MYRES 2004

Noble Gas Constraints on Mantle Structure and Convection

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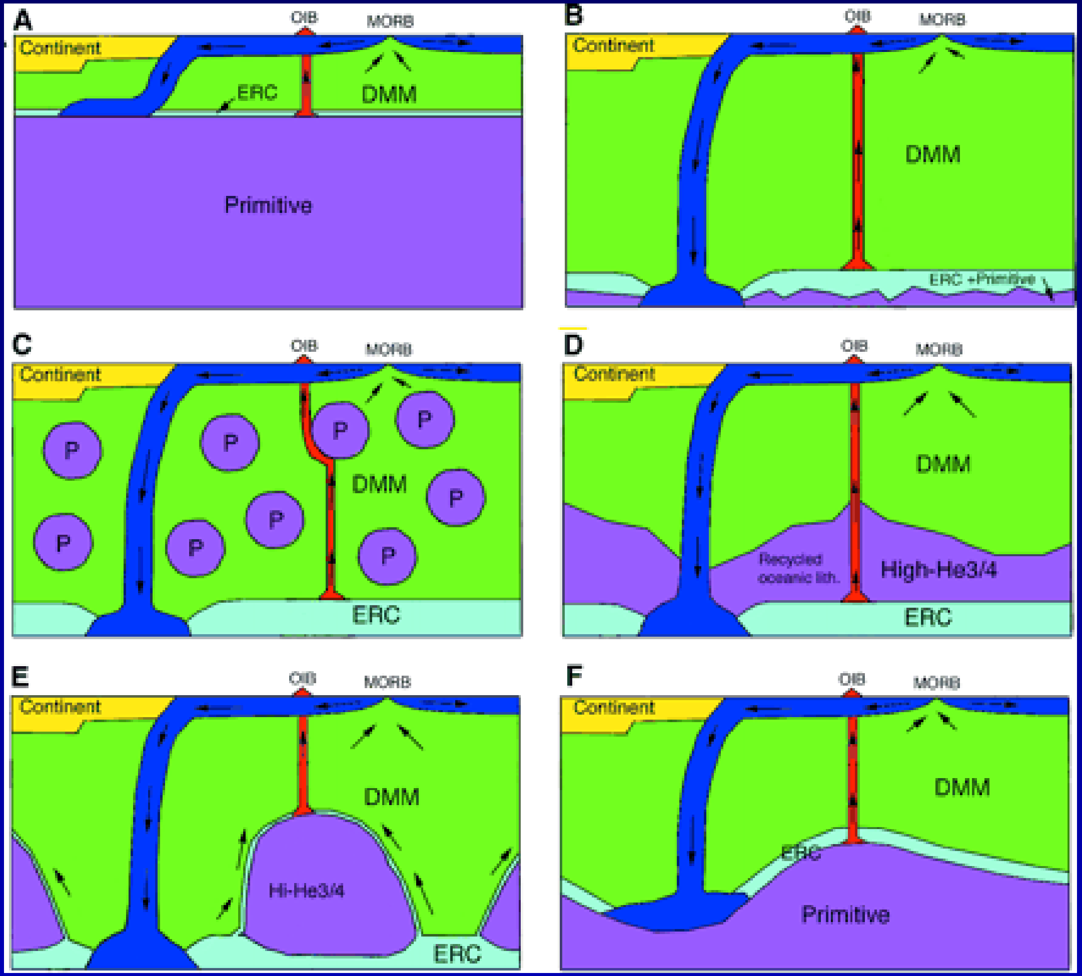
Which (if any) of these views of the mantle are correct?



Tackley, 2000

What are the constraints on mantle reservoirs provided by the noble gases?

- what we know, what we infer, and what we do not understand

Outline

- Helium, Neon, and Argon isotopic composition of Mid Ocean Ridge Basalts (MORBs) and Ocean Island Basalts (OIBs) – observations and constraints
- Missing Argon problem
- He Heat paradox
- Combined noble gases and lithophile tracers (Sr, Nd, Pb)
- Noble gas concentrations and elemental ratios- challenges in reconciling isotopic and elemental composition

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 (i.e. prefers melt over minerals)

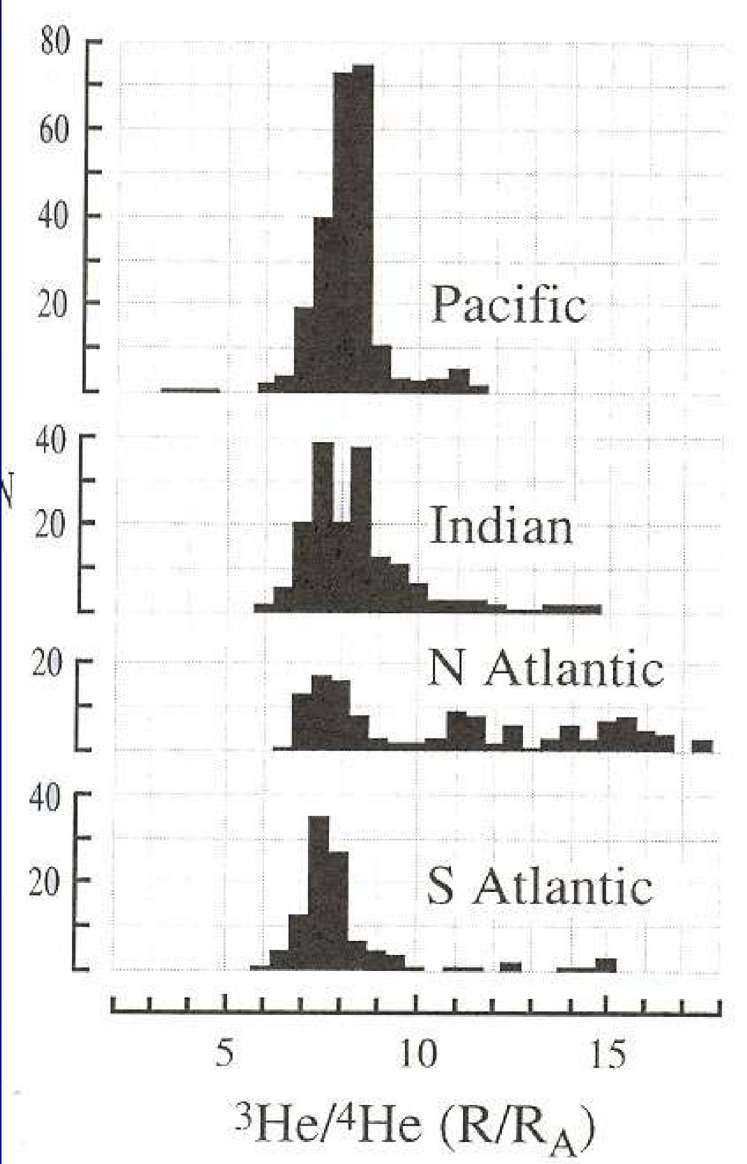
- Helium *expected* to be more incompatible than U and Th during mantle melting

- Helium not recycled back into the mantle

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

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

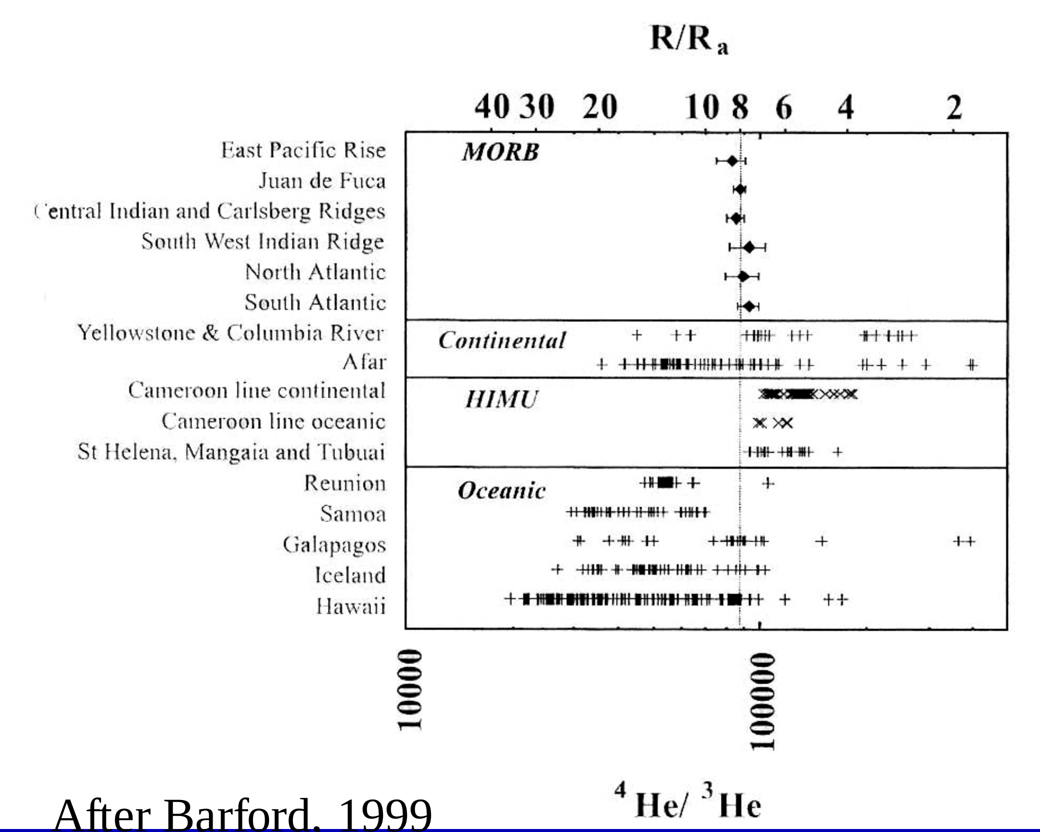
- $^3He/^4He$ ratios reported relative to the atmospheric ratio of 1.39 x 10^{-6}
- No relation between isotopic composition and spreading rate but the variance is inversely related to spreading rate
- Either reflects
  - efficiency of mixing in the upper mantle
  - differences in degree of magma homogenization



Graham 2002

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

- The mean $^3He/^4He$ ratio from different ridge segments is 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

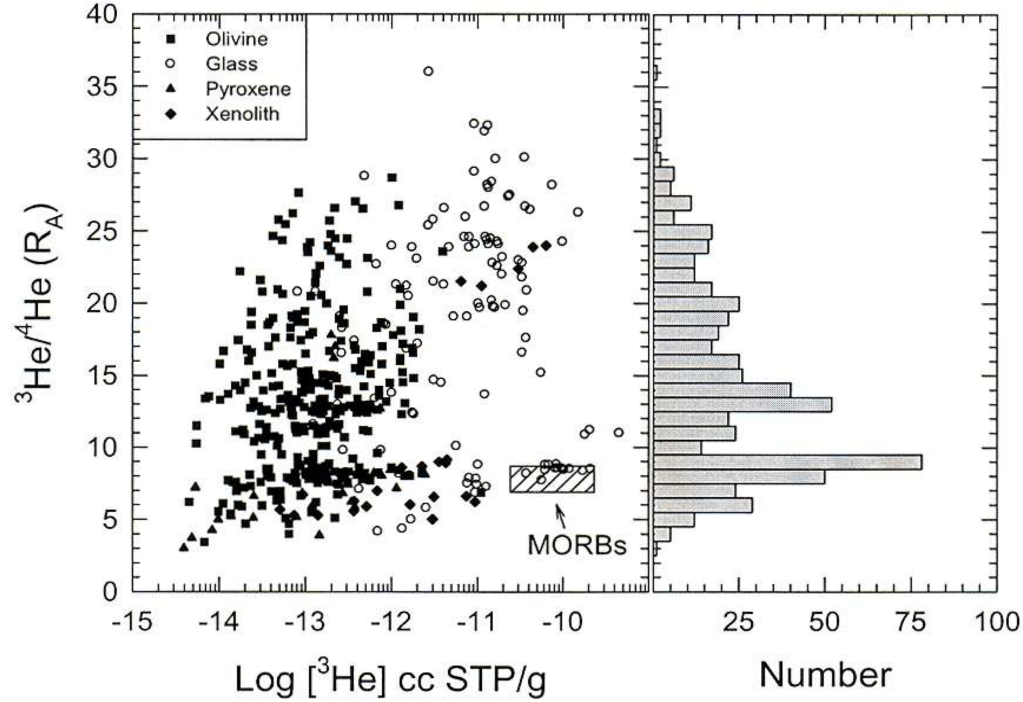


After Barford, 1999

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

Farley and Neroda 1998



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

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

Geochemistry of Ne

- Neon has three isotopes ^{20}Ne, ^{21}Ne, and ^{22}Ne
- ^{20}Ne is primordial
- ^{21}Ne is produced by nucleogenic reactions in the mantle:
  - $^{18}O(\alpha, n)^{21}Ne$ and $^{24}Mg(n, \alpha)^{21}Ne$
  - α from U decay; neutrons from spontaneous fission; production ratio of $^{21}Ne/^{4}He$ is $\sim 10^{-7}$
- ^{22}Ne is primordial. There may be a small nucleogenic production of ^{22}Ne, [$^{19}F(\alpha, n)^{22}Ne$] but it is likely to be negligible
- $^{20}Ne/^{22}Ne$ does not vary in the mantle derived rocks; $^{21}Ne/^{22}Ne$ does
- Ne is expected to be more incompatible than U and Th during mantle melting => low $^{21}Ne/^{22}Ne$ ratios reflect less degassed mantle material

Ne isotopic composition of mantle derived rocks

Less degassed ⟷ More degassed

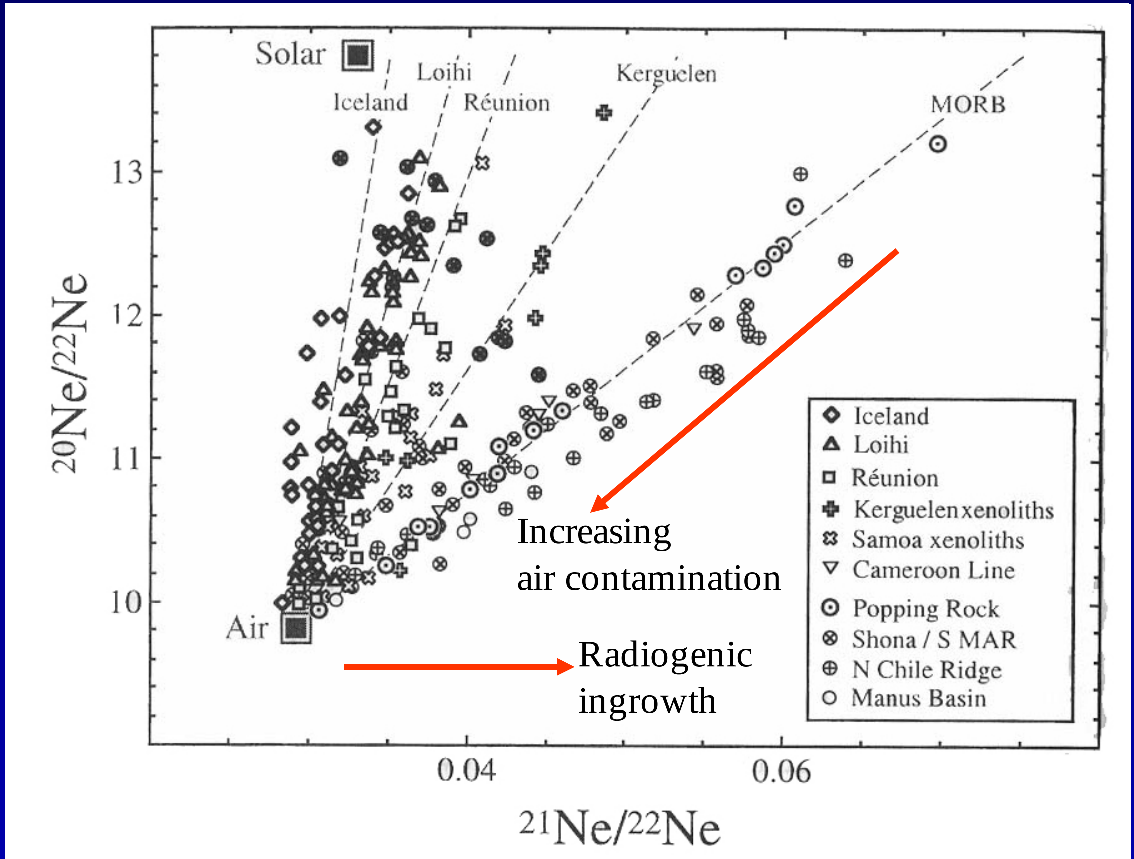


Figure from Graham 2002

- 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

- Three stable isotopes of Ar, ^{36}Ar, ^{38}Ar, ^{40}Ar
- ^{36}Ar and ^{38}Ar are primordial
- ^{40}Ar produced by radioactive decay of ^{40}K
- Ar is expected to be more incompatible than K during mantle melting
- If so high $^{40}Ar/^{36}Ar$ reflects degassed mantle material

Geochemistry of Ar

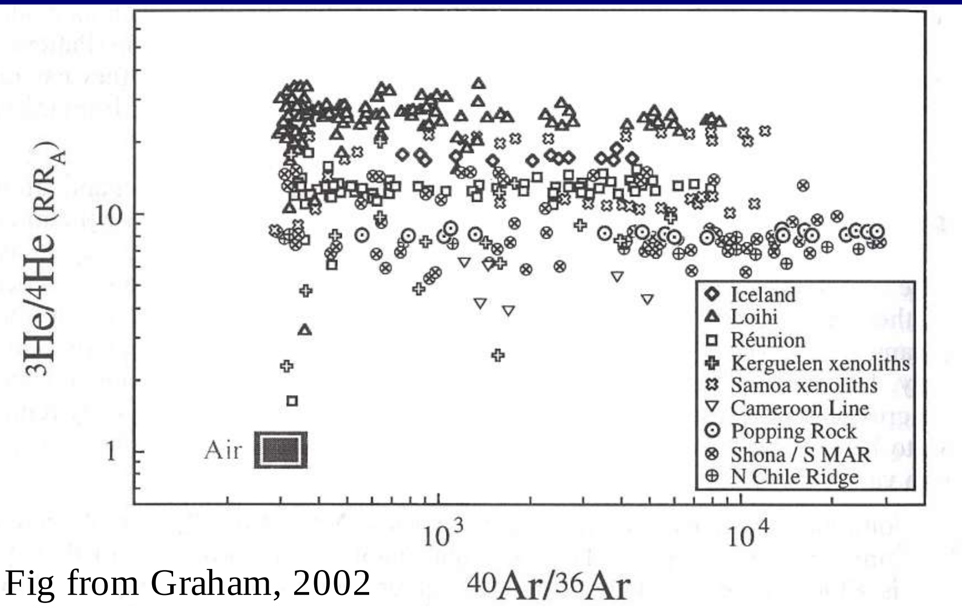


Fig from Graham, 2002

- 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

Geochemistry of Ar

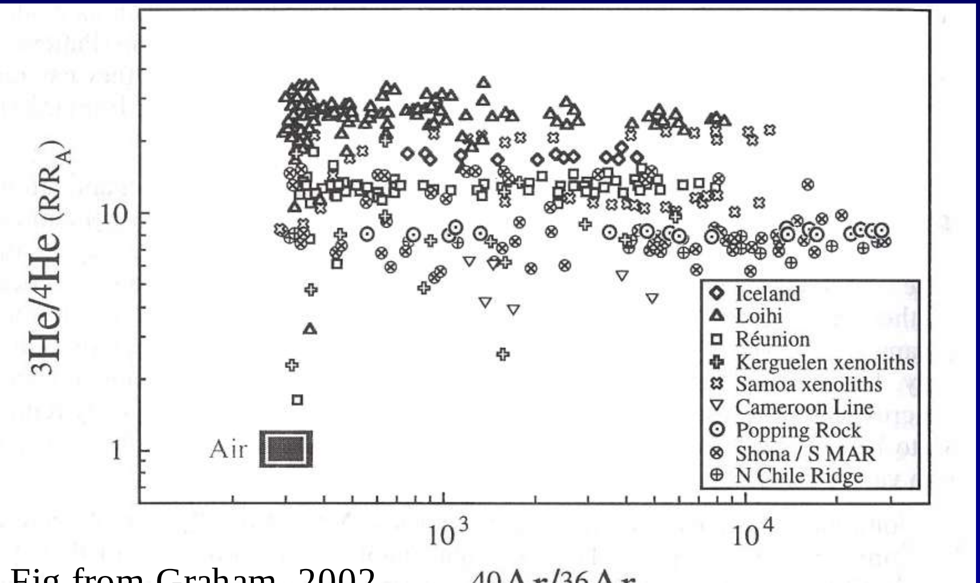


Fig from Graham, 2002

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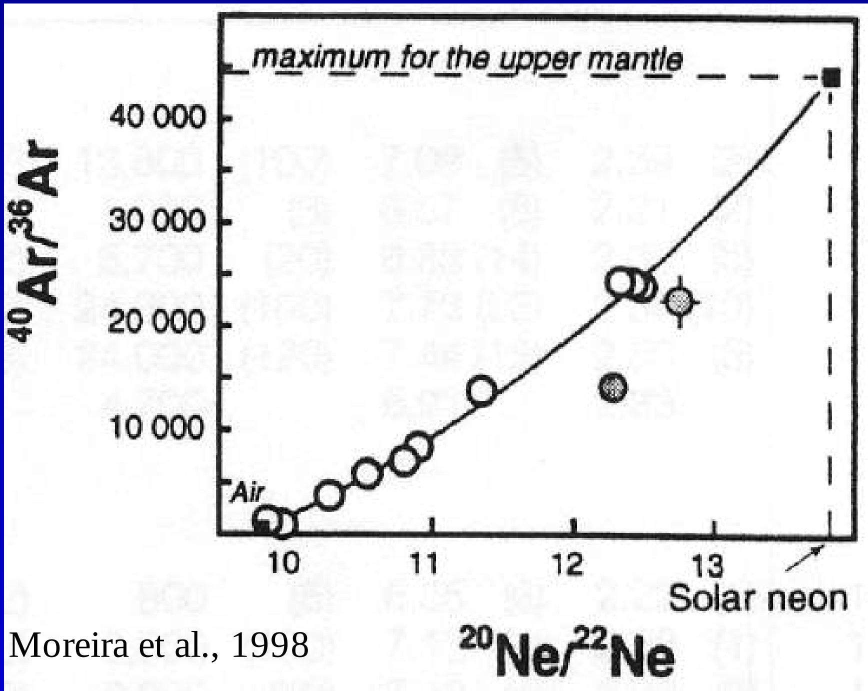
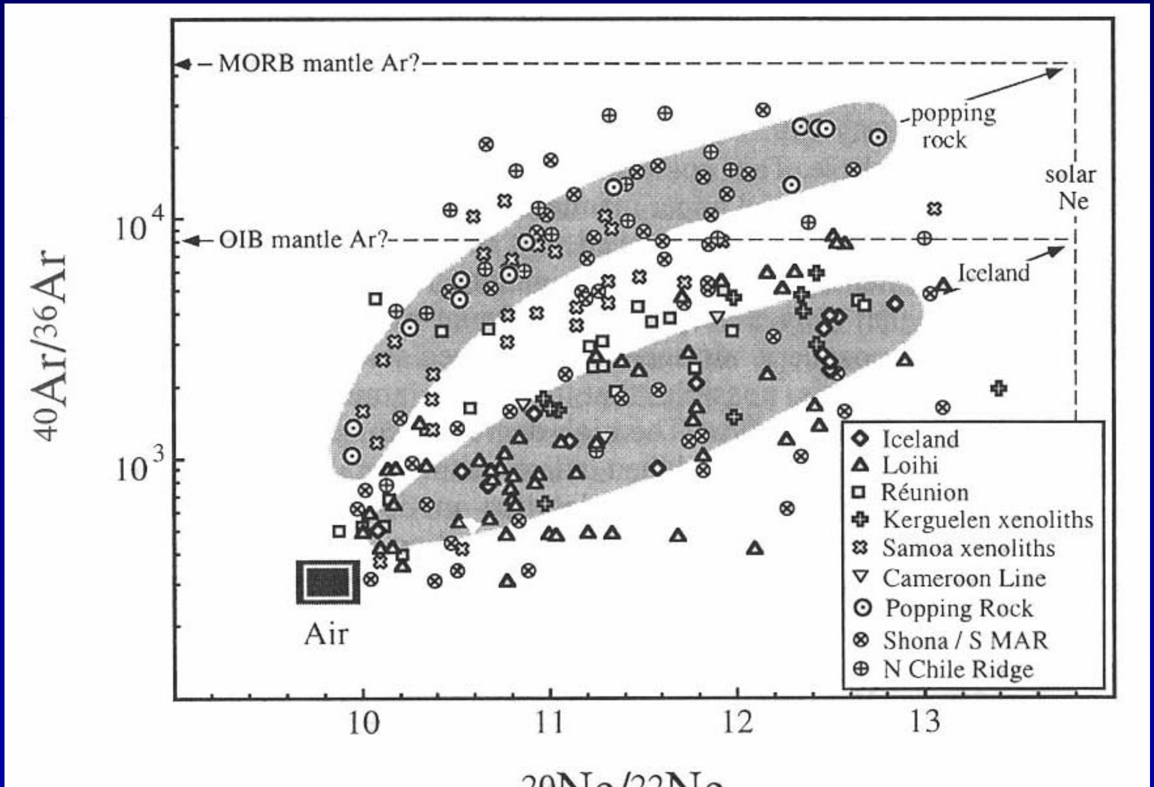
- Even when $^{3}He/^{4}He$ ratios are as high as 30 R_A, $^{40}Ar/^{36}Ar$ ratios can be atmospheric

- $^{20}Ne/^{22}Ne$ 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



Moreira et al., 1998

Geochemistry of Ar



From Graham, 2002

- MORB mantle $^{40}Ar/^{36}Ar$ values are ~ 40,000
- 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……

2. MORBs are more homogenous compared to OIBs

4. Many OIBs sample a mantle source that is significantly less degassed than the mantle source tapped by MORBs

Evidence for undegassed reservoir: 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} g of ^{40}Ar has to be in the mantle

Evidence for undegassed reservoir: The missing Argon problem

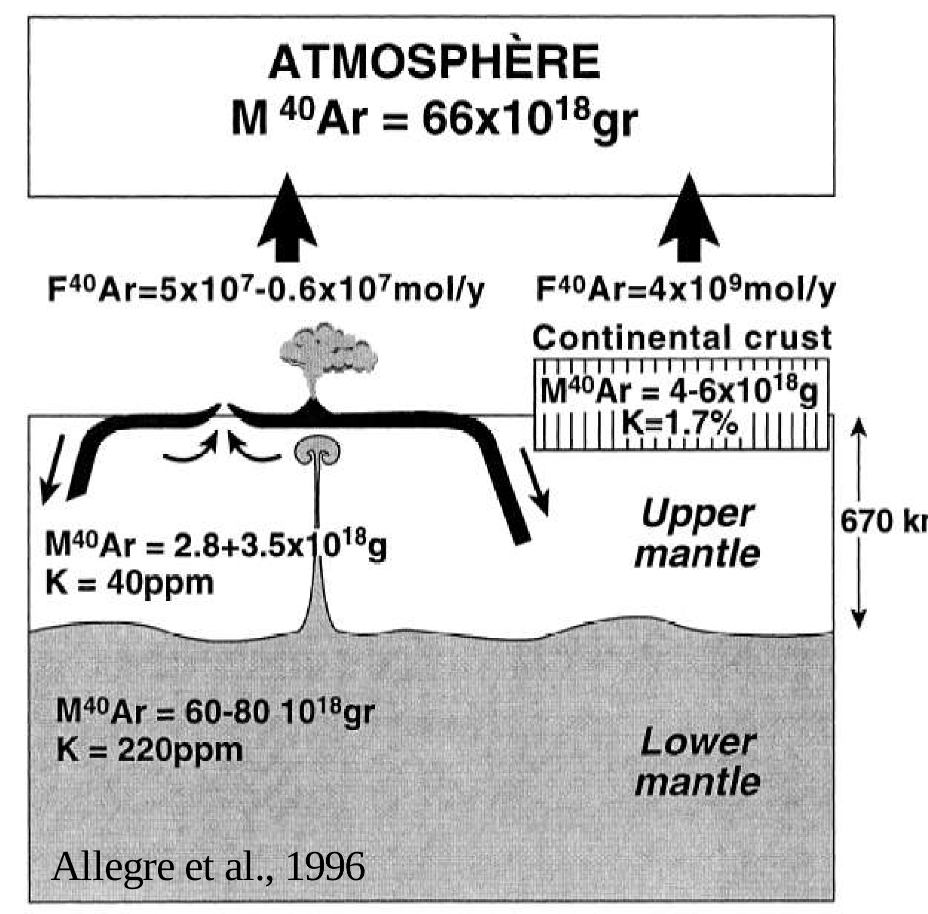
I) Constraints from ^{40}Ar flux

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

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

  If MORB mantle representative of entire mantle and if lithosphere completely degassed, ^{40}Ar content in mantle 1.4-1.8 10^{18}g

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



If MORB mantle extends to 670 km, 0.6-4.6 x 10^{18} g of ^{40}Ar in upper mantle and 59 x 10^{18}g of ^{40}Ar in the lower mantle, corresponding to a K concentration of about 230ppm; consistent with K content of bulk Earth

Evidence for undegassed reservoir: The missing Argon problem

II) Constraints from Potassium content

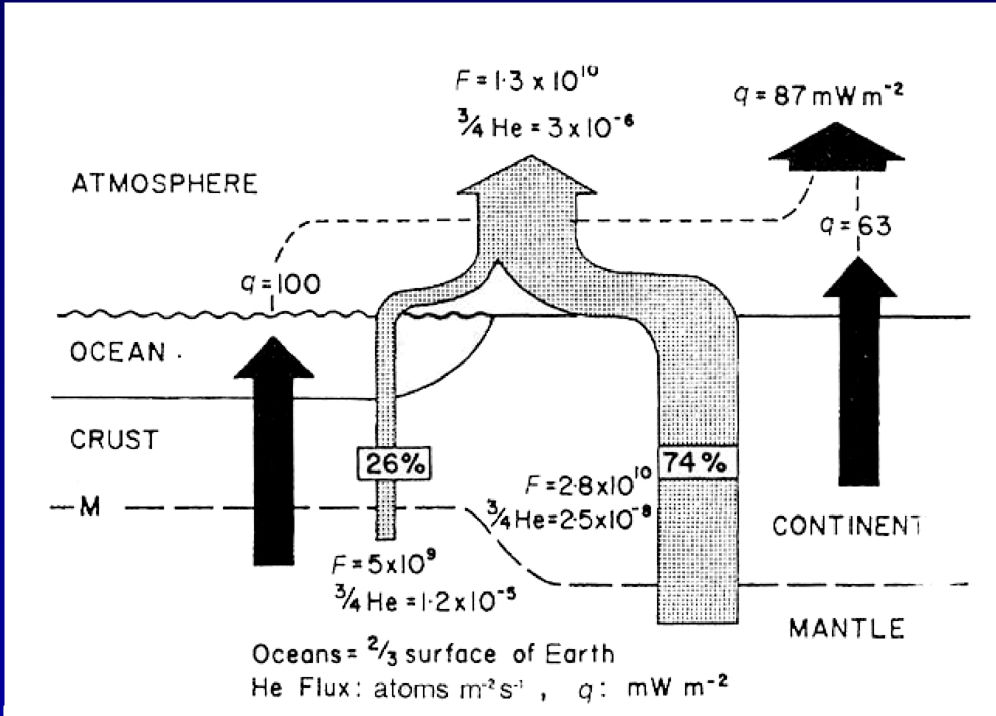
- K content of MORB source is 40-50 ppm; if representative of entire mantle produces 22-28 x 10^{18} g of ^{40}Ar
  - -significantly less than the 63-80 x 10^{18} g of ^{40}Ar calculated to be in the mantle
- If mantle is layered at 670 km 7.3-9. x 10^{18} g ^{40}Ar in the upper mantle

  => 54-74 x 10^{18} g in the lower mantle, corresponding to an K content of 230 ppm in the lower 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., Albarede, 1998; Lassiter, 2002)

The Helium Heat Paradox



O'Nions and Oxburgh, 1983

- ~75% of He entering the atmosphere is from continental crust
- ~25% from the mantle
- ~10% of the He from the mantle is primordial and the rest is radiogenic

The Helium Heat Paradox

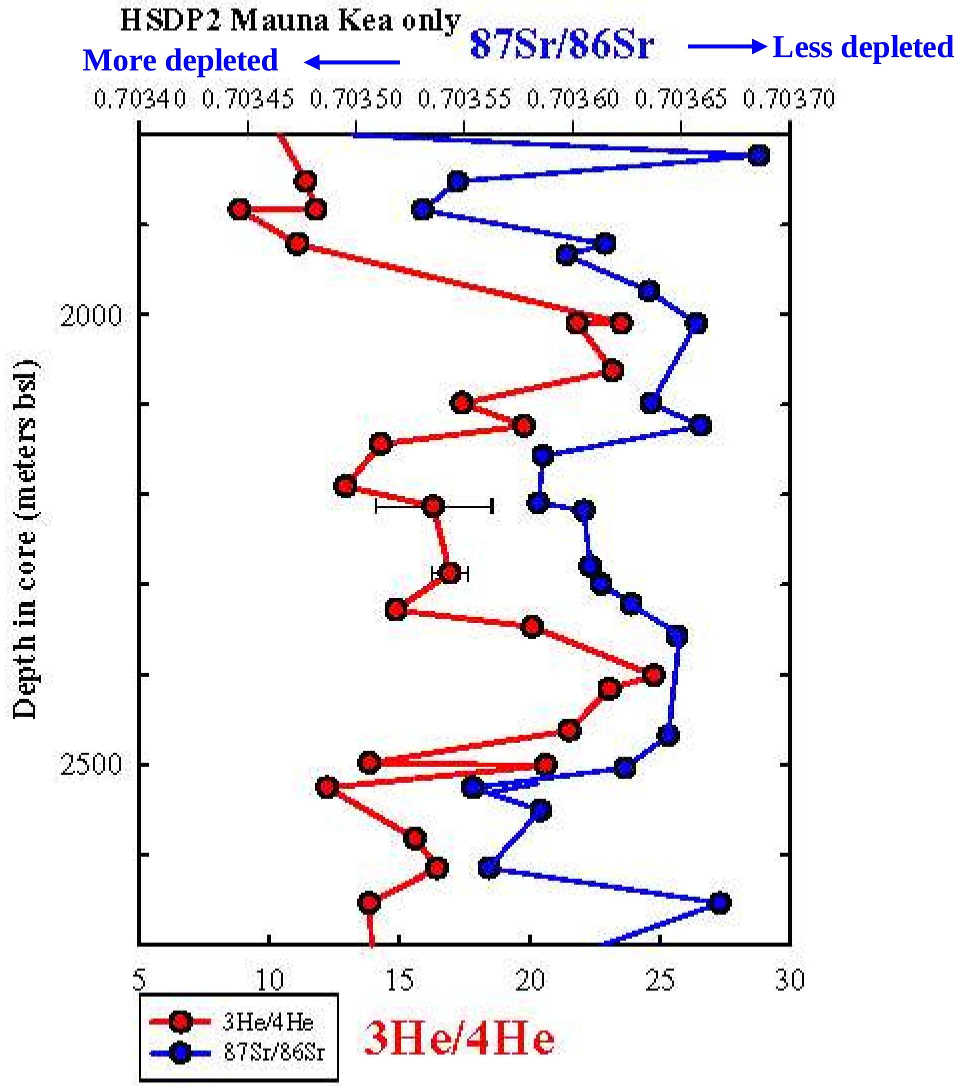
- ^{4}He produced by radioactive decay of U and Th
- 10^{-12} J of energy is liberated for each alpha decay
- The radiogenic ^{4}He flux from the mantle corresponds to 2.4 TW of heat production
- Terrestrial heat flux is 44 TW (Pollack et al., 1993) -- 5-10 TW from crust (e.g., Rudnick and Fountain, 1995) , 3-7 from core (Buffett et al., 1996) ; and 27-36 TW from the mantle
- Of 27-36 TW from the mantle, 18–22 is secular cooling; radiogenic heat is between 9-14 TW, factor of 4-6 greater than the 2.4 TW of heat that is supported by the ^{4}He flux
- Implies a boundary layer in the mantle that passes heat but mostly retains ^{4}He (O'Nions and Oxburgh, 1983)

Relationship between He and other lithophile tracers

- He isotopic variations are strongly coupled to variations in other lithophile tracers (Sr, Nd, Pb)

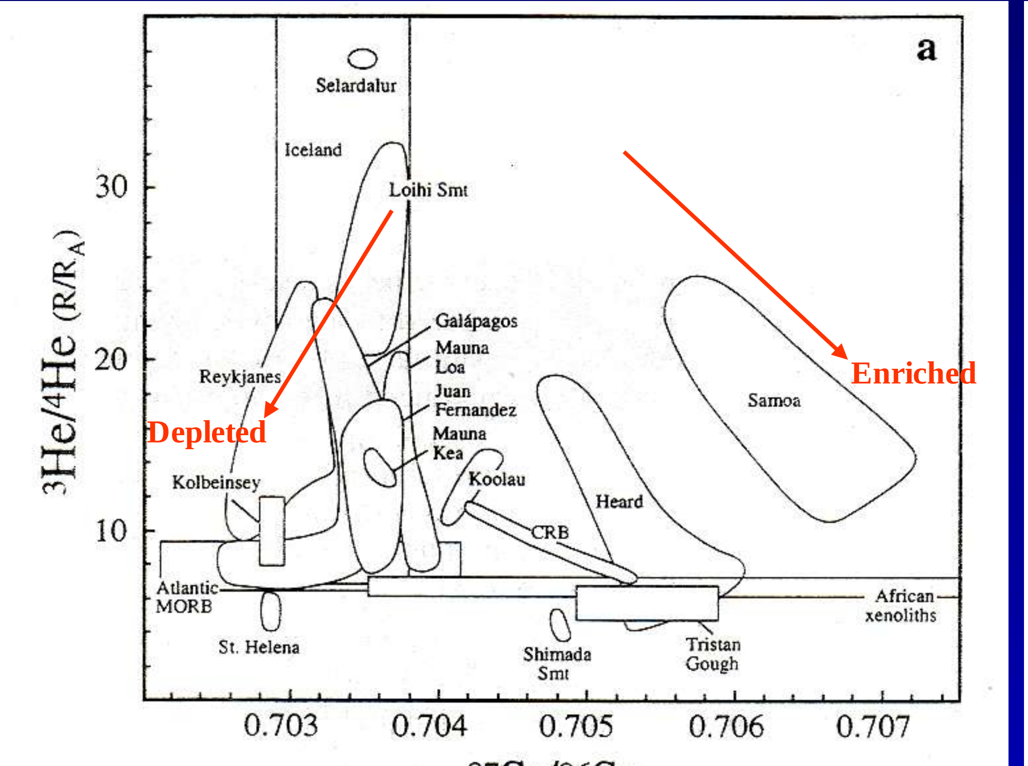
- Higher $^3He/^4He$ ratios are associated with *less* depleted $^{87}Sr/^{86}Sr$ isotopic signal

⇒ high $^3He/^4He$ ratios are indicative of less degassed mantle

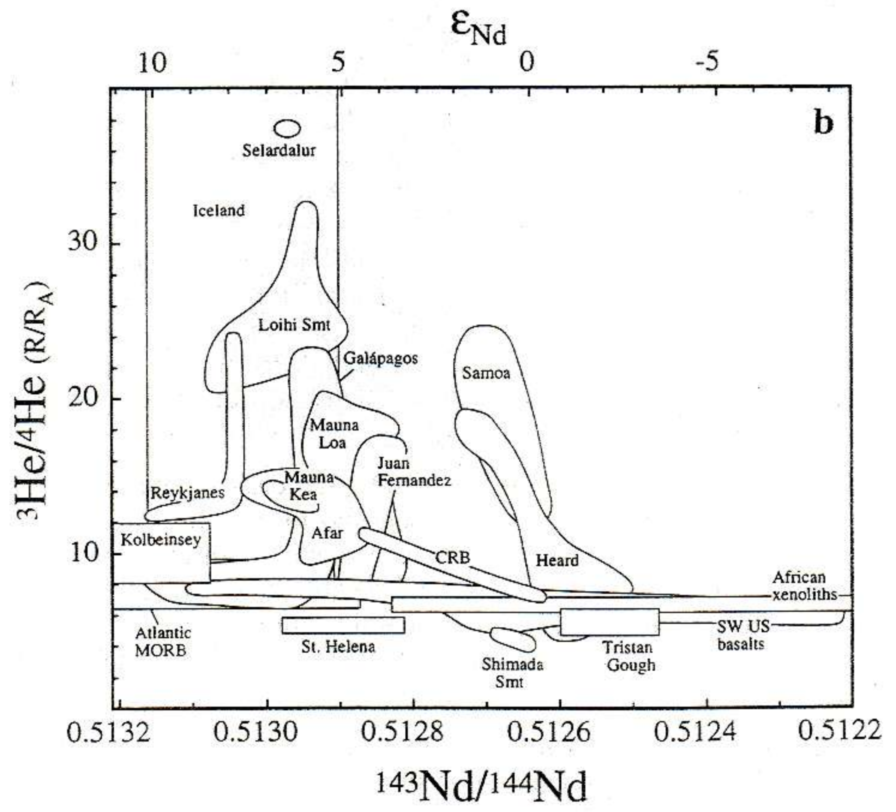


Above data is from the 3 km deep drill hole from Mauna Kea, Hawaii (Kurz et al., 2004)

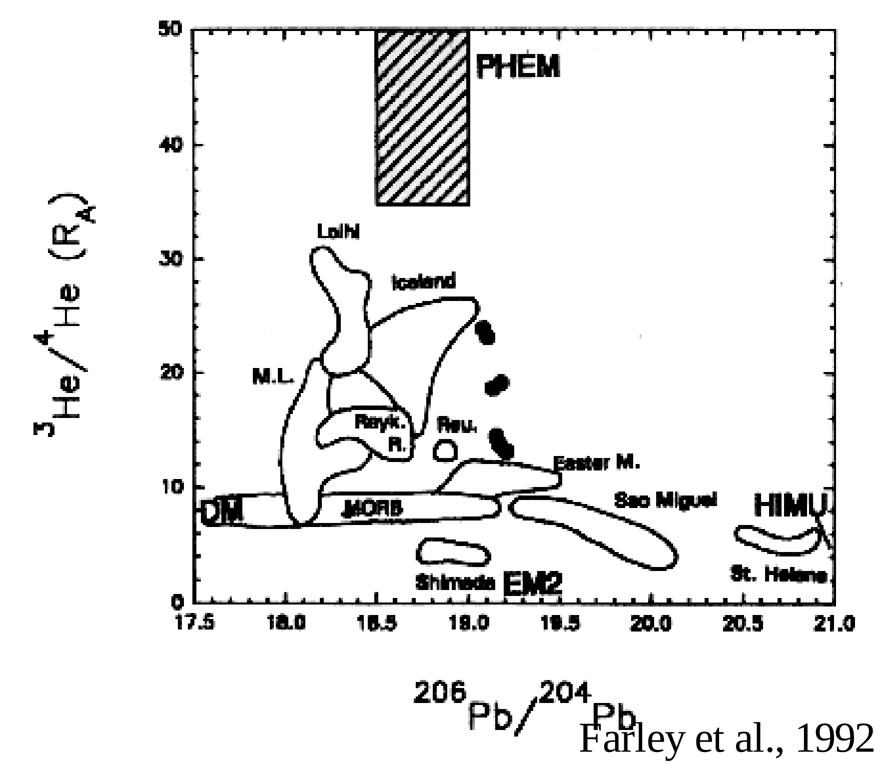
Global relationship between He and other lithophile tracers: The wormograms



From Graham (2002)



Global relationship between He and other lithophile tracers



- Observations:
- Highest $^3He/^4He$ ratios occur at intermediate values of Sr, Nd, and Pb and not associated with either the most depleted or most enriched mantle end-members
- Isotopic arrays from individual ocean islands convergence to a composition that is internal to the mantle end-members defined in Sr, Nd, and Pb isotopic space

Global relationship between He and other lithophile tracers

Inferences:

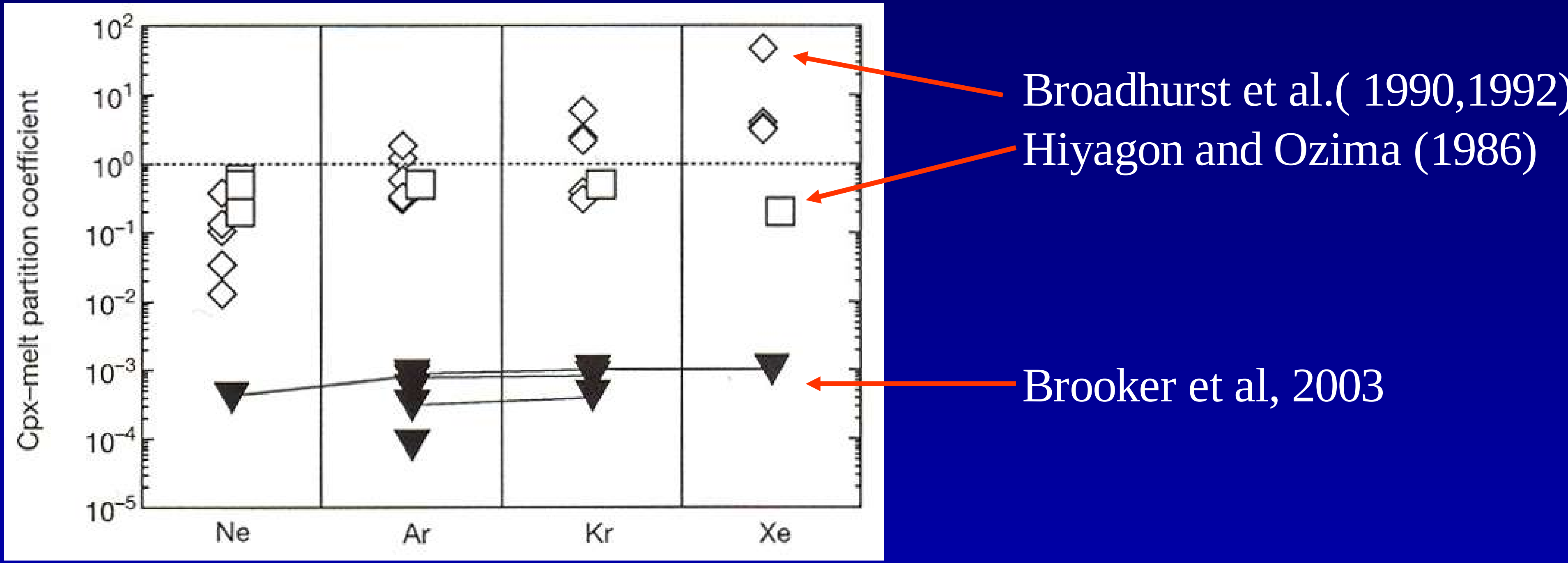
- High $^{3}He/^{4}He$ ratios from a single, relatively undegassed mantle source that is characterized by well defined Sr, Nd, and Pb isotopic composition

- $^{3}He/^{4}He$ is one of the reasons to come up with a component (PHEM, FOZO, C) that is internal to the other mantle end-members in Sr, Nd, and Pb isotopic space (EM1, EM2 HIMU, DM)

- FOZO/C has Sr, Nd, Pb isotopic composition that is slightly depleted in comparison to primitive mantle; PHEM is primitive

- But there appears to be a problem: mixing hyperbolas seem to curve the wrong way… undegassed reservoir should have higher He concentration

Partition coefficient for noble gas



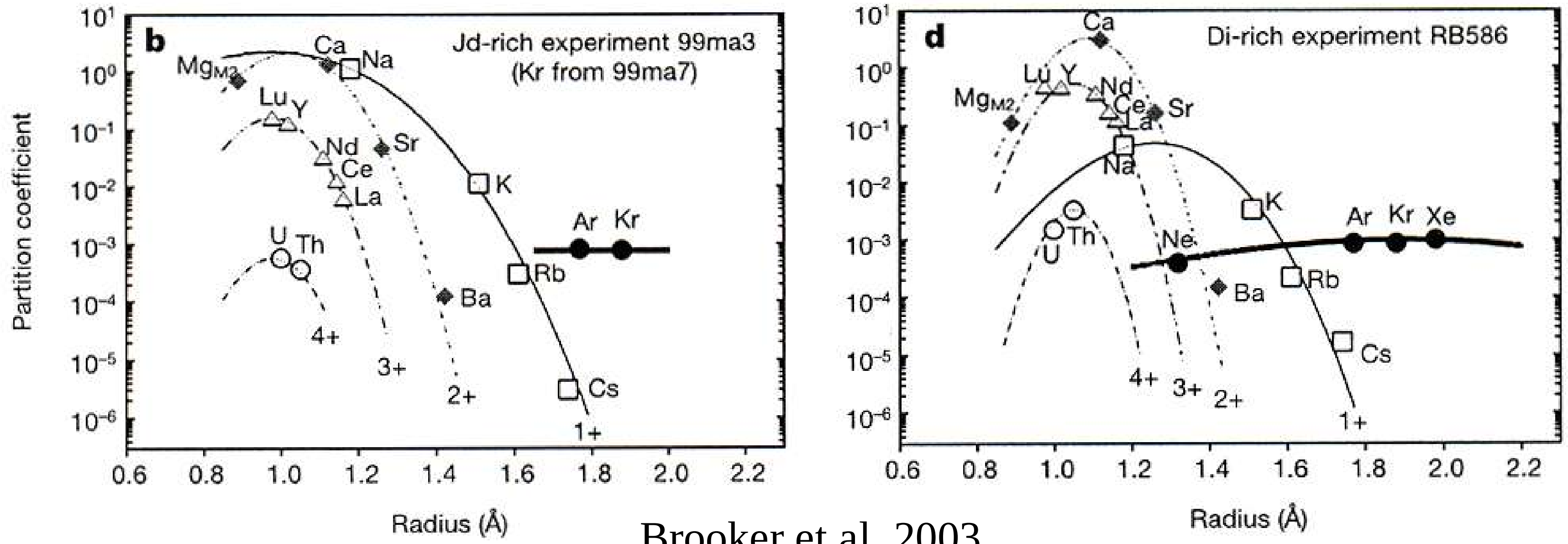
Cpx-melt partition coeffcients

Hard to determine experimentally because of the formation of fluid inclusion; noble gases will prefer a fluid over a melt

But ability to measure partition coefficient getting better

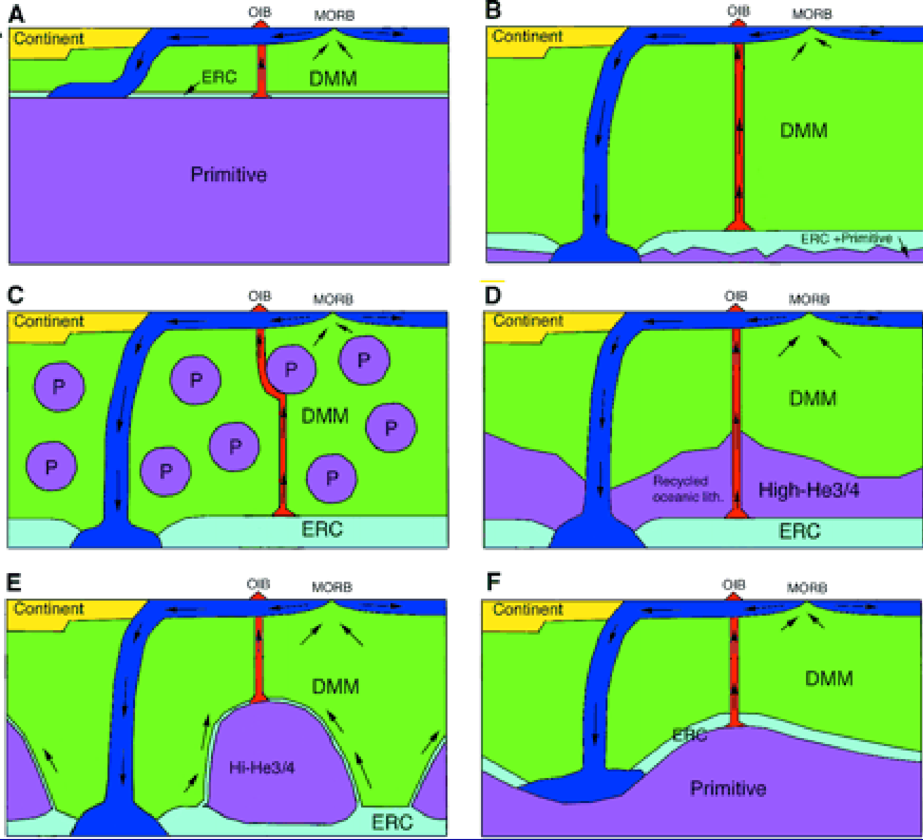
Partition coefficient of the noble gases

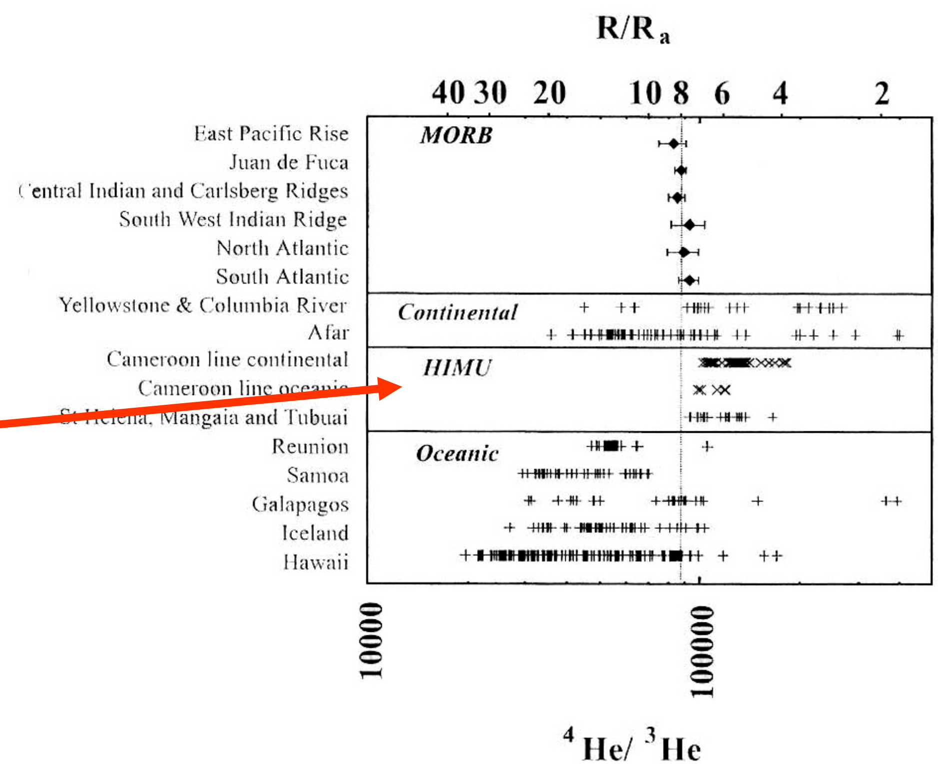
Are the noble gases (^{4}He, ^{21}Ne, ^{40}Ar) really more incompatible than their radiogenic parents (e.g., U, Th, K)?



Brooker et al, 2003

- 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,

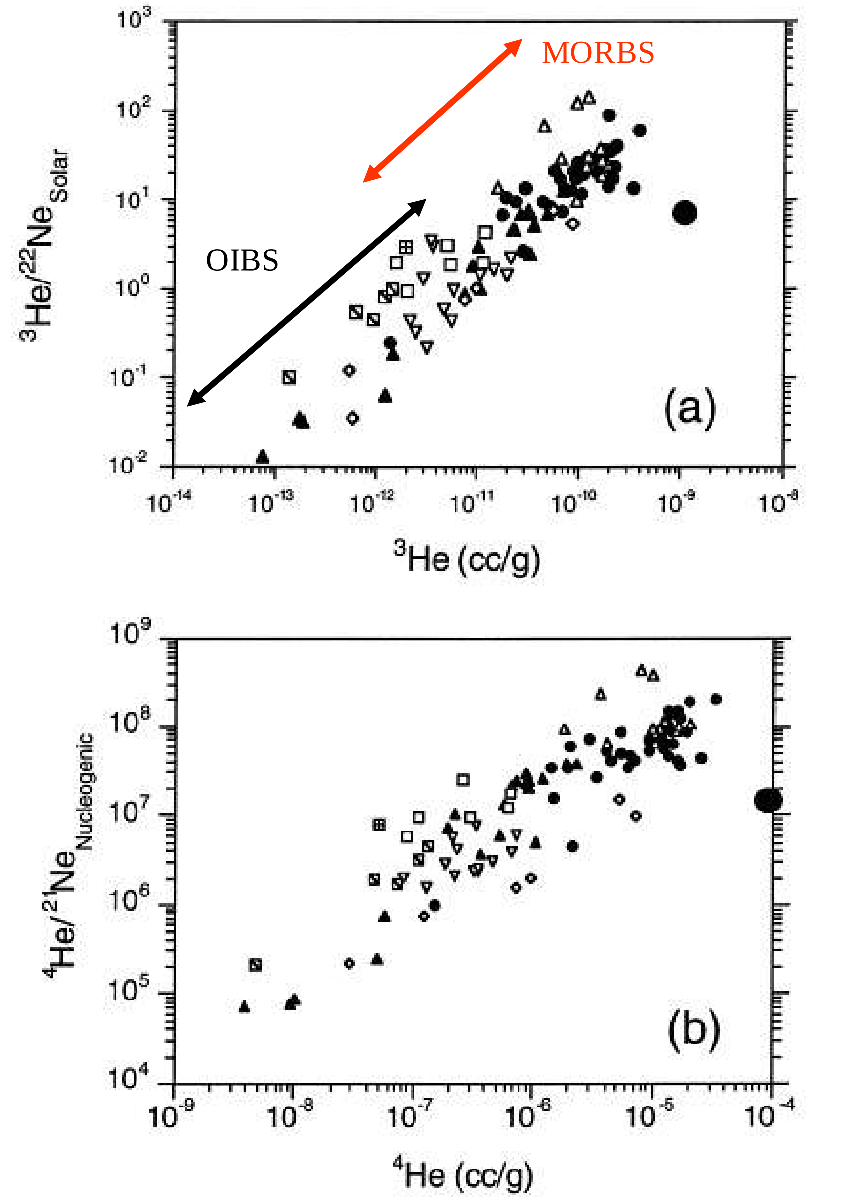




But recycled crust does not have high $^3He/^4He$

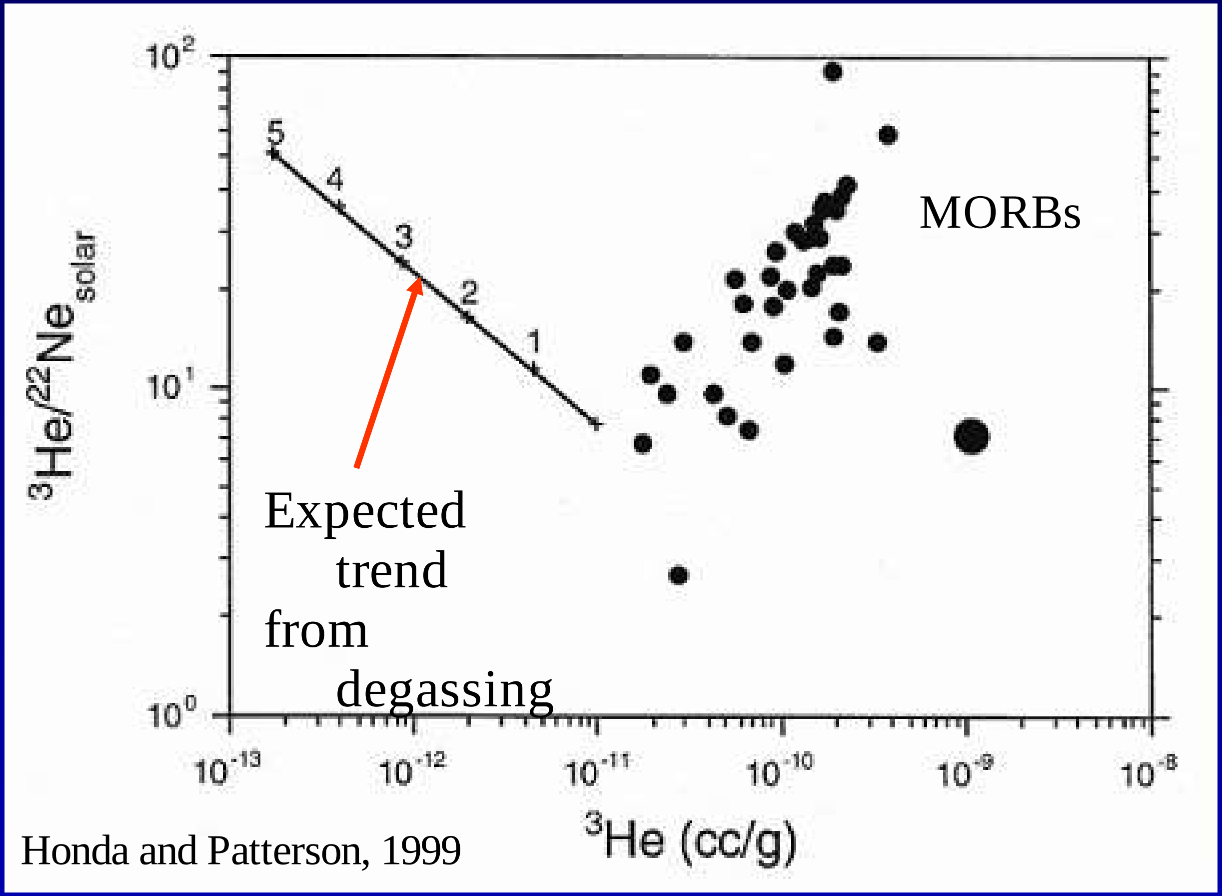
Noble Gas Concentrations

- Previously noted that based in the curvature of mixing hyperbolas He concentrations might be higher in MORBs than OIBs
- The figures show that is indeed the case
- 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…



Honda and Patterson, 1999

Noble gas elemental ratios

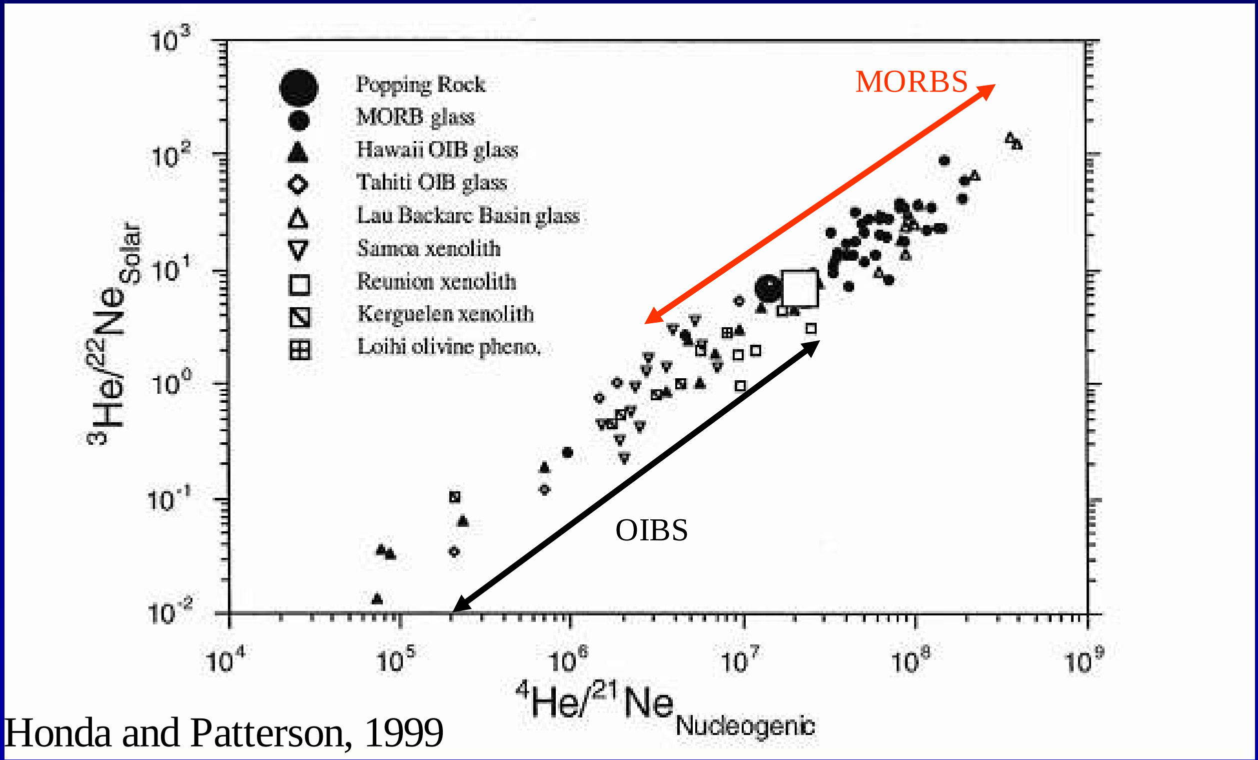


He more soluble in basaltic melt than Ne, which is more soluble than Ar

=> With increasing degassing He/Ne ratios increase and Ne/Ar ratios increase

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

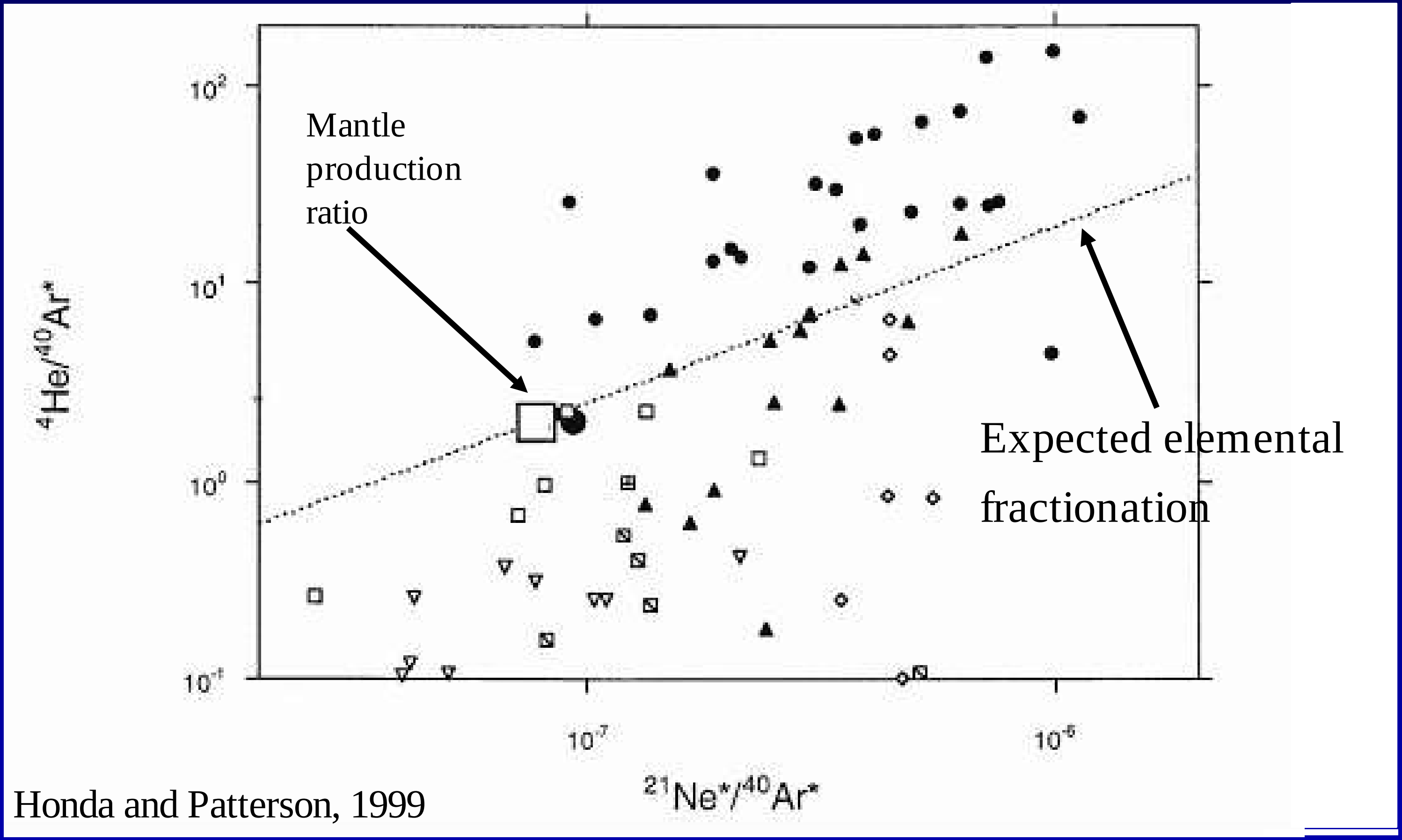
Noble gas elemental ratios



Honda and Patterson, 1999

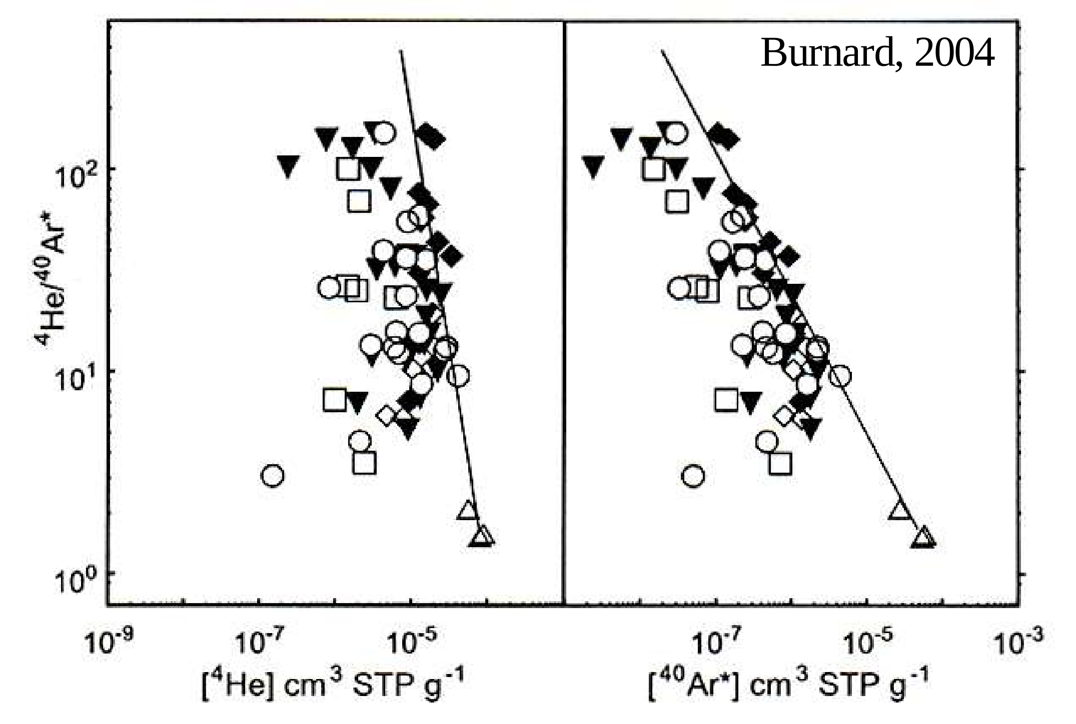
- Fractionation has to be recent, otherwise the slope would not be 1 and the $^{4}He/^{21}Ne$ ratio would have evolved back to the production value of ~10^{7}

Noble gas elemental ratios



- OIBs are not depleted in He; rather MORBs are enriched in He with respect to Ne and Ar
- Enrichment of He with respect to Ar significantly greater than predicted for simple mass dependent process

Noble gas elemental ratios



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

Open question: What controls the noble gas concentration and elemental ratios in oceanic basalts?

Conclusion

- From $^{3}He/^{4}He$, $^{21}Ne/^{22}Ne$, and $^{40}Ar/^{36}Ar$ ratios we know there exists a *relatively undegassed* reservoir in the Earth that is tapped at many ocean islands; MORBs sample a more degassed and processed mantle source

- An undegassed reservoir is supported by ^{40}Ar and the helium heat paradox

- Based on correlations between $^{3}He/^{4}He$ ratios and other isotopic tracers (Sr, Nd, Pb), the undegassed reservoir has the composition of primitive mantle, or is slightly depleted relative to primitive mantle; the slight depletion is consistent with the inferred $^{40}Ar/^{36}Ar$ ratio of ~8000 for the OIB source

Conclusion (continued)

- Noble gas elemental ratios indicate that MORBs have higher He concentration than OIBs that cannot be explained away by simple magmatic degassing

- The higher He concentration in MORBs reflects a recent enrichment of He, and not likely to be a characteristic of the MORB source itself. The physical mechanism through which MORBs acquire a high He concentration remains unidentified

Important questions that need to be answered

- Are the noble gases really more incompatible than their radioactive parents U, Th, and K during partial melting? Can the noble gases be partitioned into the core?
- What physical mechanism(s) control gas loss during mid ocean ridge and ocean island volcanism? Can we ‘see through’ such gas loss processes to infer the concentrations in the different mantle reservoirs?
- What are the characteristics of the heavy noble gases in OIBs and what role does subduction play in recycling of the heavy noble gases (Ar-Xe)?