Early mantle differentiation and preservation of primordial reservoirs
The case of the atmosphere/mantle system

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Outline

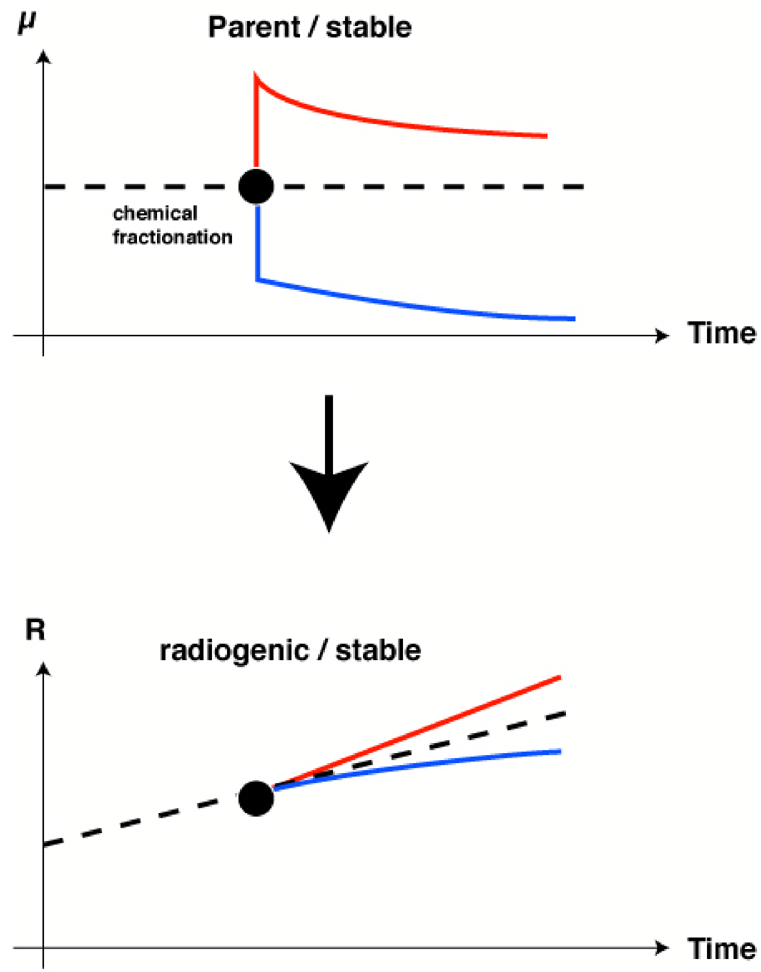
- Studying the Mantle – Atmosphere system
- When occurred mantle degassing ?
- A “primitive” undegassed reservoir in the deep mantle ?
- Is it preserved for 4.4Ga? If so, where it is ?

Isotope geochemistry made simple

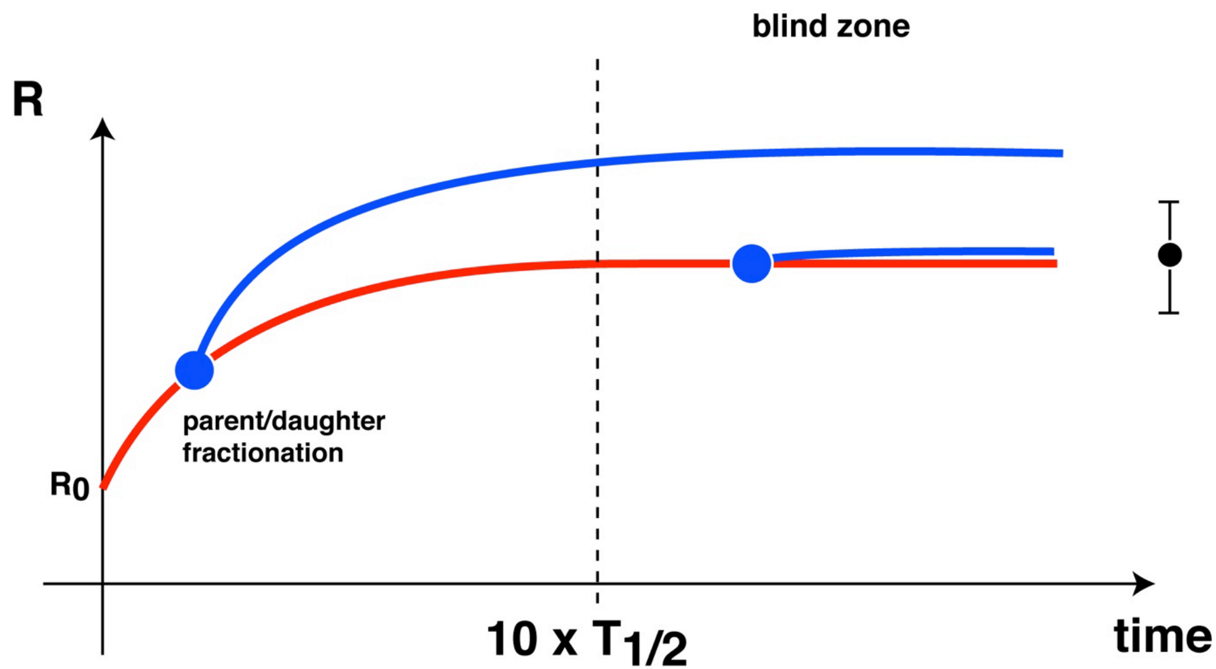
- A radiogenic isotopic ratio reflects a chemical fractionation and time
- A chemical fractionation is the translation to chemistry of a geological event (core formation, melting, crystallization, degassing, …)
- “stable” isotopic ratios can fractionate during some chemical or physical processes but this will negligible for radiogenic isotopes.

Radiogenic isotopic ratios (1): long period

- F=daughter, S=stable, P=parent
- R=F/S (isotopic ratio)
- μ=P/S (chemical ratio)
- $R(t)=R_0+\mu(t)[e^{\lambda t}-1]$

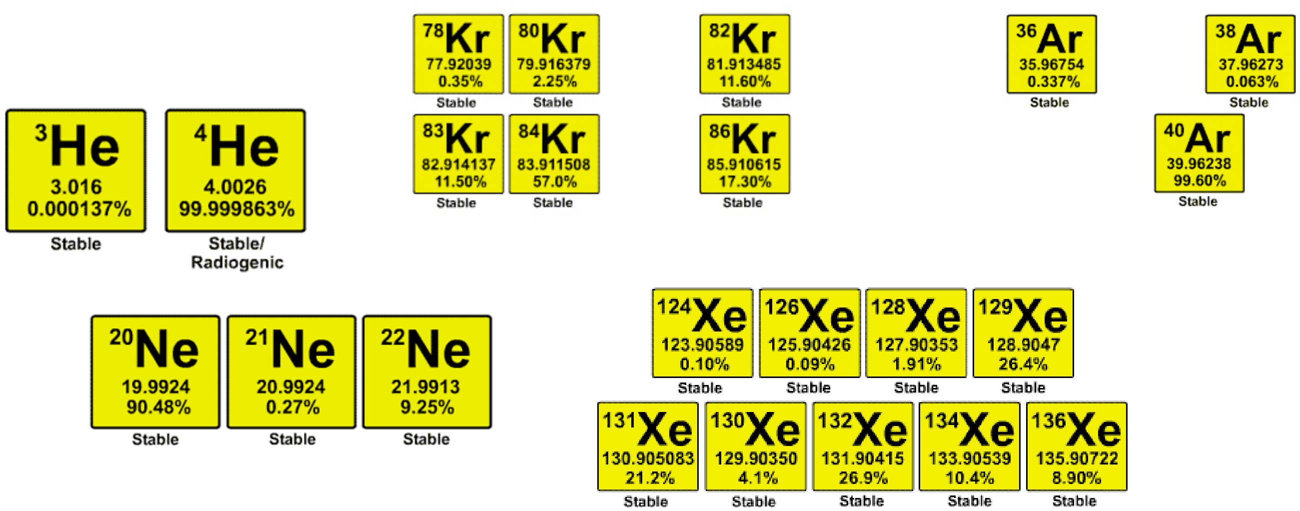


Radiogenic isotopic ratios (2): short period



Noble gas geochemistry: a tool to constrain mantle/Atmosphere evolution

- A single family – chemically inert
- Radiogenic isotopes are used to constrain time-evolution of the mantle/atmosphere system
- Non-radiogenic isotopes can be used as “stable” isotopes for physical processes during accretion



Noble gases of special interest today

- Helium: ^{4}He is radiogenic (U, Th), ^{3}He is primordial. Important: helium can leave the atmosphere: interesting for flux determination

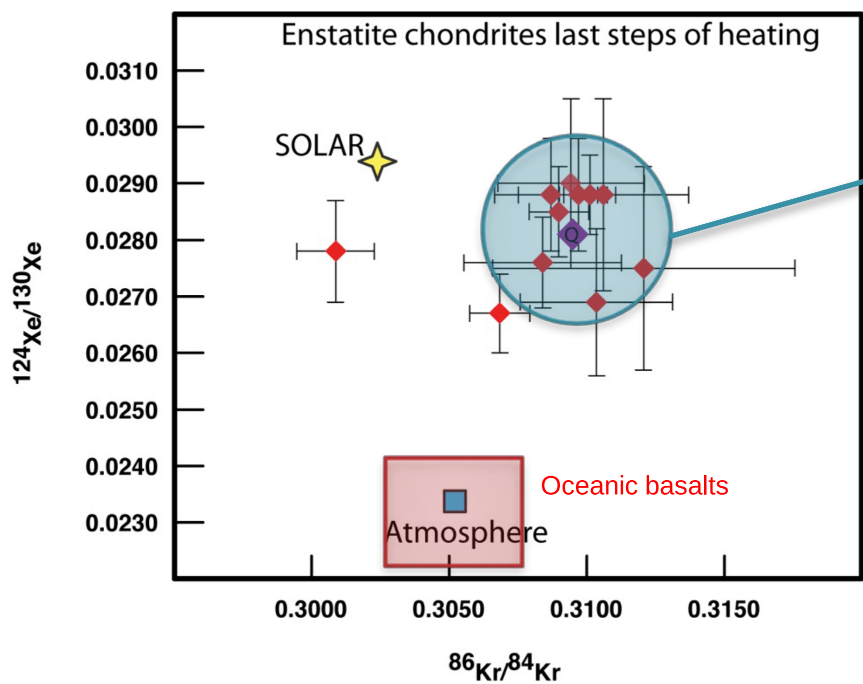
- Neon: three isotopes, ^{21}Ne is “radiogenic”, ^{20}Ne, ^{22}Ne are stable

- Argon: ^{40}Ar is radiogenic (^{40}K). Important: $^{40}Ar_0 \sim 0$

- Xenon: couple ^{129}I-^{129}Xe ($T_{1/2}$:=17Ma)

On the difficulty to have the composition of the primordial mantle

- Earth is **not** chondritic for noble gases
- It is unknown why
- Origin of the chondritic compositions is unknown



Carbonaceous Component of unknown origin
Degassed at high T, acid resistant

Either not present either lost during Earth accretion

Roubinet, Thèse

Some evidences that (a part of) atmosphere is degassed from the mantle

-
  - ^{40}Ar is entirely of radiogenic origin
  - ^{40}Ar is 1% in atmosphere
  - So mantle was degassed to produce the atmosphere
-
  - Non-radiogenic isotopic ratios of the xenon are similar in the mantle and in the atmosphere, and this is an unique signature in the solar system
-
  - ^{3}He is detected above ridges or OIB, so the mantle is still degassing primordial isotopes

Evidences for a less degassed reservoir in deep Earth

(1) Argon budget (Allègre et al., 1995)

CC: [U]=15±3ppb
EC: [U]=8±3ppb
OC: [U]=14±4ppb

→

CC: [K]=290ppm in silicate Earth
EC: [K]=152ppm in silicate Earth
OC: [K]=270ppm in silicate Earth

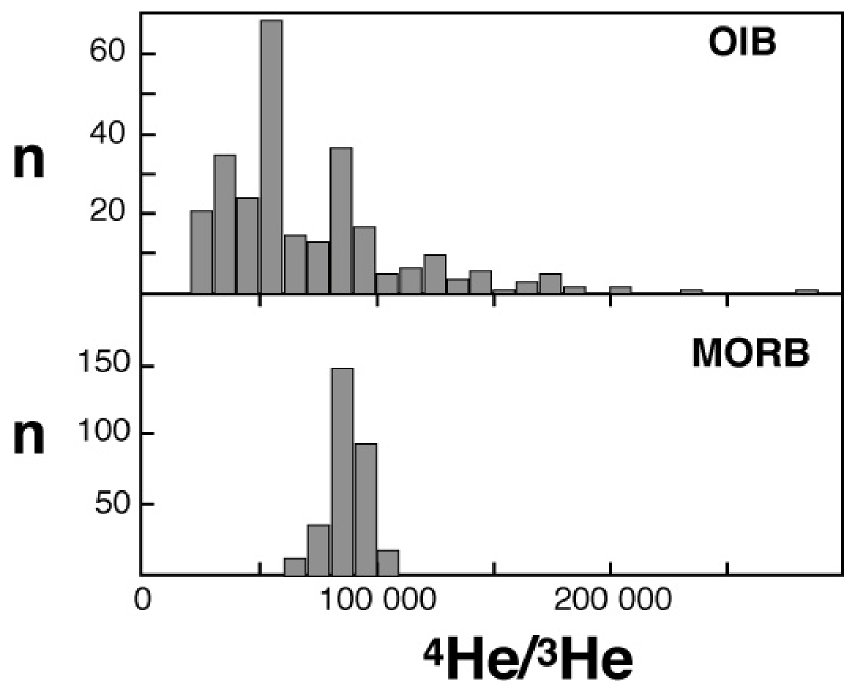
↓

For CC: 57% of the ^{40}Ar is in the lower mantle; 5% in UM)
For EC: 20% of the ^{40}Ar is in the lower mantle; 10% in UM)

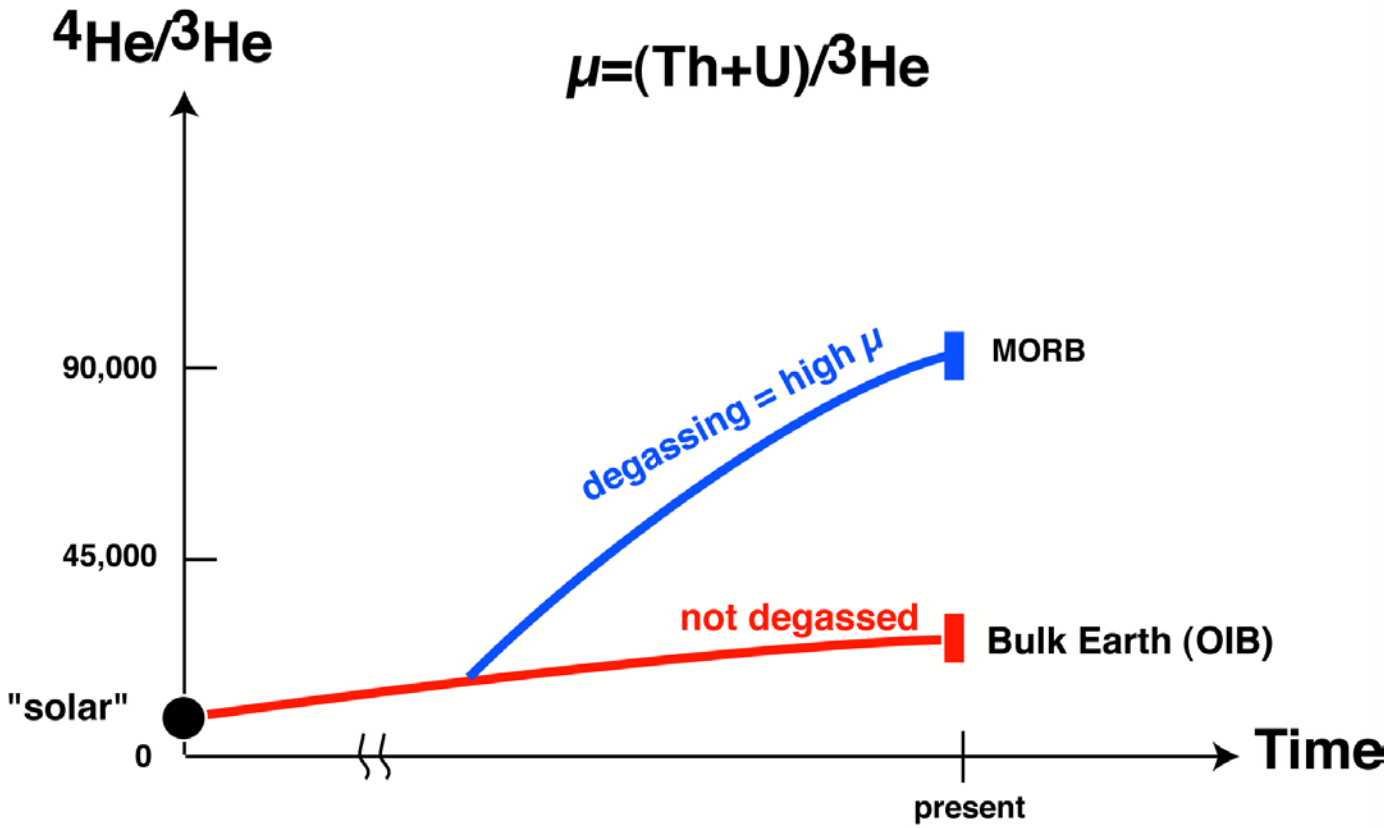
Mantle is not fully degassed of its radiogenic argon

Helium isotopic ratios as evidence for an undegassed mantle

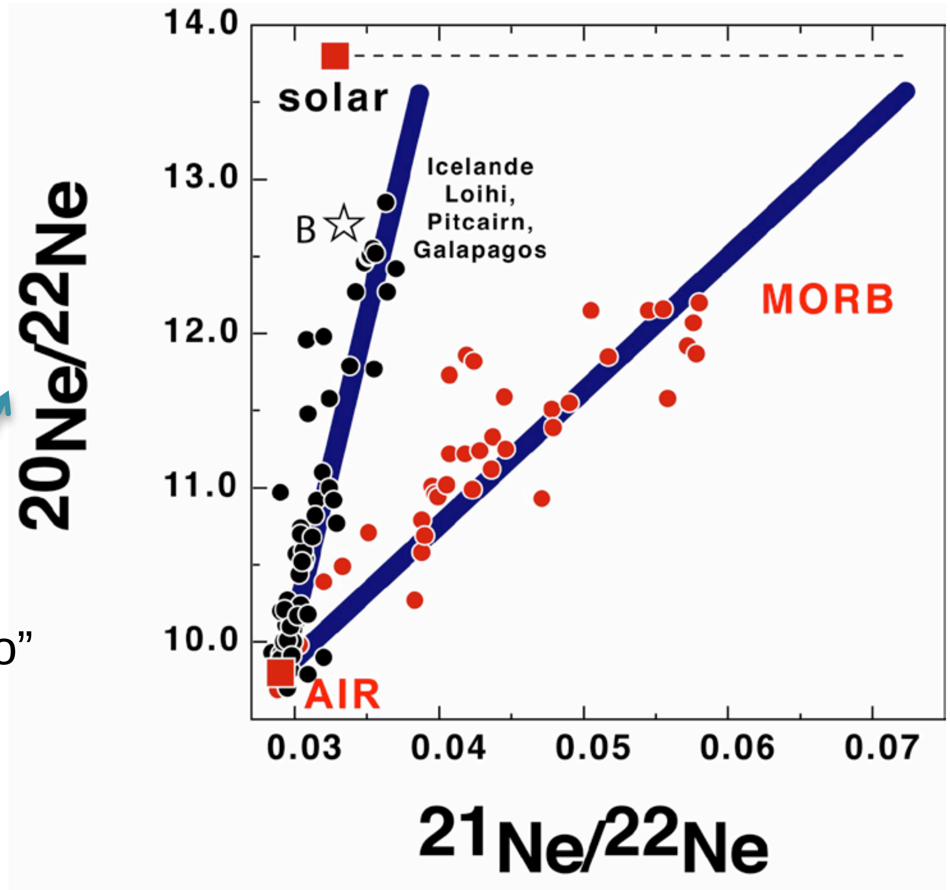
- ^4He is radiogenic (U, Th), ^3He is primordial
- MORB source is relatively homogeneous in respect with helium
- Most OIBs have lower $^4He/^3He$ ratios (lower $^3He/^4He$) than MORB



$$\left(\frac{^4He}{^3He}\right) \approx \left(\frac{^4He}{^3He}\right)_0 + \left(\frac{U+Th}{^3He}\right) \cdot f(t)$$

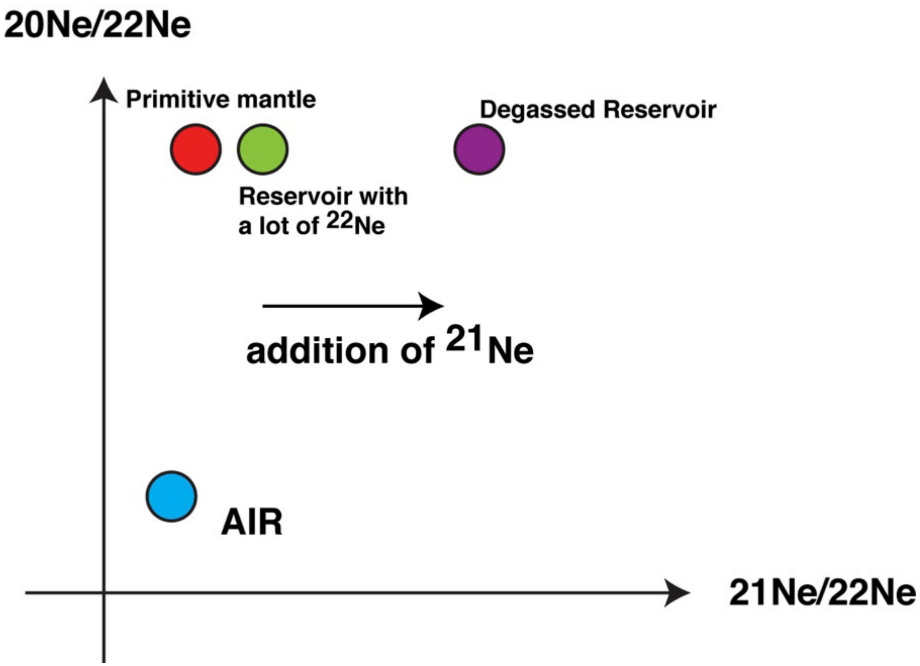


Neon isotopes



"stable ratio"

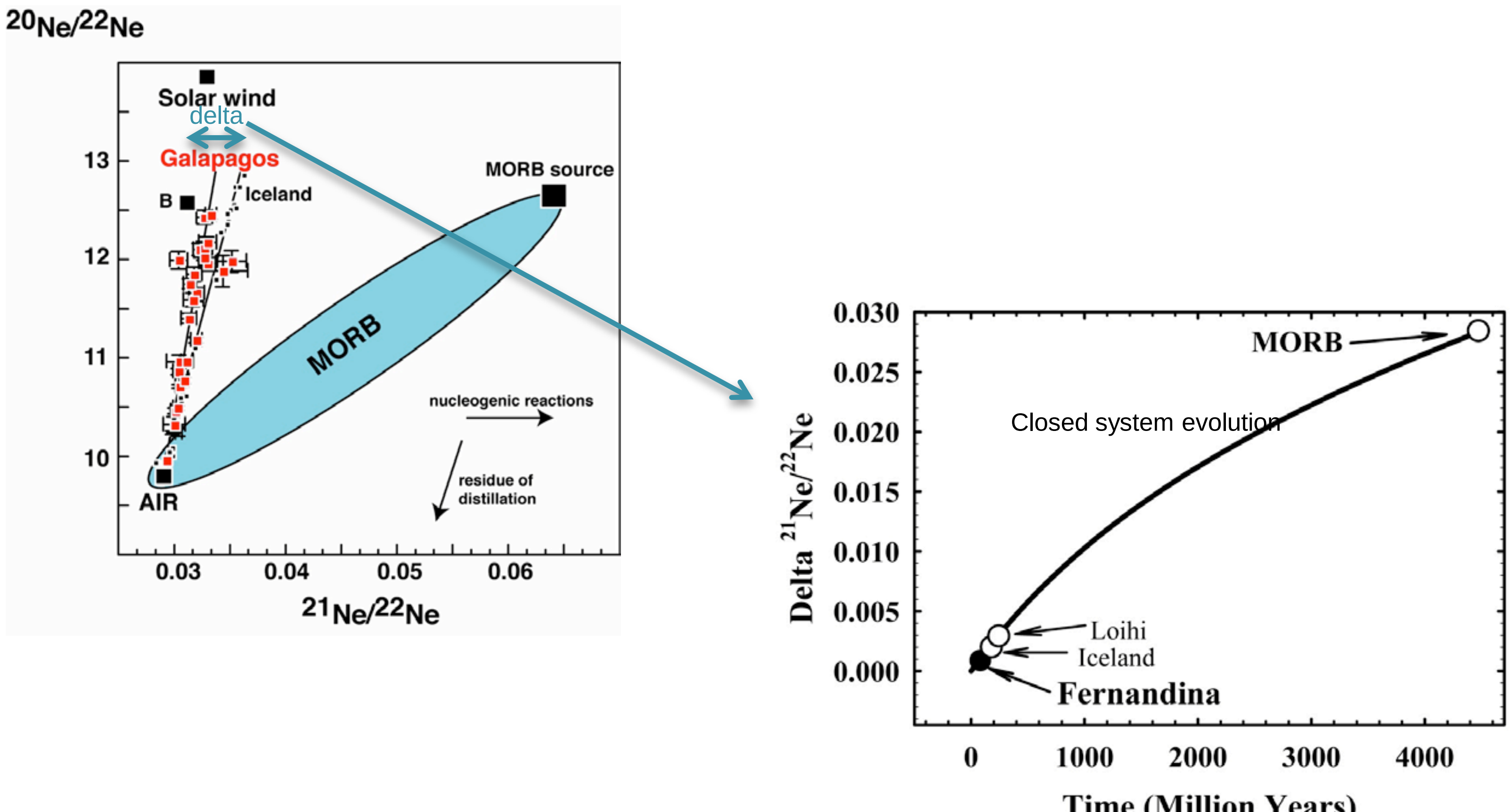
"radiogenic ratio"



Month salary x2

Month salary x1.0000000000000

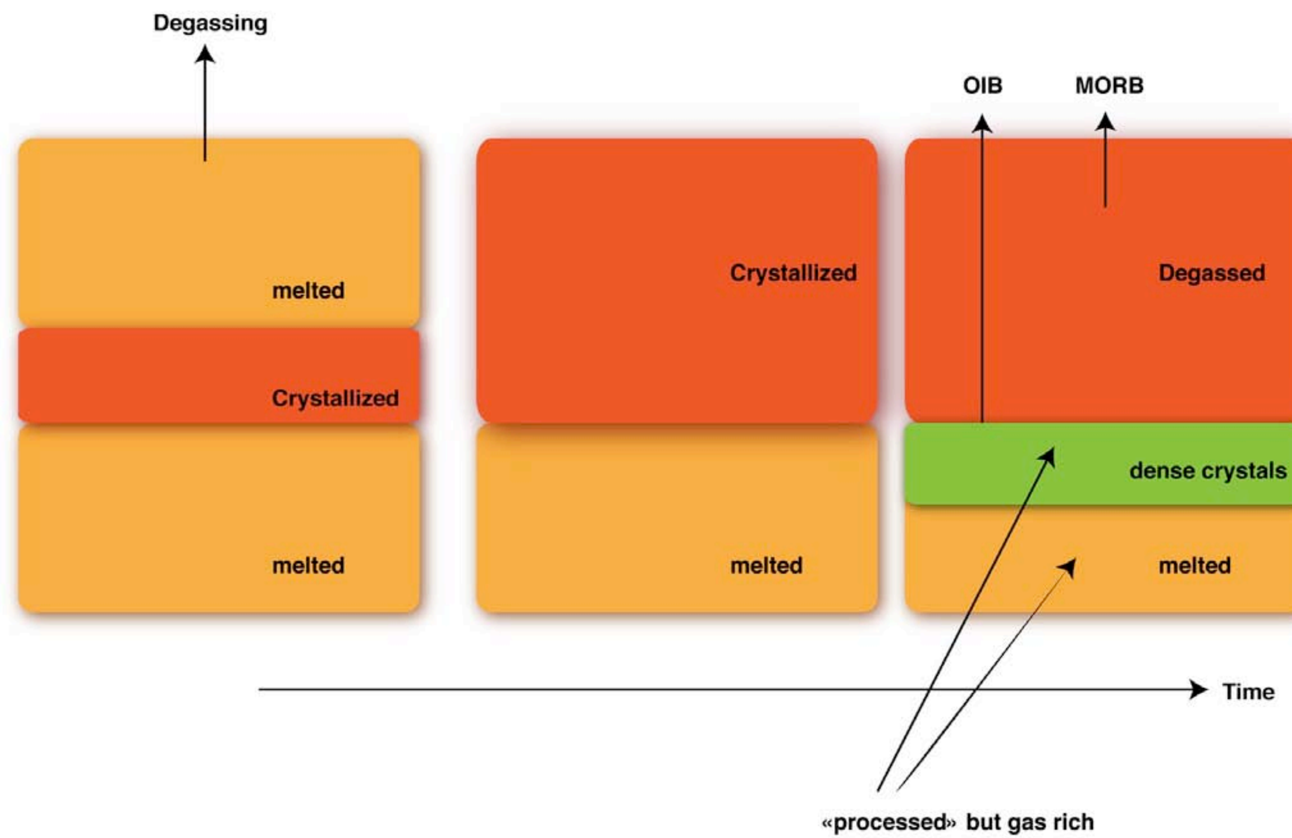
Neon suggests either it is primordial or can be a 4.4Ga depletion of a MORB-type source



Kurz et al. (2009)

If depletion, it has to be older than 4.4Ga

- He and Ne isotopic compositions require a less degassed reservoir deep in the mantle
- He and Ne suggest that this reservoir is ancient and gas-rich. It does not mean it is primitive in the sense that it was never melted or crystallized, or never saw any recycled component in it.
- The important process is degassing (requires to be at surface)



Inspired from Labrosse et al. (but with nicer colors)

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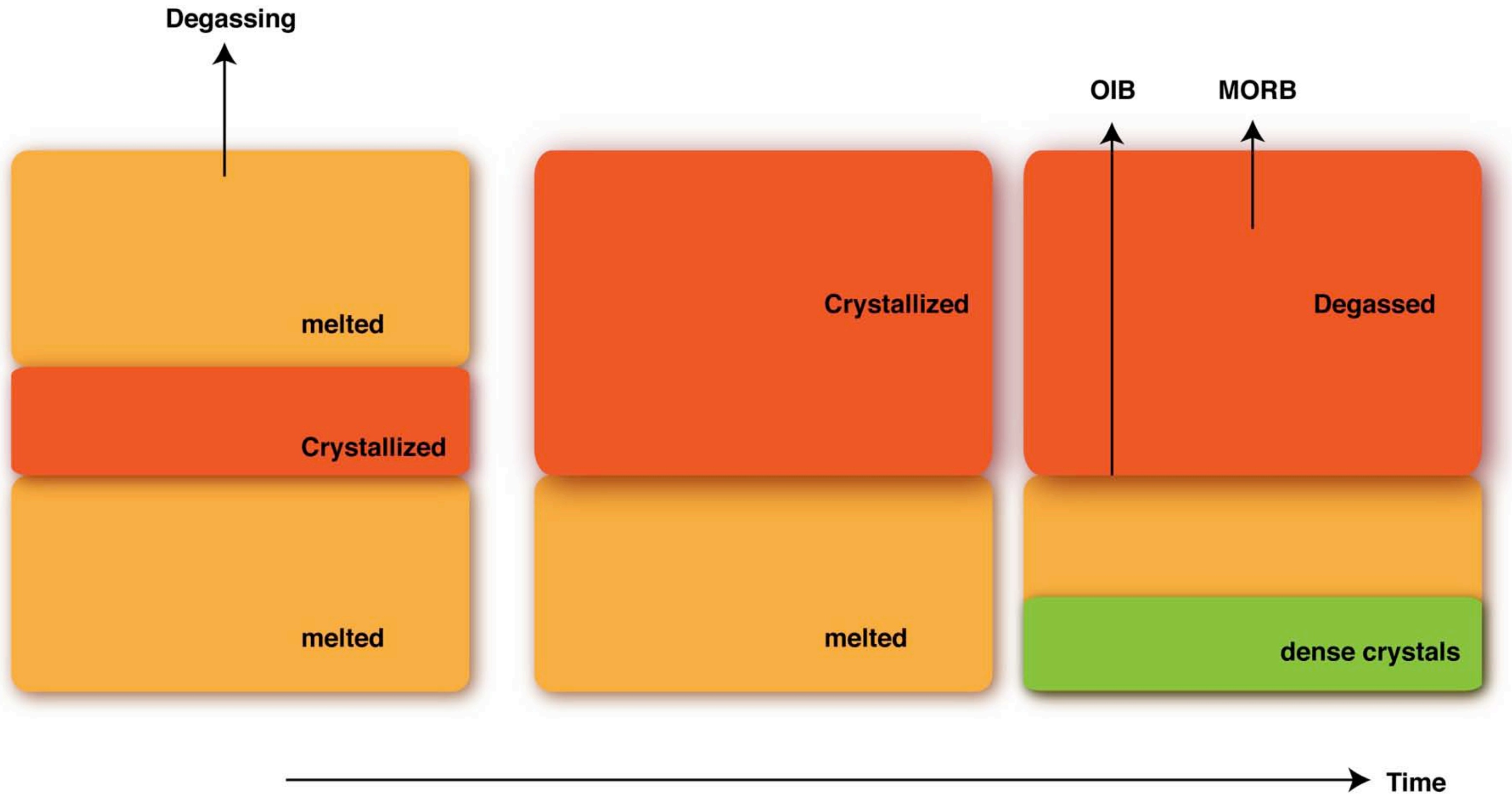

Inspired from Labrosse et al. (yesterday talk)

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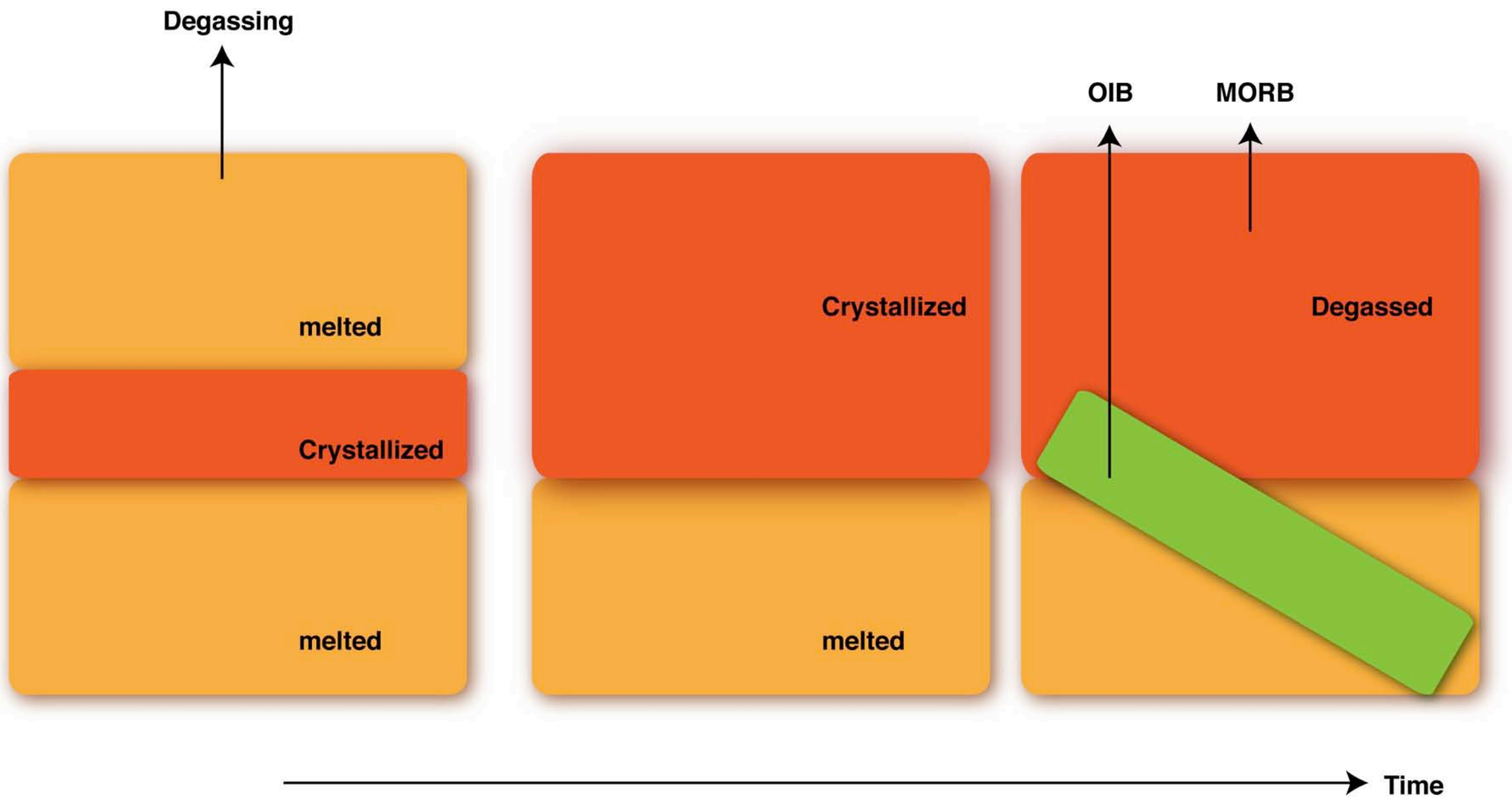
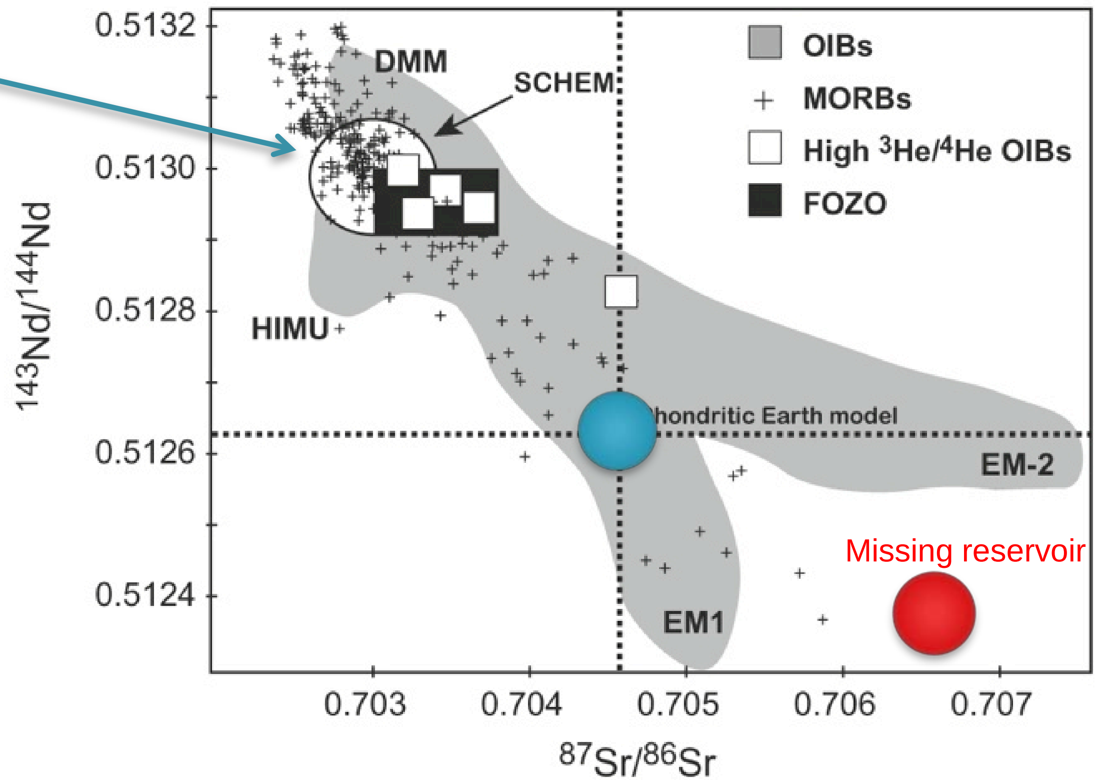


Inspired from Labrosse et al. (next year talk)

Indeed, the high $^3He/^4He$ mantle is not chondritic for Nd

Reservoir deduced from ^{142}Nd excess



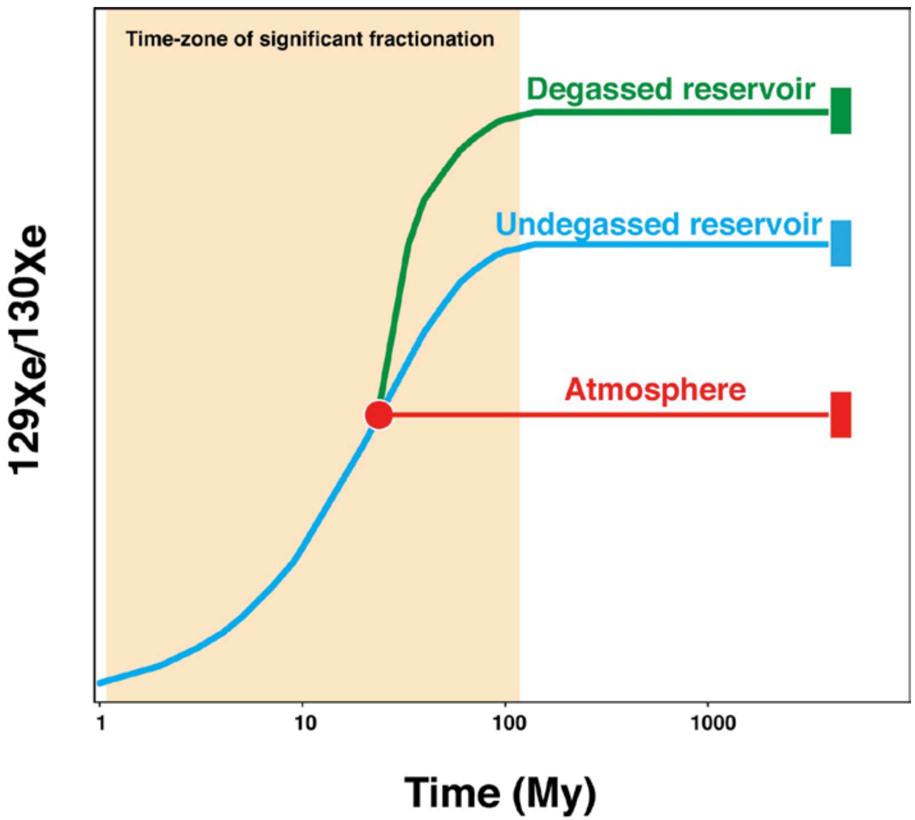
Caro and Bourdon (2010)

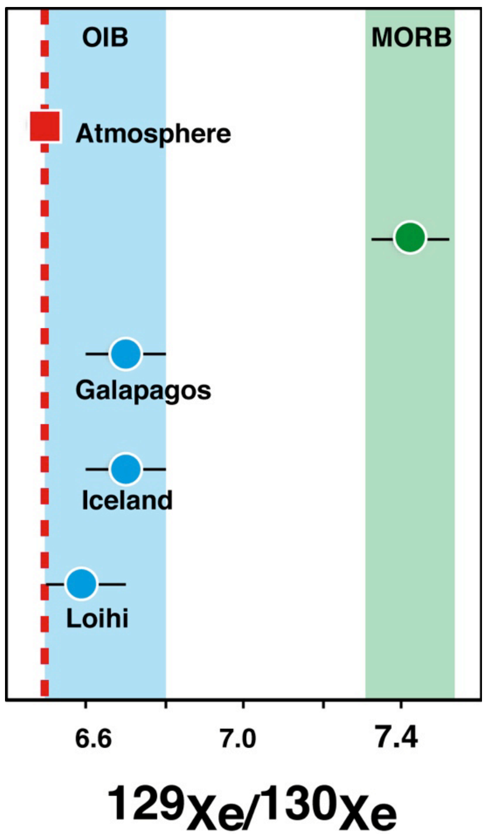
Either Earth is not chondritic for Nd, or there is some missing reservoir

Same process to explain non chondritic Xe isotopes ?

Evidence for an isolation of the OIB source since 4.4Ga

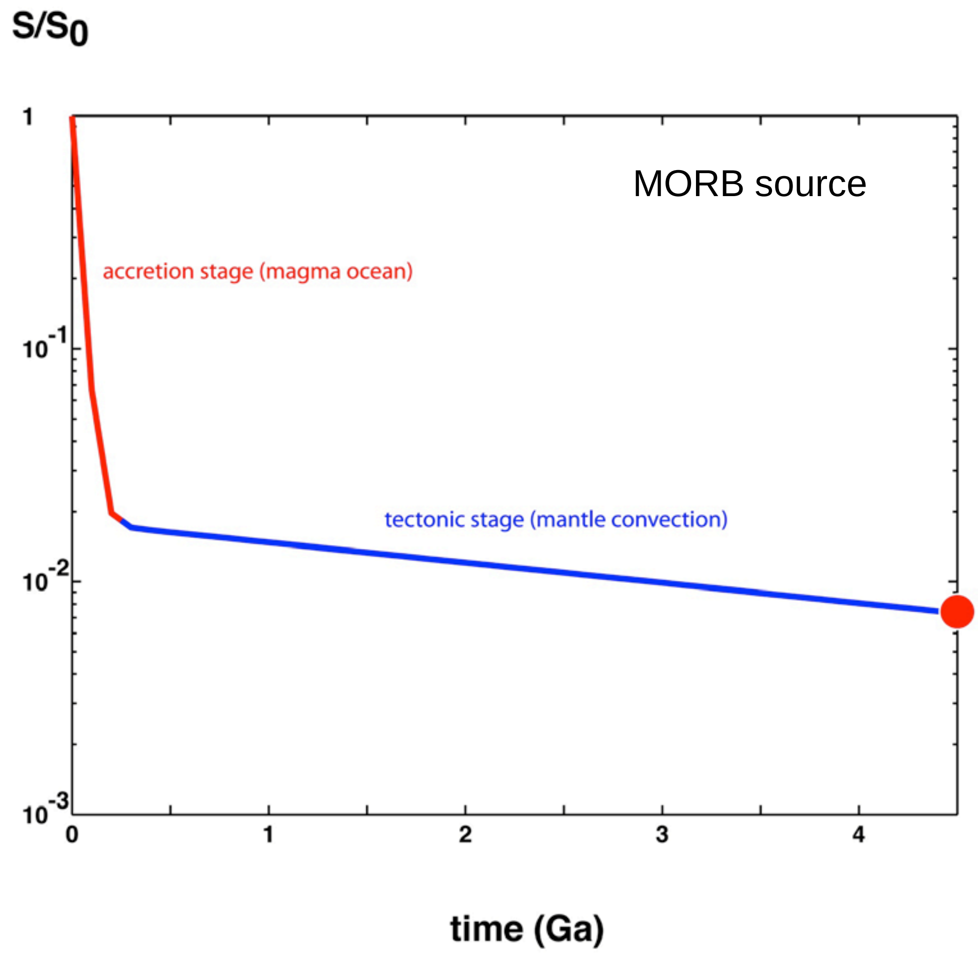
- Use of short life radioactive elements such as ^{129}I (17My) or ^{244}Pu (80My)





First order models of mantle degassing

- Use of K-Ar, ^{3}He flux, I-Xe



Conclusions 1

- Evidences that atmosphere is degassed from the mantle (massively during the first 100My, and then slower)
- MORB source is degassed
- A deep reservoir, sampled by oceanic island basalts, is rich in primordial He, Ne and in radiogenic Ar.
- It may not be primitive in the sense of lithophile elements, but it was not degassed.

Conclusions 2

- $^{129}Xe/^{130}Xe$ ratios suggest that MORB and OIB sources are separated since more than 4.4Ga
- Exact volume of the undegassed reservoir is unknown because primordial abundances are unknown since Earth is not chondritic for noble gases
- It can be the lower mantle (layered mantle)
- It can be located in piles at the bottom of the mantle (cf Labrosse et al. or Coltice et al.)
- Constraints on the magma ocean: cannot have a vigorous convection if whole mantle is melted
- Core is unlikely because noble gases are not siderophile elements.