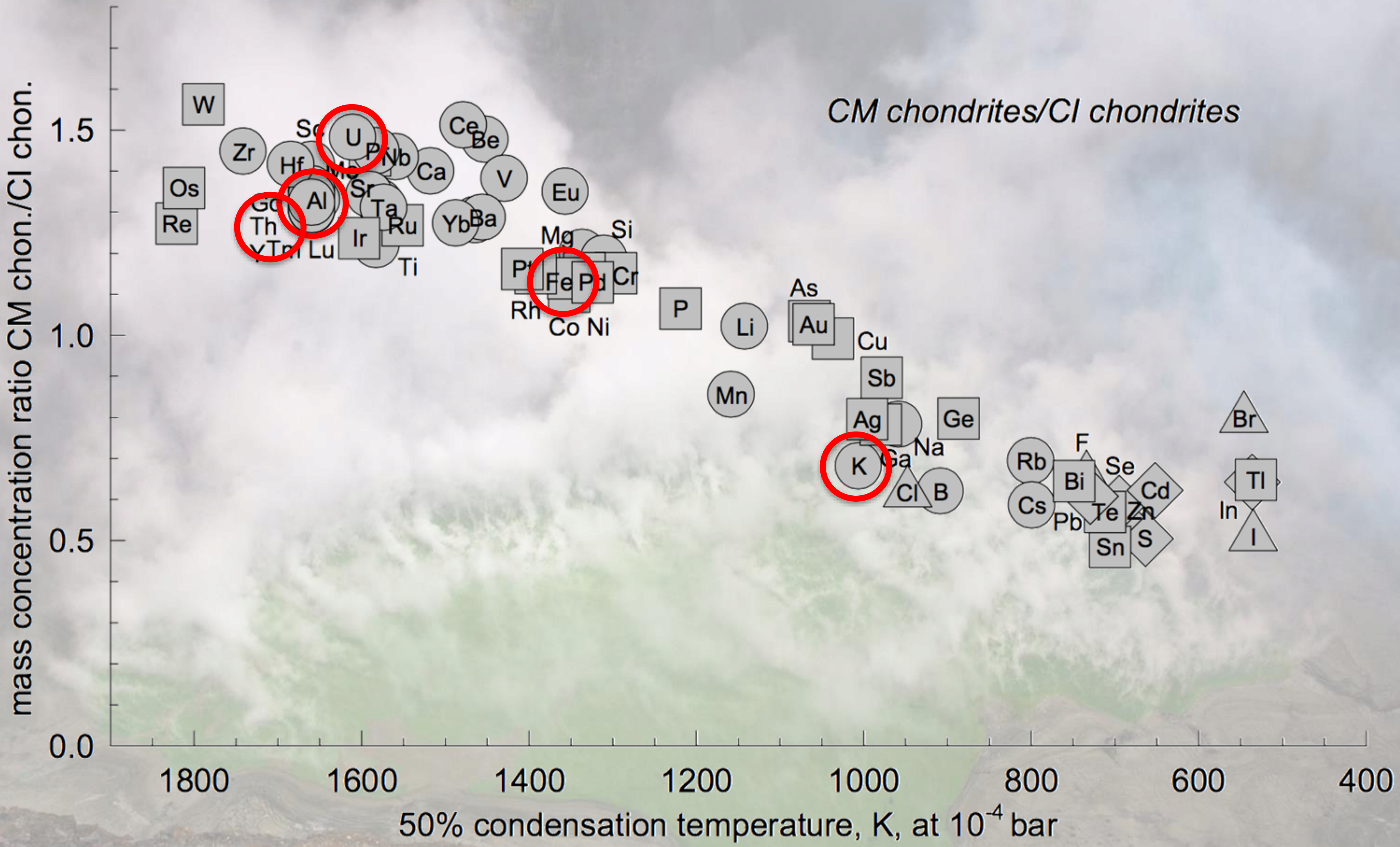
1.3 Long-lived isotopes



^{238}U: $t_{1/2} = 4.4688$ Gy

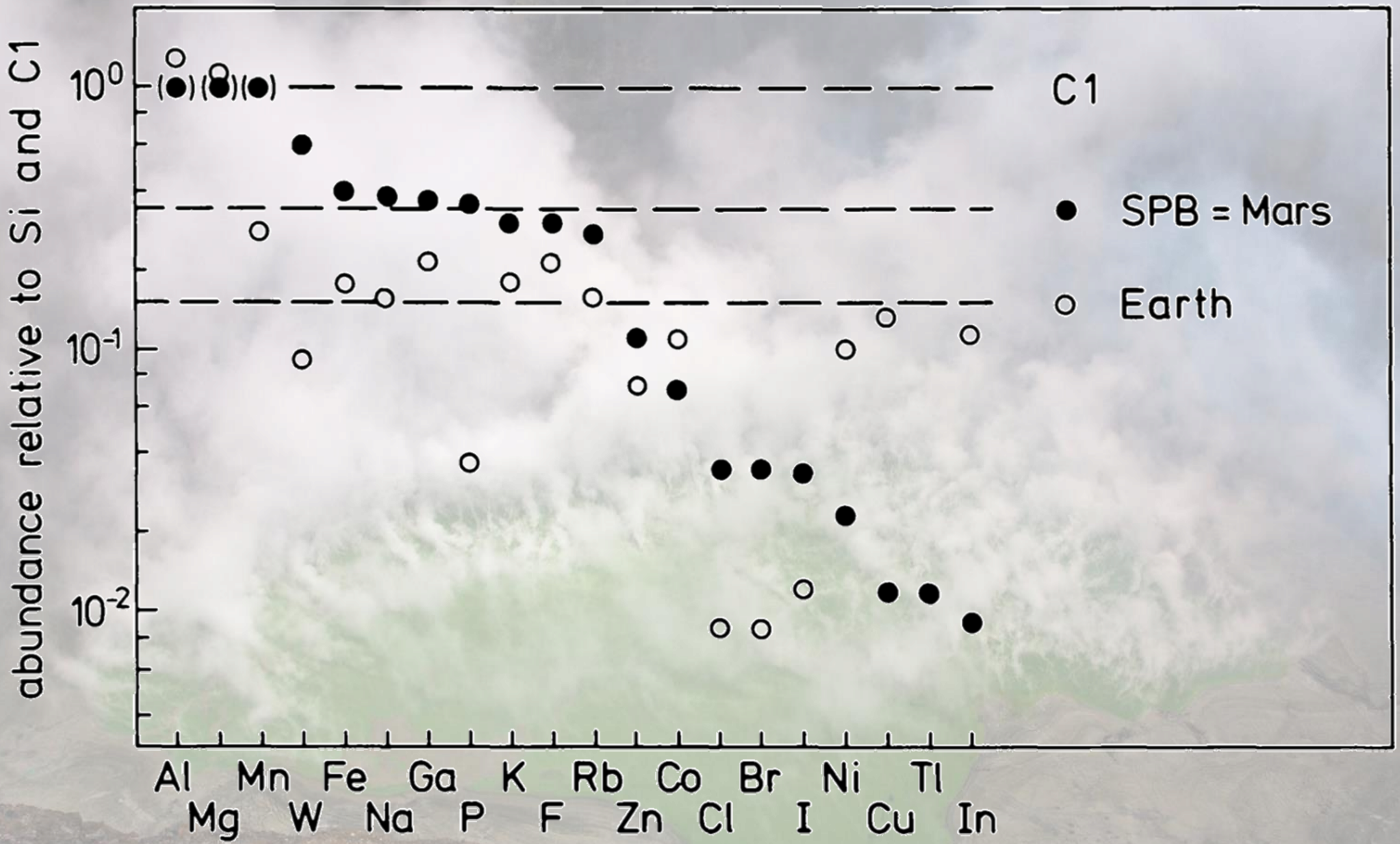
$$^{238}\mathrm{U} \rightarrow \ ^{206}\ \mathrm{Pb} + 8\,^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

Are K, Th, and U equally abundant in all planets ?



Lodders et al. 2009

Comparison of Earth and Mars primitive mantle composition



Dreibus and Wanke 1985

Exercises – Energy budgets

Ex. 1 - Comparing sources of energy

a) Calculate and compare accretion energy and energy from ^{26}Al and ^{60}Fe as a function of size (10, 100, and 1000 km) and accretion time (t from 0 to 3 Myr) for the following compositions of protoplanets.

	Pure Al body	Pure Fe body	Chondritic
Al	100%	-	0.9%
Fe	-	100%	18.5 %

b) Calculate and compare accretion energy and energy from long-lived isotopes as a function of size (100, 1000 km) for the following composition of protoplanets.

	Pure K body	Pure Th body	Pure U body	Chondritic
K	100%	-	-	600 ppm
Th	-	100%	-	19 ppb
U	-	-	100%	8 ppb

Energy budget of Earth and Mars

Short-lived isotopes

$^{26}Al/^{27}Al$	$5*10^{-5}$
$^{60}Fe/^{56}Fe$	$1*10^{-6}$
Total disintegration energy ^{26}Al	$6.4*10^{-13}$ J/atom
Total disintegration energy ^{60}Fe	$4.9*10^{-13}$ J/atom
Atomic mass Al	26.98 u
Atomic mass Fe	55.85 u

Long-lived isotopes

$u = 1.66*10^{-27}$ kg

Fraction ^{40}K	0.01167%
Fraction ^{238}U	99.28%
Total disintegration energy ^{40}K	$2.11*10^{-13}$ J/atom
Total disintegration energy ^{232}Th	$6.5*10^{-13}$ J/atom
Total disintegration energy ^{238}U	$7.7*10^{-13}$ J/atom
Atomic mass K	39.09 u
Atomic mass Th	232.04 u
Atomic mass U	238.03 u