Noble Gas Constraints on Mantle Structure

Harvard EPS 260 – MIT12.570
Sujoy Mukhopadhyay
Harvard University

He isotope geochemistry

- Two isotopes of helium: ^{3}He and ^{4}He
  ^{3}He is primordial
  ^{4}He produced by radioactive decay of U and Th

- He isotopes are a measure of time-integrated (U+Th)/^{3}He ratio:

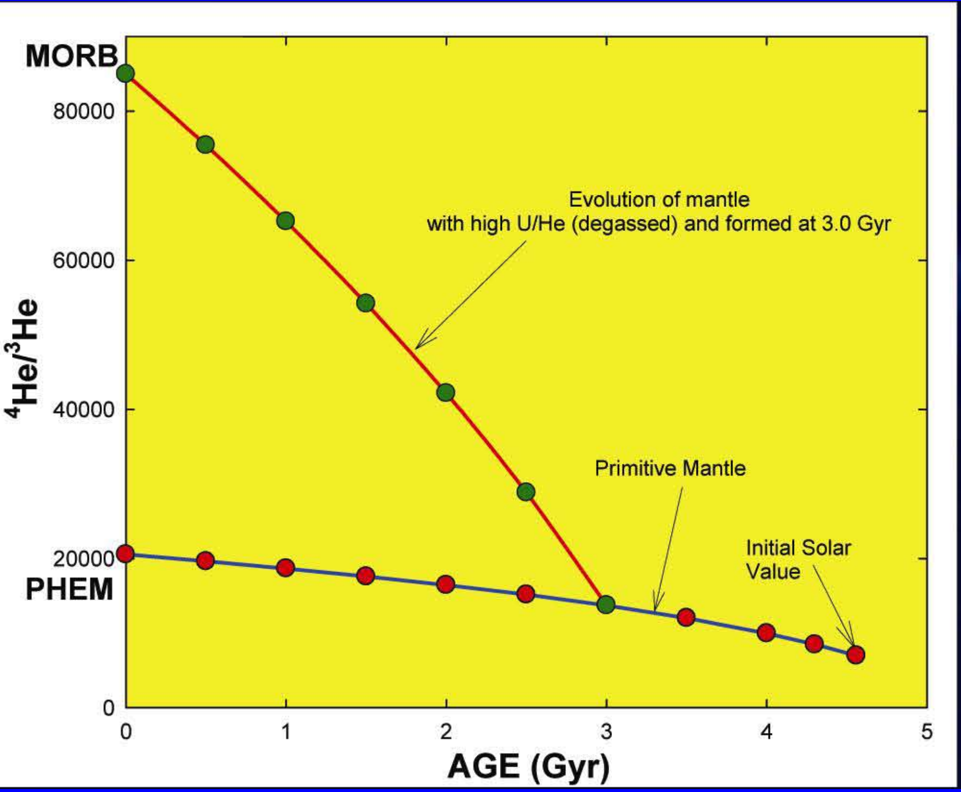
$$\frac{^4\mathrm{He}}{^3\mathrm{He}} = \left(\frac{^4\mathrm{He}}{^3\mathrm{He}}\right)_o + 8\frac{^{238}\mathrm{U}}{^3\mathrm{He}}\left(e^{\lambda_{238}t} - 1\right) + 7\frac{^{235}\mathrm{U}}{^3\mathrm{He}}\left(e^{\lambda_{235}t} - 1\right) + 6\frac{^{232}\mathrm{Th}}{^3\mathrm{He}}\left(e^{\lambda_{232}t} - 1\right)$$

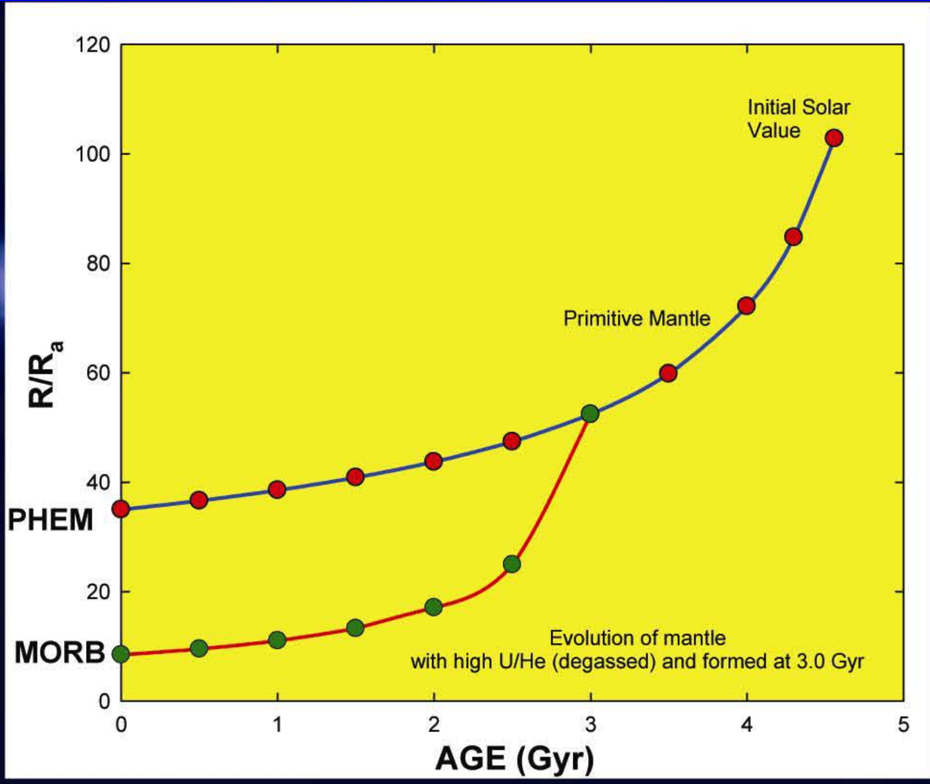
- Helium behaves as an incompatible element during mantle melting

- Helium expected to be more incompatible than U and Th during mantle melting

If so high ^{3}He/^{4}He ratios reflect less degassed mantle material

Helium isotopic evolution in a two layer mantle evolution of helium isotopes





He isotope geochemistry

- Two isotopes of helium: ^{3}He and ^{4}He
  ^{3}He is primordial
  ^{4}He produced by radioactive decay of U and Th

- He isotopes are a measure of time-integrated (U+Th)/^{3}He ratio:

$$\frac{^4\mathrm{He}}{^3\mathrm{He}} = \left(\frac{^4\mathrm{He}}{^3\mathrm{He}}\right)_o + 8\frac{^{238}\mathrm{U}}{^3\mathrm{He}}\left(\mathrm{e}^{\lambda_{238}t} - 1\right) + 7\frac{^{235}\mathrm{U}}{^3\mathrm{He}}\left(\mathrm{e}^{\lambda_{235}t} - 1\right) + 6\frac{^{232}\mathrm{Th}}{^3\mathrm{He}}\left(\mathrm{e}^{\lambda_{232}t} - 1\right)$$

- Helium behaves as an incompatible element during mantle melting

- Helium expected to be more incompatible than U and Th during mantle melting

If so high ^{3}He/^{4}He ratios reflect less degassed mantle material

Histogram of He isotope ratios in mid-ocean ridge basalts (MORBs)

- No relation between isotopic composition and spreading rate but the variance is inversely related to spreading rate

- Either reflects

  - efficiency of mixing in the upper mantle

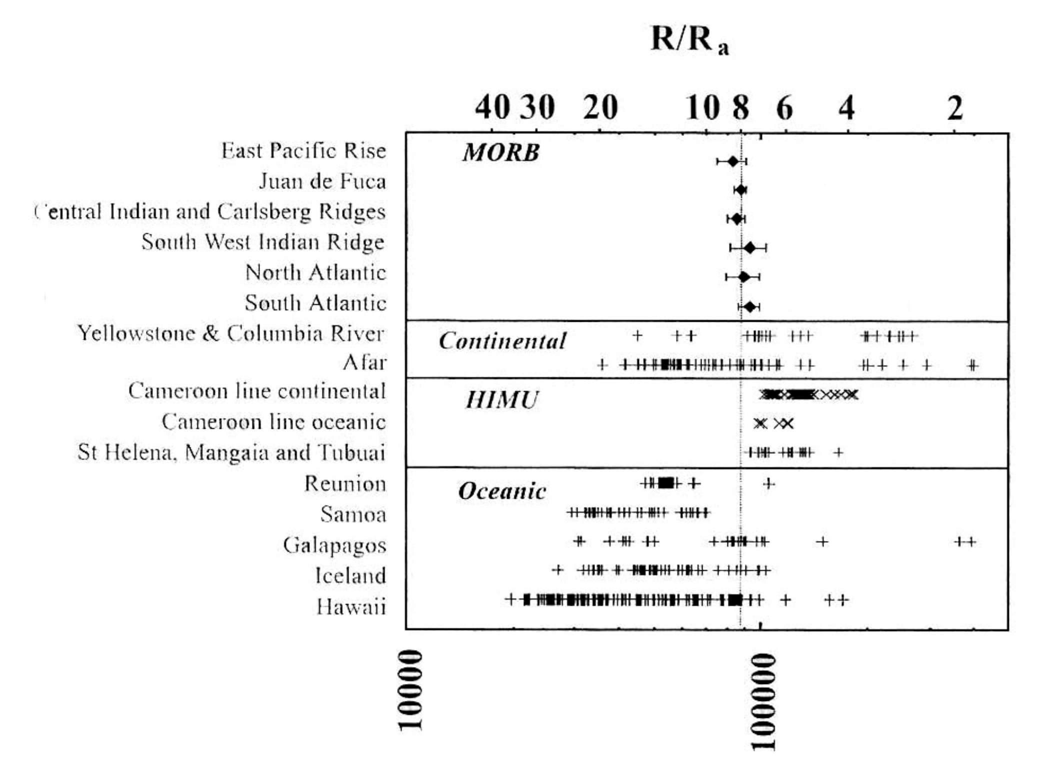
  - differences in degree of magma homogenization

Image removed due to copyright considerations.
Please see:

Graham, David W. "Noble Gas Isotope Geochemistry of Mid-Ocean Ridge and Ocean Island Basalts: Characterization of Mantle Source Reservoirs." In *Noble Gases in Geochemistry and Cosmochemistry*. Edited by D. Porcelli, C. J. Ballentine and R. Wieler. *Reviews in Mineralogy and Geochemistry*. Vol. 47. Washington, DC: Mineralogiocal Society of America, pp. 247-319, 2002.

Comparison of He isotope ratios from selected MORs, OIBs, and continental hotspots

- The mean $^3He/^4He$ ratio from different ridge segments are nearly identical although the variance is different
- OIBs are much more variable
- $^3He/^4He$ ratios less than MORBs are frequently associated with radiogenic Pb (HIMU) and reflects recycled components in the mantle



After Barford, 1999

He isotope ratios in ocean island basalts (OIBs)

- OIBs display a very large range in He isotopic composition
- He isotopic distribution has a double-peak; maxima at 8 R_A and 13 R_A
- The first maxima is identical to the mean from MORBs
  - Clear indication of the involvement of depleted mantle in ocean island volcanism
- The 2nd peak is somewhat surprising and its meaning is unclear

Image removed due to copyright considerations.

Please see:

Farley, K. A., and E. Neroda. "Noble gases in the Earth's mantle." *Ann Rev Earth Planet Sci* 26 (1998): 189-218.

MORBs: sample well-mixed degassed mantle with low $^3He/U+Th$

OIBs: sample heterogeneous, less degassed mantle with high $^3He/U+Th$

Ne isotopic composition of mantle derived rocks

Image removed due to copyright considerations.
Please see:

Graham, David W. "Noble Gas Isotope Geochemistry of Mid-Ocean Ridge and Ocean Island Basalts: Characterization of Mantle Source Reservoirs." In *Noble Gases in Geochemistry and Cosmochemistry*. Edited by D. Porcelli, C. J. Ballentine and R. Wieler. *Reviews in Mineralogy and Geochemistry*. Vol. 47. Washington, DC: Mineralogiocal Society of America, pp. 247-319, 2002.

- Mantle $^{20}Ne/^{22}Ne$ ratio is fixed; $^{21}Ne/^{22}Ne$ varies because of radiogenic ingrowth and varying degrees of degassing
- Different ocean islands have distinct $^{21}Ne/^{22}Ne$ ratios; either reflects varying amounts of MORB mantle addition to the OIB source(s) or different parts of the mantle have been degassed and processed to different degrees

Geochemistry of Ar

Image removed due to copyright considerations.
Please see:

Graham, David W. "Noble Gas Isotope Geochemistry of Mid-Ocean Ridge and Ocean Island Basalts: Characterization of Mantle Source Reservoirs." In *Noble Gases in Geochemistry and Cosmochemistry*. Edited by D. Porcelli, C. J. Ballentine and R. Wieler. *Reviews in Mineralogy and Geochemistry*. Vol. 47. Washington, DC: Mineralogiocal Society of America, pp. 247-319, 2002.

- 1% Ar in the atmosphere
- Significant air contamination for Ar
- Even when $^{3}He/^{4}He$ ratios are as high as 30 R_A, $^{40}Ar/^{36}Ar$ ratios can be atmospheric

- $^{20}Ne/^{22}Ne$ ratio in the mantle does not vary
- Ar isotopic ratios in mantle derived rocks can be corrected for air contamination by extrapolating the $^{40}Ar/^{36}Ar$ ratio to the upper mantle $^{20}Ne/^{22}Ne$ value

Image removed due to copyright considerations.
Please see:

Moreira, M., J. Kunz, and C. J. Allegre. "Rare gas systematics in popping rock: isotopic and elemental compositions in the upper mantle." *Science* 279 (1998): 1178-81.

Geochemistry of Ar

Image removed due to copyright considerations.
Please see:

Graham, David W. "Noble Gas Isotope Geochemistry of Mid-Ocean Ridge and Ocean Island Basalts: Characterization of Mantle Source Reservoirs." In *Noble Gases in Geochemistry and Cosmochemistry*. Edited by D. Porcelli, C. J. Ballentine and R. Wieler. *Reviews in Mineralogy and Geochemistry*. Vol. 47. Washington, DC: Mineralogiocal Society of America, pp. 247-319, 2002.

- MORB mantle $^{40}Ar/^{36}Ar$ values are ~ 40000
- OIBs have lower $^{40}Ar/^{36}Ar$ ratios; reasonable limit is 8000

- A value of 8000 *does not* represent pristine mantle material; must indicate some processing, although significantly less degassed than the mantle source sampled by MORBs

The picture that emerges so far……

1. MORBs are more homogenous compared to OIBs

2. MORBs dominantly sample a mantle source that is more processed and degassed compared to most OIBs

Evidence for a layered structure: The Missing Argon problem

- K content of Earth derived from the K/U ratio of 12700 in MORBs and U content of 20-22.5 ppb
- Implied K content of bulk Earth is 250-285 ppm
- Total ^{40}Ar produced over Earth history = 140-156 x 10^{18} g
- ^{40}Ar in the atmosphere = 66 x 10^{18} g (~50%)
- ^{40}Ar in the crust = 9-12 x 10^{18} g

63-80 x 10^{18} of ^{40}Ar has to be in the mantle

Evidence for a layered structure: The Missing Argon problem

I) Constraints from ^{40}Ar flux

- ^{4}He flux at ridge = 9.46×10^{7} moles/yr
- $^{4}He/^{40}Ar$ ratio in MORBs 2-15

  => ^{40}Ar flux $0.63\text{-}5 \times 10^{7}$ moles/yr
- Mass of oceanic lithosphere passing through ridges = 5.76×10^{17} g/yr

If MORB mantle representative of entire mantle and if lithosphere completely degassed, ^{40}Ar content in mantle $1.8\text{-}14\ 10^{18}$g

Lower than the $63\text{-}81 \times 10^{18}$g estimated (Allegre et al., 1996) and requires a hidden reservoir for ^{40}Ar

Evidence for a layered structure: The Missing Argon problem

II) Constraints from Potassium content

- K content of MORB source is 40-50 ppm; if representative of entire mantle produces 22-28 x 10^{18} g of ^{40}Ar

    -significantly less than the 63-80 x 10^{18} g of ^{40}Ar calculated to be in the mantle

Bottom line: The constraints from ^{40}Ar require some sort of layering or a hidden reservoir in the mantle

Any wiggle room? Maybe we do not know the K/U ratio of the mantle as well as we think (e.g., Lassiter 2004)

Image removed due to copyright considerations.
Please see:

Lassiter, J.C. "The role of encycled oceanic crust in the potassium and argon budget of the Earth: Towards a resolution of the "Missing argon" problem. *Geochemistry Geophysics Geosystems* 5, no. Q11012, doi: 10.1029/2004GC000711 (2004): 16.

Noble Gas Concentrations

- He concentrations higher in MORBs than OIBs
- Maybe not too surprising since most OIBs are erupted at shallower water depths than MORBs; so would be degassed more
- Turns out that such an explanation is not really tenable…

Image removed due to copyright considerations.
Please see:

Honda, Masahiko, and Desmond B Patterson. "Systematic elemental fractionation of mantle-derived helium, neon, and argon in mid-oceanic ridge glasses." *Geochimica et Cosmochimica Acta* 63, no. 18 (September 1999): 2863-2874.

Noble gas elemental ratios

Image removed due to copyright considerations.
Please see:

Honda, Masahiko, and Desmond B Patterson. "Systematic elemental fractionation of mantle-derived helium, neon, and argon in mid-oceanic ridge glasses." *Geochimica et Cosmochimica Acta* 63, no. 18 (September 1999): 2863-2874.

Solubility controlled degassing does not explain the differences in gas concentration between MORBs and OIBs.

Noble gas elemental ratios

Image removed due to copyright considerations.
Please see:

Honda, Masahiko, and Desmond B Patterson. "Systematic elemental fractionation of mantle-derived helium, neon, and argon in mid-oceanic ridge glasses." *Geochimica et Cosmochimica Acta* 63, no. 18 (September 1999): 2863-2874.

- Fractionation has to be recent, otherwise the slope would not be 1 and the $^{4}He/^{21}Ne$ ratio would have evolved back to the production value of ~2 x 10^{-7}

Noble gas elemental ratios

Image removed due to copyright considerations.
Please see:

Burnard, Pete. "Diffusive fractionation of noble gases and helium isotopes during mantle melting." *Earth and Planetary Science Letters* 220, no. 3-4 (April 2004): 287-295. Elsevier.

- The Ar concentration decreases with degassing as expected
- For some MORBs suites, as $^{4}He/^{40}Ar$ ratio increases (more degassed), He concentration increases as well!! So the problem appears to be with He

Partition coefficient of the noble gases

Are the noble gases (^{4}He, ^{21}Ne, ^{40}Ar) really more incompatible than their radiogenic parents (e.g., U, Th, K)?

Image removed due to copyright considerations.
Please see:

Brooker, R. A., V. Heber, S. P. Kelley, and B. J. Wood. "Noble Gas Partitioning Behaviour During Mantle Melting: A Possible Explanation for "The He Paradox"?" *Nature* 423 (2003): 738-741.

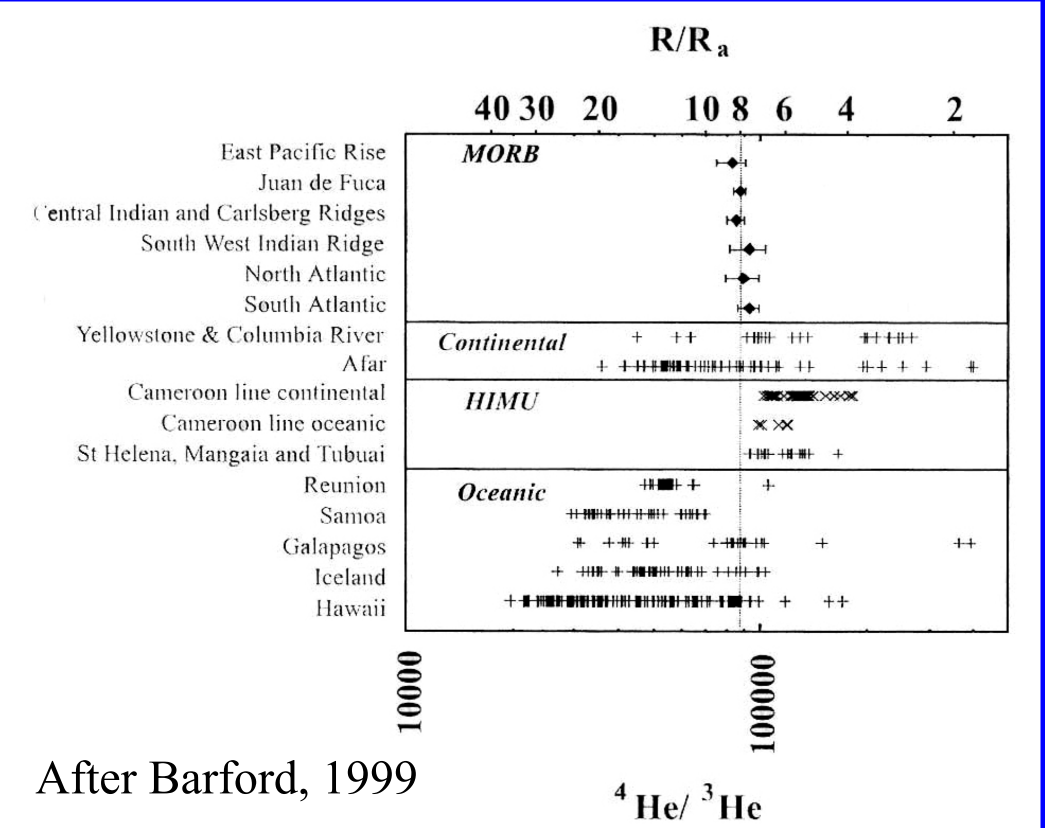
- For clinopyroxene, Ar slightly more incompatible than K
- Experimental data still not good enough to show conclusively how He behaves with respect to U and Th
- Time integrated ratios however provide some insights; for example high ^{3}He/^{4}He ratios are never associated with the most depleted isotopic signatures of Sr and Nd, => seems to imply that He is more incompatible than U and Th

Proving that He is more or less incompatible than U and Th will be a major challenge but will have tremendous implications for mantle geodynamics

Can nature tell us something about of partition coefficients? Maybe……

Time integrated ratios however provide some insights; for example high $^{3}He/^{4}He$ ratios are never associated with the most depleted isotopic signatures of Sr and Nd

-> seems to imply that He is more incompatible than U and Th



After Barford, 1999

Global relationship between He and other lithophile tracers: The wormograms

Image removed due to copyright considerations.
Please see:

Graham, David W. "Noble Gas Isotope Geochemistry of Mid-Ocean Ridge and Ocean Island Basalts: Characterization of Mantle Source Reservoirs." In *Noble Gases in Geochemistry and Cosmochemistry.* Edited by D. Porcelli, C. J. Ballentine and R. Wieler. *Reviews in Mineralogy and Geochemistry.* Vol. 47. Washington, DC: Mineralogiocal Society of America, pp. 247-319, 2002.

Inferences:

High $^{3}He/^{4}He$ ratios from a single, relatively undegassed mantle source that is characterized by well defined Sr, Nd, and Pb isotopic composition

Primitive mantle may not exist but a reservoir that is less degassed than the MORB mantle almost certainly does.

Relationship between He and other lithophile tracers

- If high $^{3}He/^{4}He$ ratios are due to an ancient melt depletion event, high $^{3}He/^{4}He$ ratios should be associated with very depleted Sr-isotopic composition.

- Higher $^{3}He/^{4}He$ ratios are associated with *less* depleted $^{87}Sr/^{86}Sr$ isotopic signal

$\Rightarrow$ high $^{3}He/^{4}He$ ratios are indicative of less degassed mantle

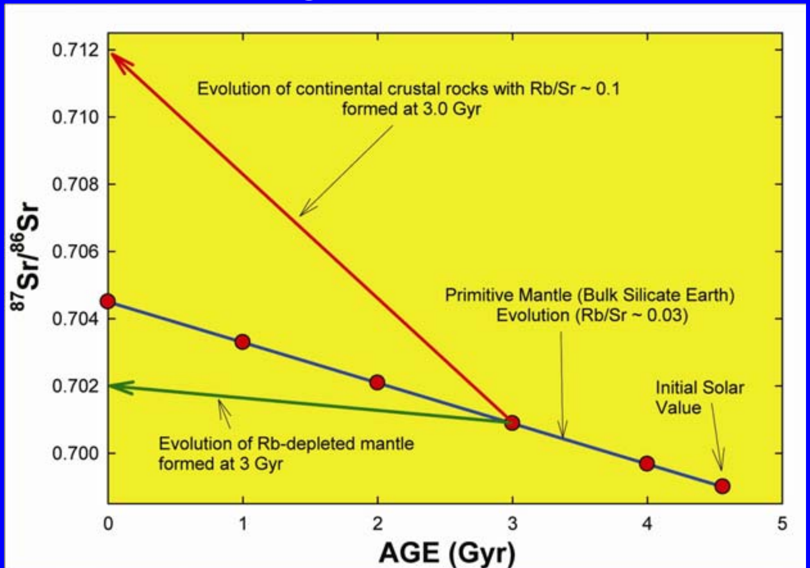


Image removed due to copyright considerations.
Please see:

Kurz, M. D. "Rapid helium isotopic variability in Mauna Kea shield lava from the Hawaiian Scientific Drilling Project." *Geochemistry Geophysics Geosystems* 5, no. 4 (2004): Q04G14.