

# Radiogenic Isotope Systematics and Noble Gases

Sujoy Mukhopadhyay  
CIDR 2006

What I will not cover.....

## U-Th-Pb sytematics

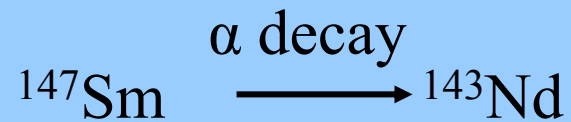
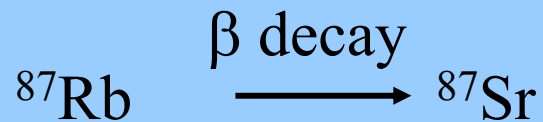
$$\left(\frac{{}^{206}\text{Pb}}{{}^{204}\text{Pb}}\right)_t = \left(\frac{{}^{206}\text{Pb}}{{}^{204}\text{Pb}}\right)_o + \left(\frac{{}^{238}\text{U}}{{}^{204}\text{Pb}}\right)_t \left(e^{\lambda_{238}t} - 1\right) \quad {}^{238}\text{U}, t_{1/2}=4.5 \text{ Ga}$$

$$\left(\frac{{}^{207}\text{Pb}}{{}^{204}\text{Pb}}\right)_t = \left(\frac{{}^{207}\text{Pb}}{{}^{204}\text{Pb}}\right)_o + \left(\frac{{}^{235}\text{U}}{{}^{204}\text{Pb}}\right)_t \left(e^{\lambda_{235}t} - 1\right) \quad {}^{235}\text{U}, t_{1/2}=0.7 \text{ Ga}$$

$$\left(\frac{{}^{208}\text{Pb}}{{}^{204}\text{Pb}}\right)_t = \left(\frac{{}^{208}\text{Pb}}{{}^{204}\text{Pb}}\right)_o + \left(\frac{{}^{232}\text{Th}}{{}^{204}\text{Pb}}\right)_t \left(e^{\lambda_{232}t} - 1\right) \quad {}^{232}\text{Th}, t_{1/2}=14 \text{ Ga}$$

More on this system in the next lecture by Stan.....

# Rb-Sr and Sm-Nd systematics



$P_r$  is radioactive parent

$D_r$  is daughter produced from radioactive decay of  $P_r$

$D_s$  is stable isotope of  $D_r$  and not produced by radioactive decay

$\lambda$  is the decay constant

$$\frac{dP}{dt} = -\lambda P$$

$$D_r = P(e^{\lambda t} - 1)$$

$$\left( \frac{D_r}{D_s} \right)_{\text{today}} = \left( \frac{D_r}{D_s} \right)_{\text{initial}} + \left( \frac{P_r}{D_s} \right)_{\text{today}} (e^{\lambda t} - 1)$$

- Stable non-radiogenic reference isotope for Nd is  $^{144}\text{Nd}$ .
- Stable non-radiogenic reference isotope for Sr is  $^{86}\text{Sr}$

## The $\varepsilon$ notation for Sm-Nd

$$\varepsilon_{Nd}(t) = \left[ \frac{\left( {}^{143}\text{Nd}/{}^{144}\text{Nd} \right)_{sample}}{\left( {}^{143}\text{Nd}/{}^{144}\text{Nd} \right)_{CHUR}} - 1 \right] \times 10^4$$

CHUR stands for *chondritic uniform reservoir*, and represents the evolution of a bulk solar system Sm/Nd ratio and initial  ${}^{143}\text{Nd}/{}^{144}\text{Nd}$ .

Samarium –Neodymium ( $^{147}\text{Sm}$ - $^{143}\text{Nd}$ ;  $t_{1/2} = 106 \text{ G.y}$ ) and Rubidium-Strontium systematics( $^{87}\text{Rb}$ - $^{87}\text{Sr}$ ;  $t_{1/2} = 48.8 \text{ G.y}$ ) Sm, Nd, Rb, and Sr are *lithophile* and incompatible.

1A																	0							
1 <b>H</b>																	2 <b>He</b>							
2A	3 <b>Li</b>	4 <b>Be</b>																	5A	6A	7A	8A	9A	10A
3 <b>Na</b>	12 <b>Mg</b>	13 <b>Al</b>	14 <b>Si</b>	15 <b>P</b>	16 <b>S</b>	17 <b>Cl</b>	18 <b>Ar</b>																	
4 <b>K</b>	20 <b>Ca</b>	21 <b>Sc</b>	22 <b>Ti</b>	23 <b>V</b>	24 <b>Cr</b>	25 <b>Mn</b>	26 <b>Fe</b>	27 <b>Co</b>	28 <b>Ni</b>	29 <b>Cu</b>	30 <b>Zn</b>	31 <b>Ga</b>	32 <b>Ge</b>	33 <b>As</b>	34 <b>Se</b>	35 <b>Br</b>	36 <b>Kr</b>							
5 <b>Rb</b>	38 <b>Sr</b>	39 <b>Y</b>	40 <b>Zr</b>	41 <b>Nb</b>	42 <b>Mo</b>	43 <b>Tc</b>	44 <b>Ru</b>	45 <b>Rh</b>	46 <b>Pd</b>	47 <b>Ag</b>	48 <b>Cd</b>	49 <b>In</b>	50 <b>Sn</b>	51 <b>Sb</b>	52 <b>Te</b>	53 <b>I</b>	54 <b>Xe</b>							
6 <b>Cs</b>	56 <b>Ba</b>	57 <b>*La</b>	72 <b>Hf</b>	73 <b>Ta</b>	74 <b>W</b>	75 <b>Re</b>	76 <b>Os</b>	77 <b>Ir</b>	78 <b>Pt</b>	79 <b>Au</b>	80 <b>Hg</b>	81 <b>Tl</b>	82 <b>Pb</b>	83 <b>Bi</b>	84 <b>Po</b>	85 <b>At</b>	86 <b>Rn</b>							
7 <b>Fr</b>	88 <b>Ra</b>	89 <b>+Ac</b>	104 <b>Rf</b>	105 <b>Ha</b>	106	107	108	109	110	111	112													

Crust

Silicate mantle

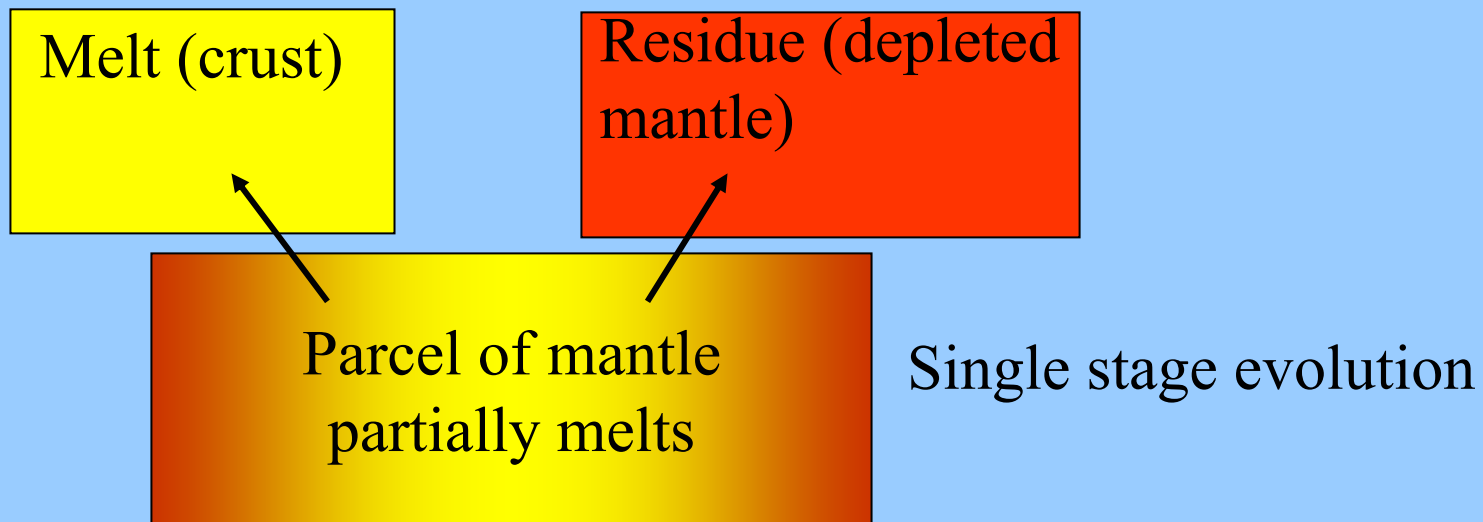
Naming conventions of new elements

\* Lanthanide Series

58 <b>Ce</b>	59 <b>Pr</b>	60 <b>Nd</b>	61 <b>Pm</b>	62 <b>Sm</b>	63 <b>Eu</b>	64 <b>Gd</b>	65 <b>Tb</b>	66 <b>Dy</b>	67 <b>Ho</b>	68 <b>Er</b>	69 <b>Tm</b>	70 <b>Yb</b>	71 <b>Lu</b>
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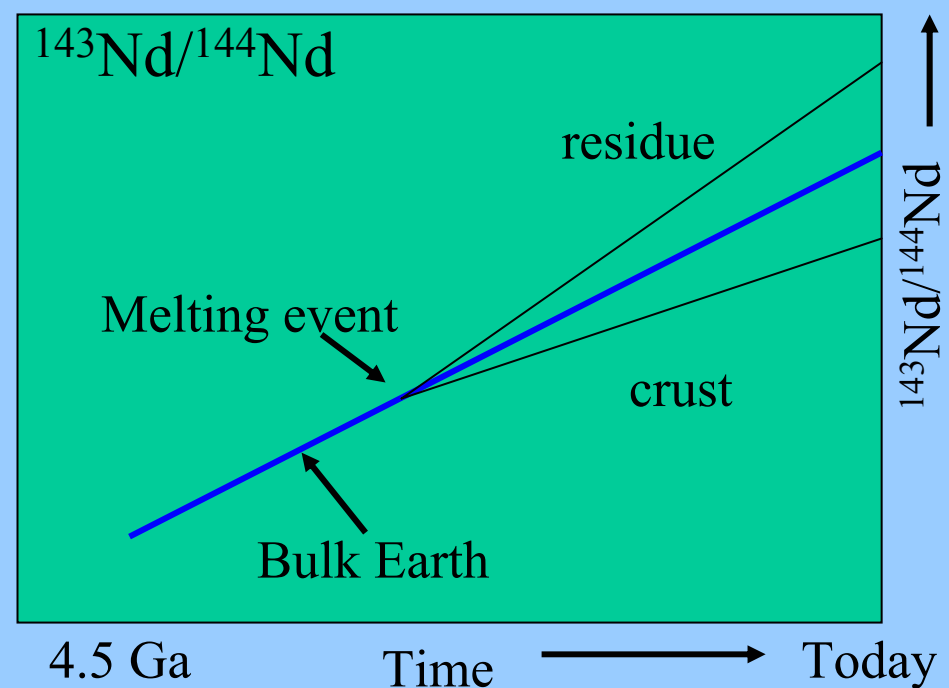
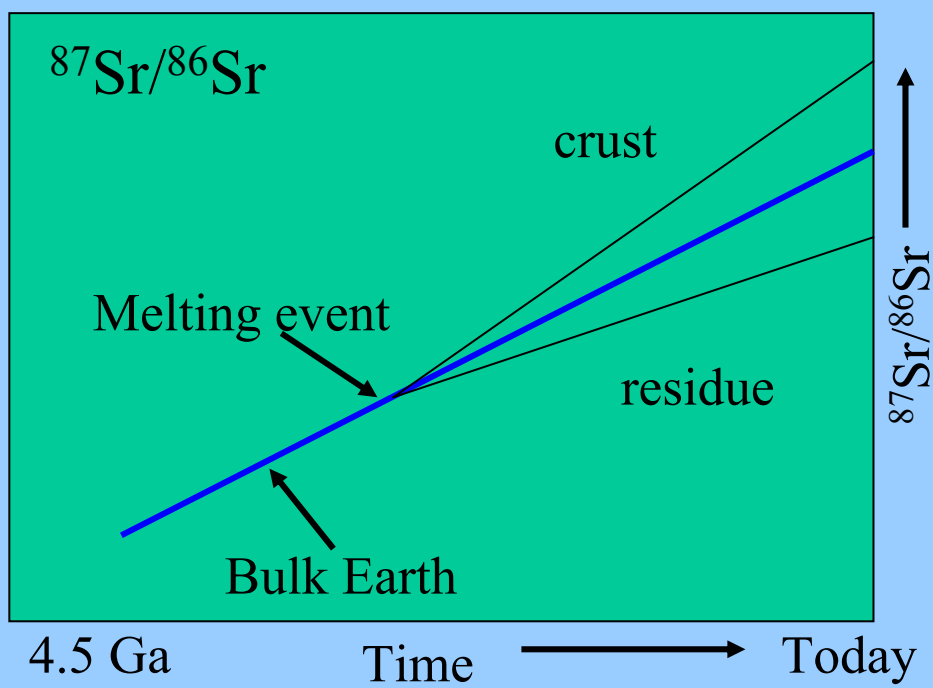
+ Actinide Series

90 <b>Th</b>	91 <b>Pa</b>	92 <b>U</b>	93 <b>Np</b>	94 <b>Pu</b>	95 <b>Am</b>	96 <b>Cm</b>	97 <b>Bk</b>	98 <b>Cf</b>	99 <b>Es</b>	100 <b>Fm</b>	101 <b>Md</b>	102 <b>No</b>	103 <b>Lr</b>
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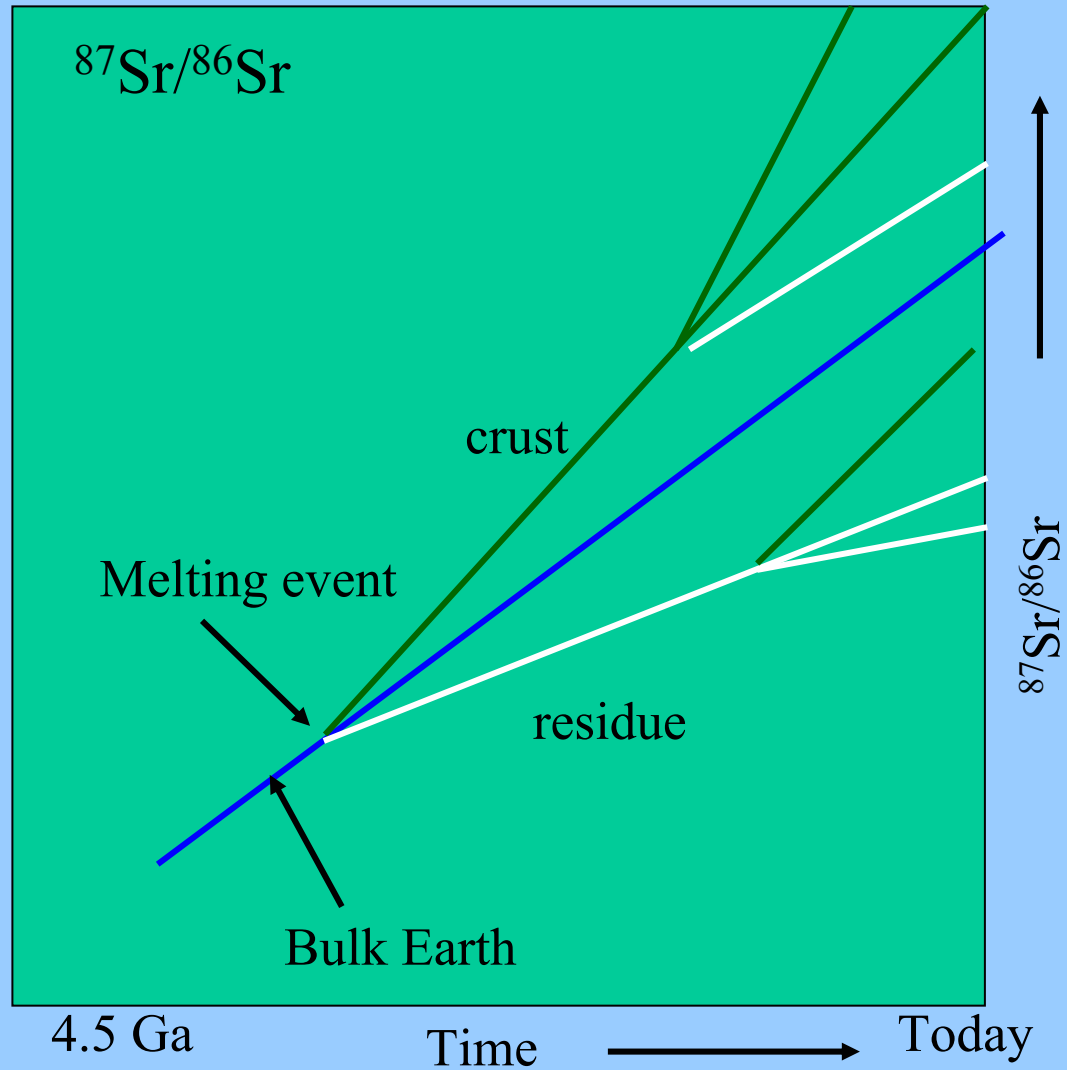


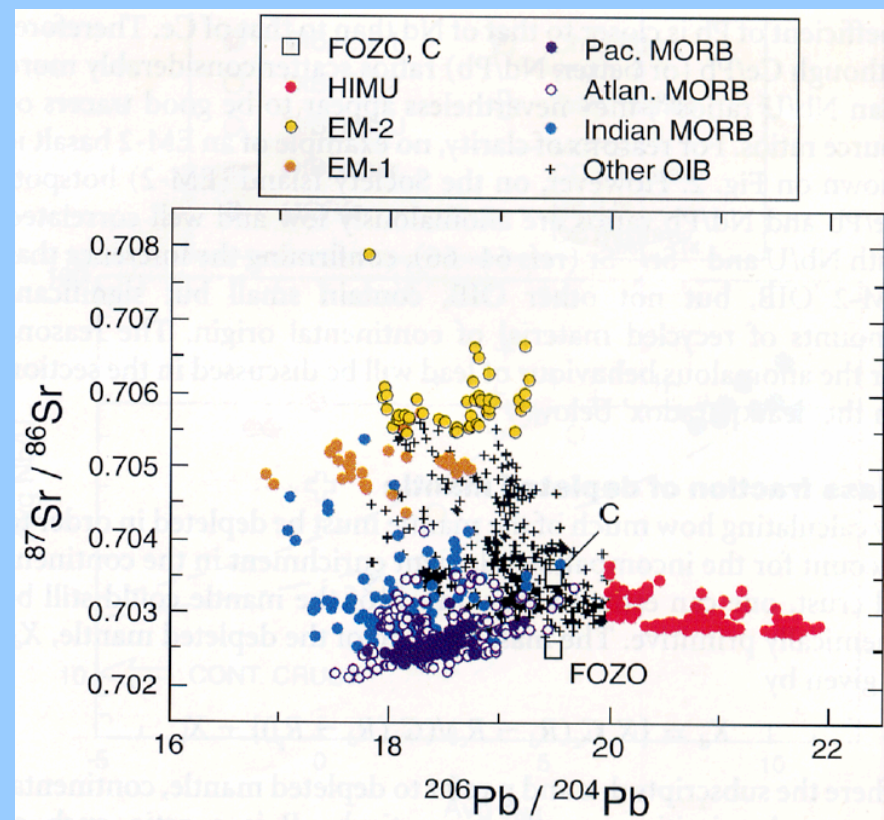
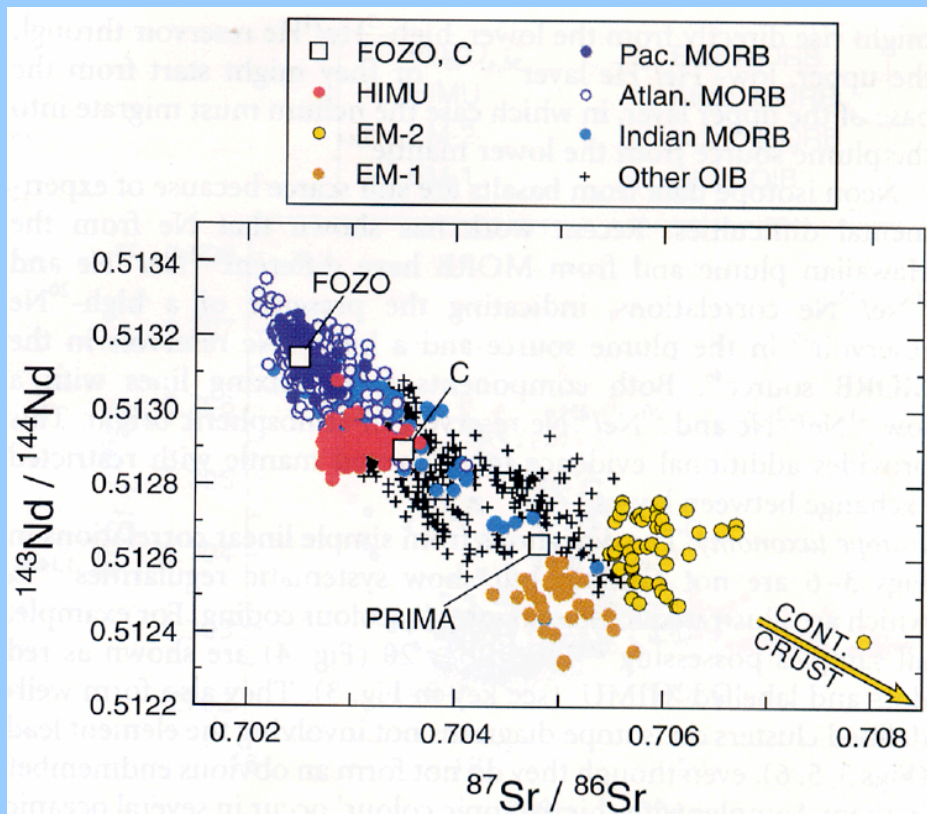
$$(\text{Rb}/\text{Sr})_{\text{melt}} > (\text{Rb}/\text{Sr})_{\text{mantle}} > (\text{Rb}/\text{Sr})_{\text{residue}} \quad {}^{87}\text{Rb} \rightarrow {}^{87}\text{Sr}$$

$$(\text{Sm}/\text{Nd})_{\text{melt}} < (\text{Sm}/\text{Nd})_{\text{mantle}} < (\text{Sm}/\text{Nd})_{\text{residue}} \quad {}^{147}\text{Sm} \rightarrow {}^{143}\text{Nd}$$



# Rb-Sr system: The tree of life



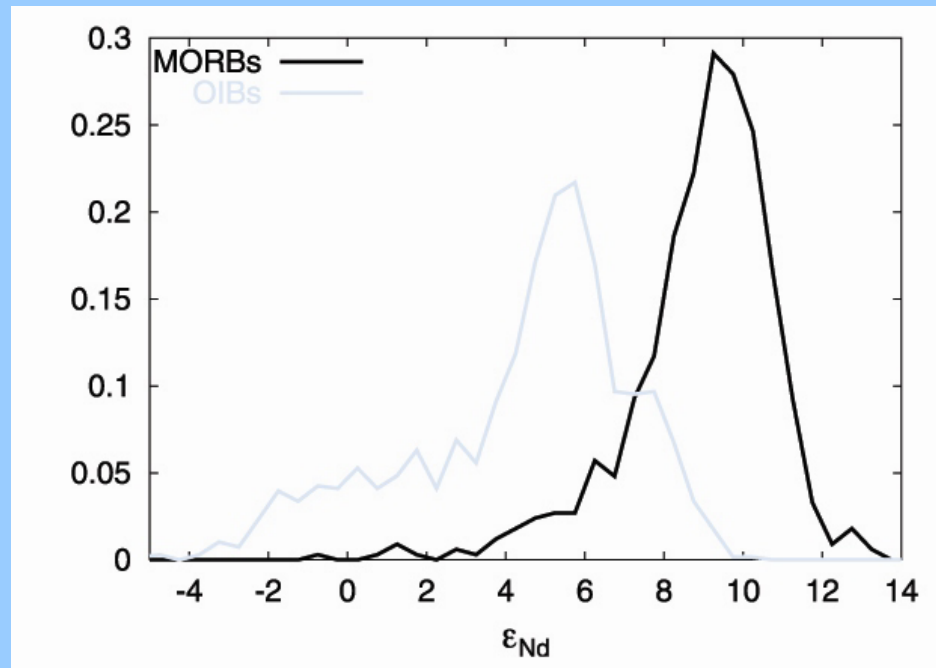


Hofmann, 1997  
Nature 385: 219-229

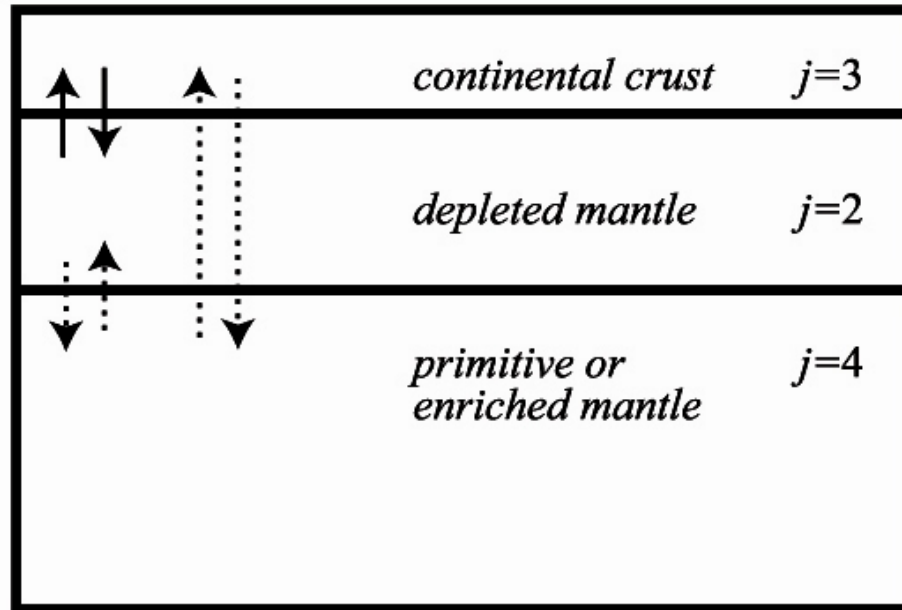


# Isotopic differences between OIBs and MORBs

## An issue of sampling lengthscales?

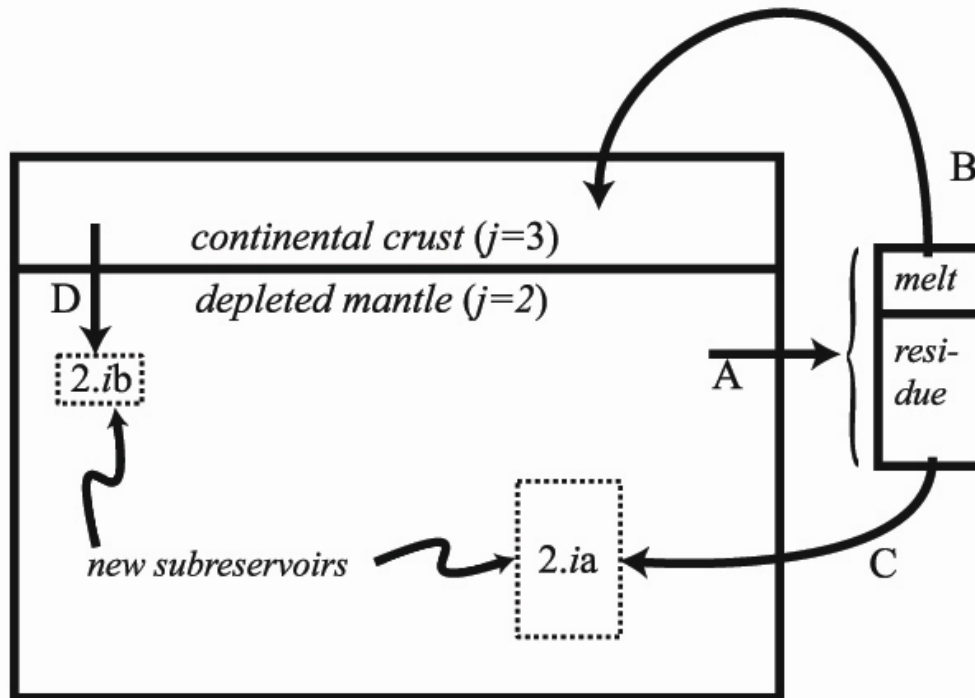


Kellogg et al., 2002



Equations derived in  
Kellogg et al., 2002

Also see DePaolo 1983  
and Jacobsen 1988



$$\frac{dM_j(t)}{dt} = \sum_{k=1}^{n_{\text{res}}} [\dot{M}_{kj}(t) - \dot{M}_{jk}(t)]$$

$$\frac{dN_{sj}(t)}{dt} = \sum_{k=1}^{n_{\text{res}}} [\dot{M}_{kj}(t) d_{skj} C_{sk}(t) - \dot{M}_{jk}(t) d_{sjk} C_{sj}(t)]$$

$$\begin{aligned} \frac{dN_{rj}(t)}{dt} \\ = \sum_{k=1}^{n_{\text{res}}} [\dot{M}_{kj}(t) d_{rkj} C_{rk}(t) - \dot{M}_{jk}(t) d_{rjk} C_{rj}(t)] - \lambda_r N_{rj}(t) \end{aligned}$$

$$\begin{aligned} \frac{dN_{dj}(t)}{dt} \\ = \sum_{k=1}^{n_{\text{res}}} [\dot{M}_{kj}(t) d_{skj} C_{dk}(t) - \dot{M}_{jk}(t) d_{sjk} C_{dj}(t)] + \lambda_r N_{rj}(t) \end{aligned}$$

$\dot{M}$  is the mass transport

C is the concentration

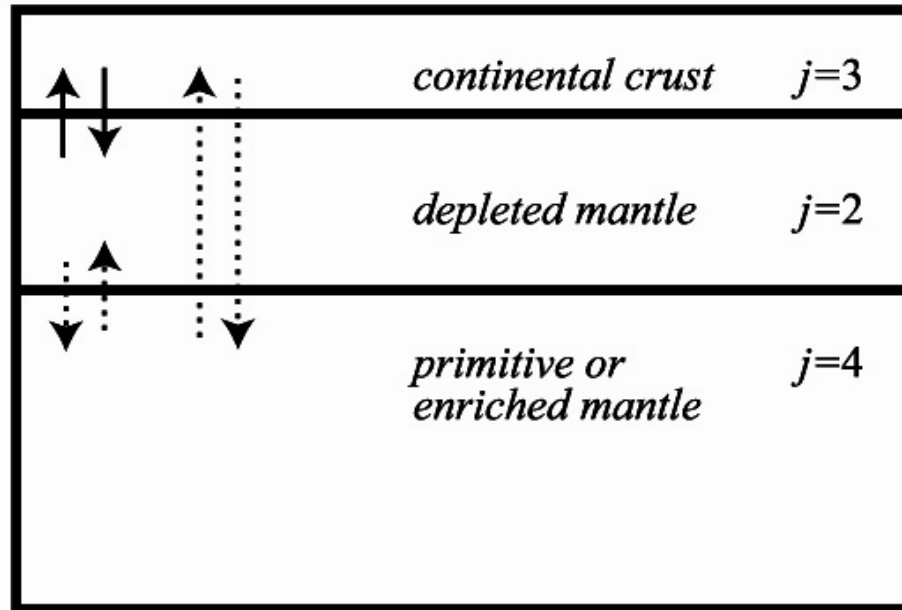
R is radioactive parent

D is the stable daughter isotope

produced by radioactive decay

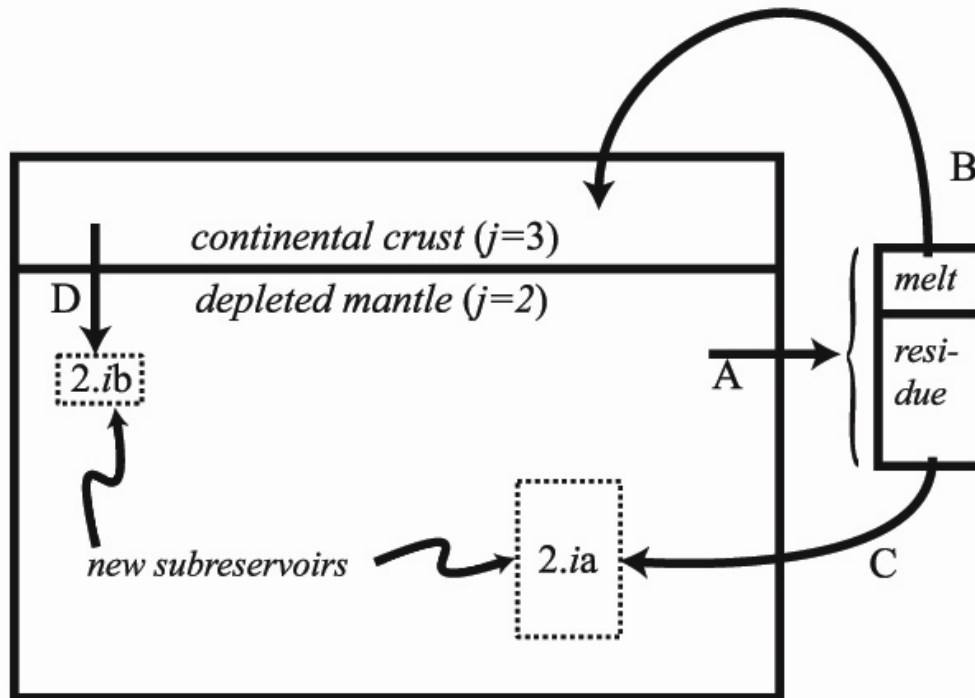
S indicates stable reference isotope

D is the decay constant

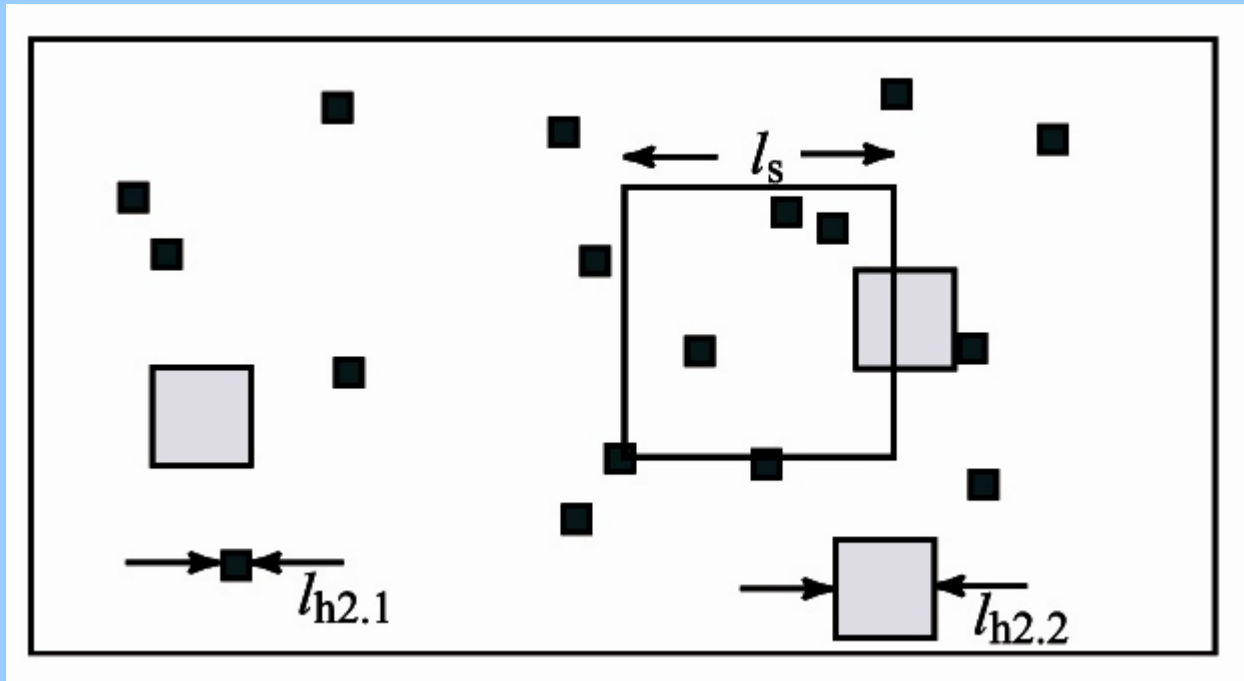


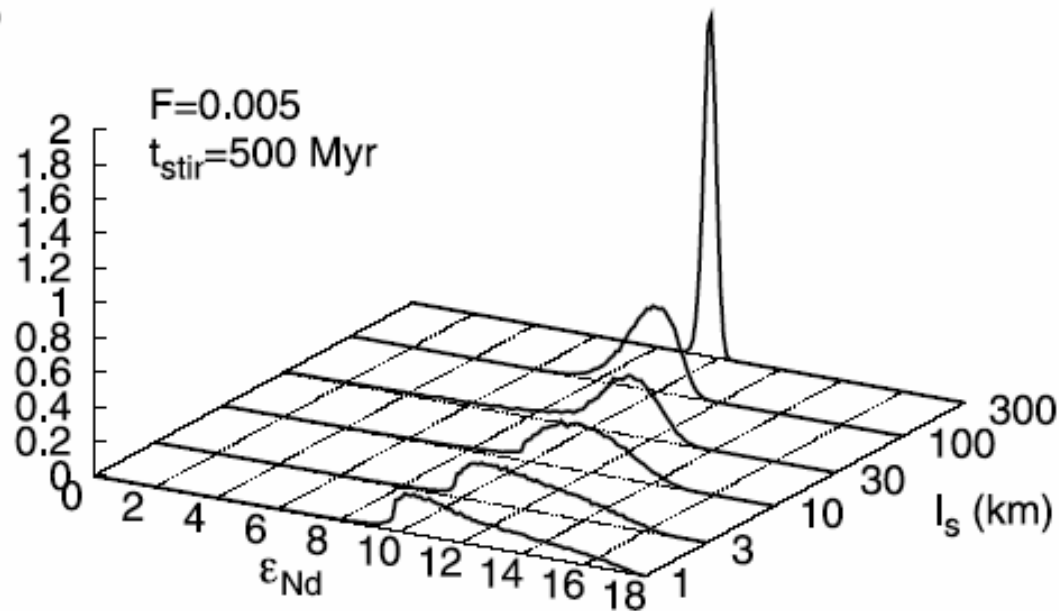
Equations derived in  
Kellogg et al., 2002

Also see DePaolo 1983  
and Jacobsen 1988



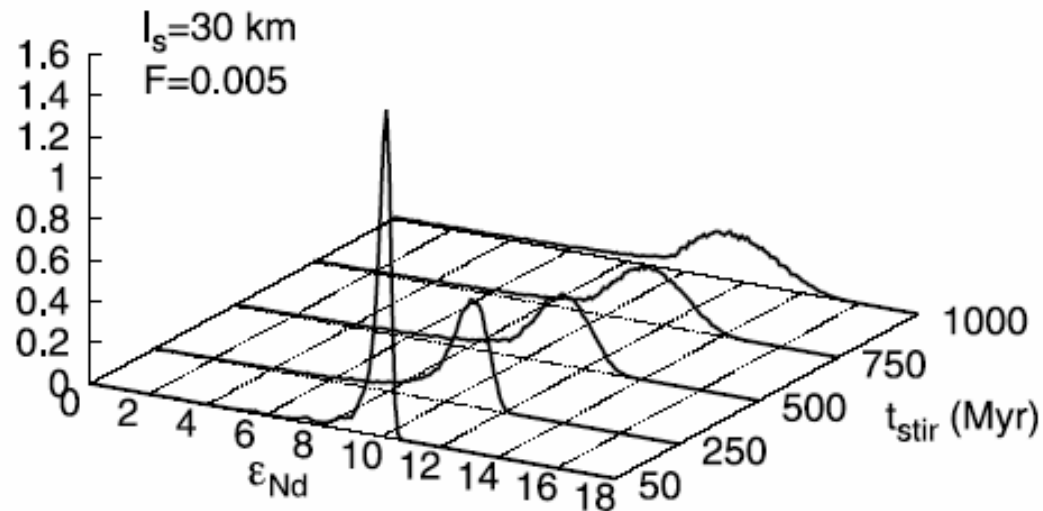
## Stirring effect

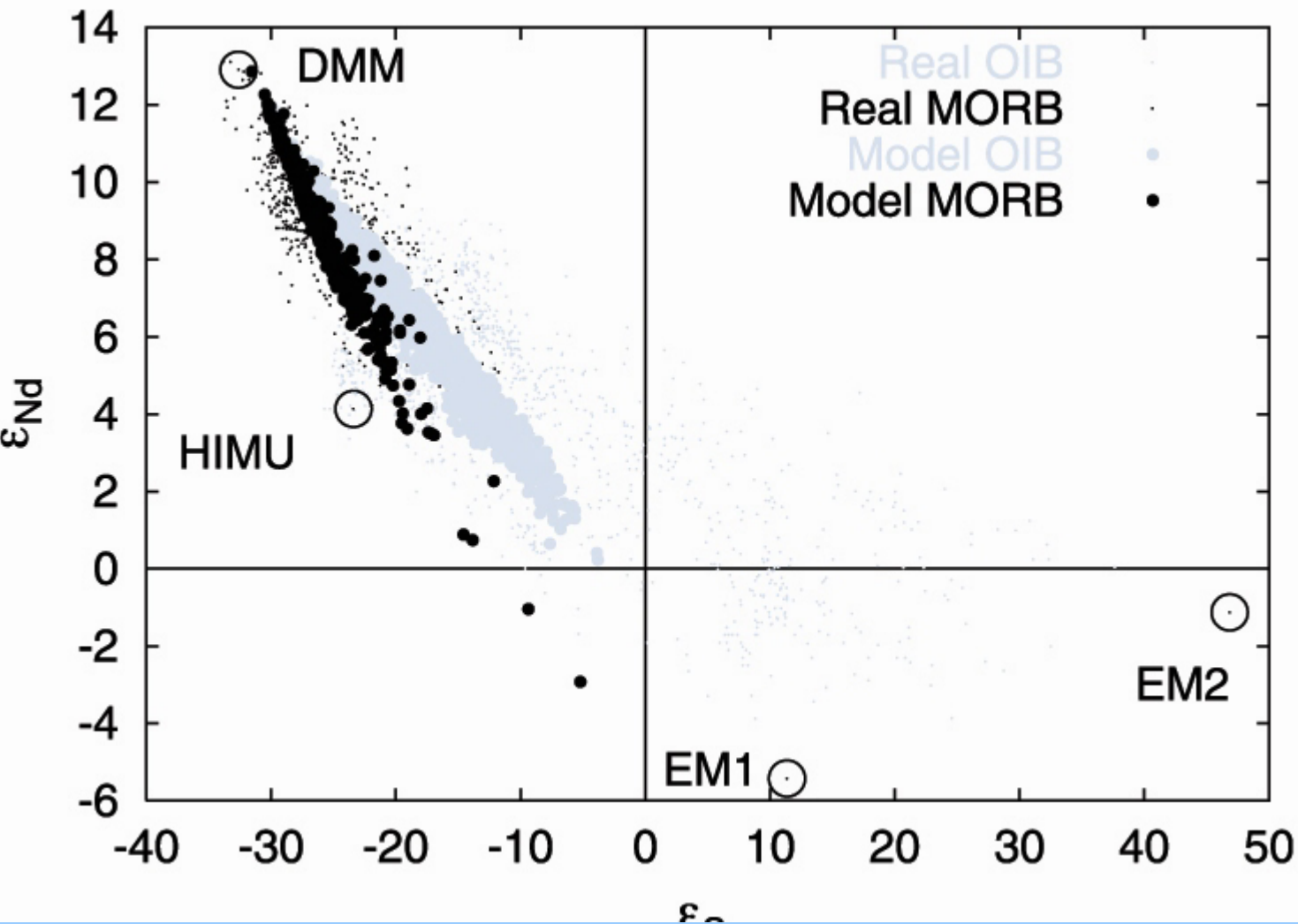


**B**

Effect of  
sampling and  
stirring time  
scale

Kellogg et al.,  
2002

**C**



The MORB distribution is reproduced

Model OIB distribution fails to capture the real distribution

# He isotope geochemistry

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

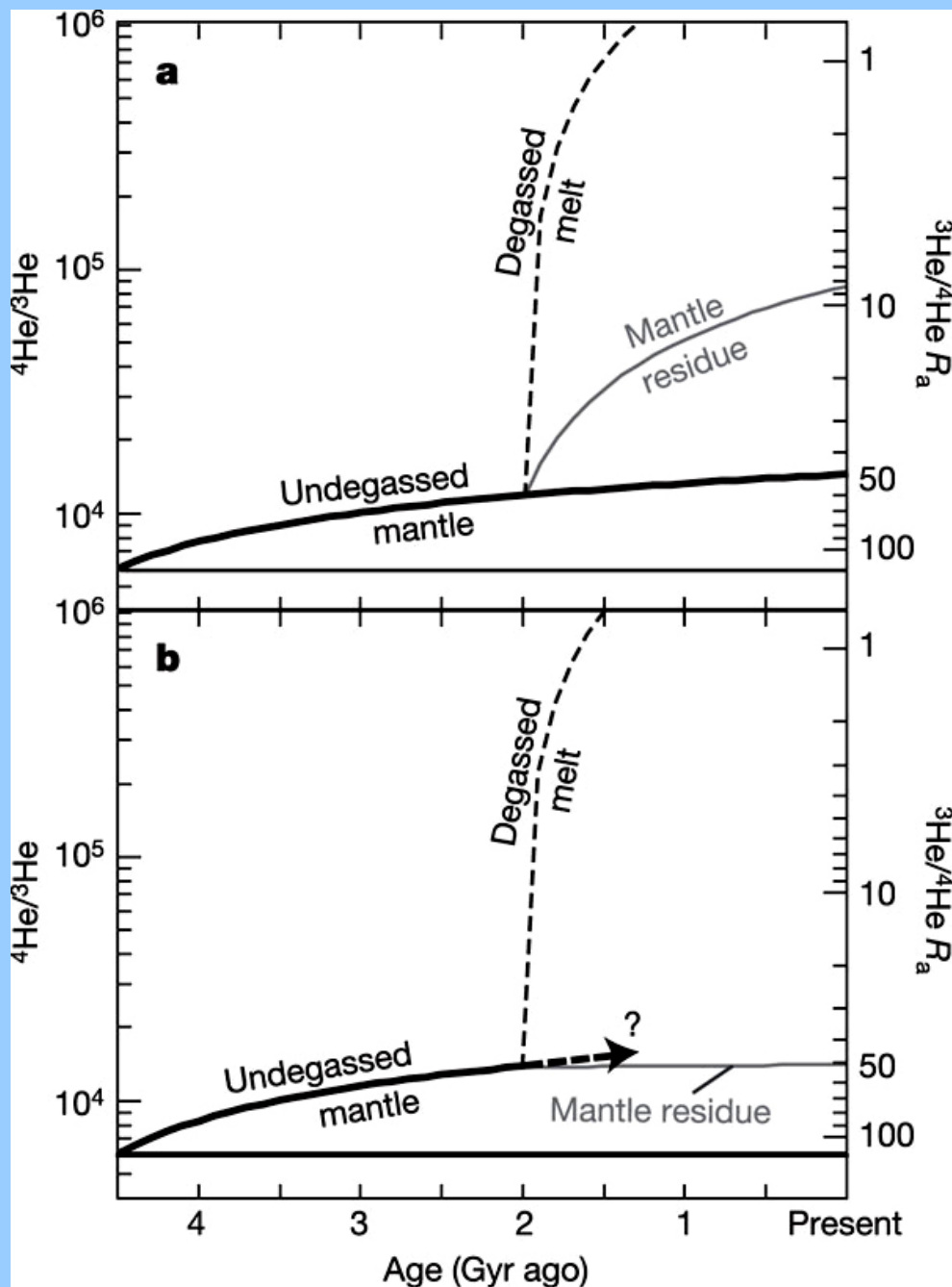
$$\frac{^4\text{He}}{^3\text{He}} = \left( \frac{^4\text{He}}{^3\text{He}} \right)_o + 8 \frac{^{238}\text{U}}{^3\text{He}} \left( e^{\lambda_{238}t} - 1 \right) + 7 \frac{^{235}\text{U}}{^3\text{He}} \left( e^{\lambda_{235}t} - 1 \right) + 6 \frac{^{232}\text{Th}}{^3\text{He}} \left( e^{\lambda_{232}t}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

- 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  $^3\text{He}/^4\text{He}$  ratios reflect less degassed mantle material

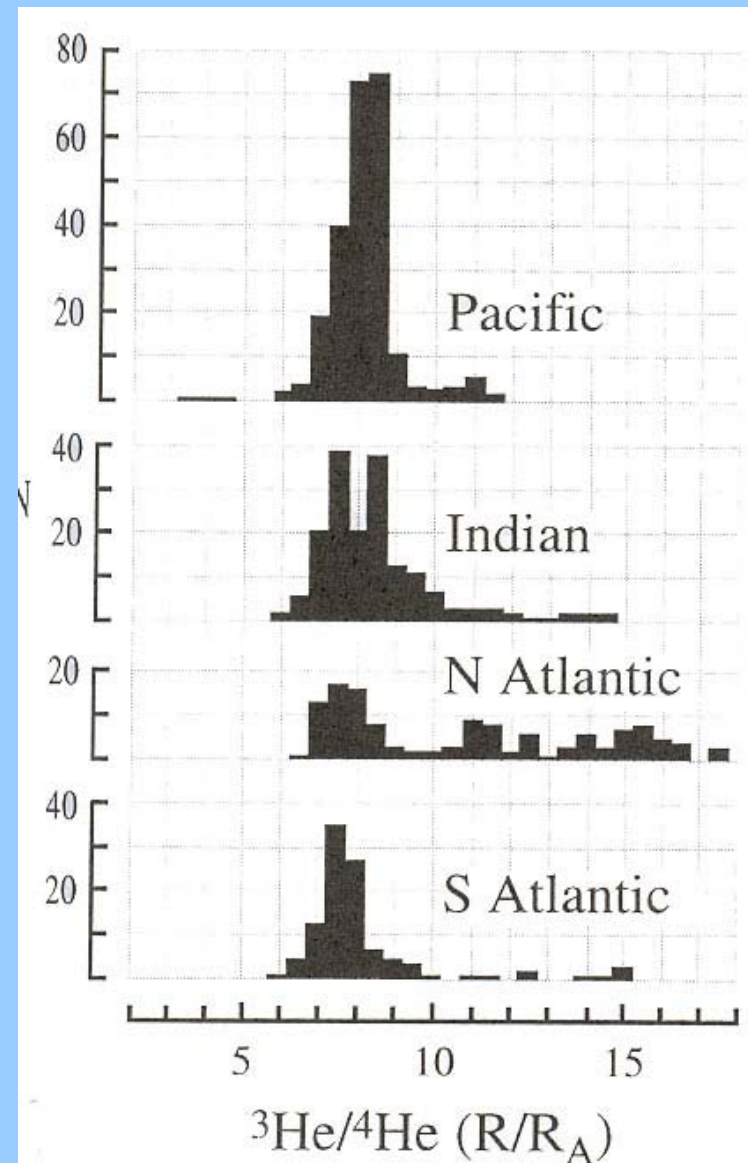


## Partitioning of Helium during mantle melting



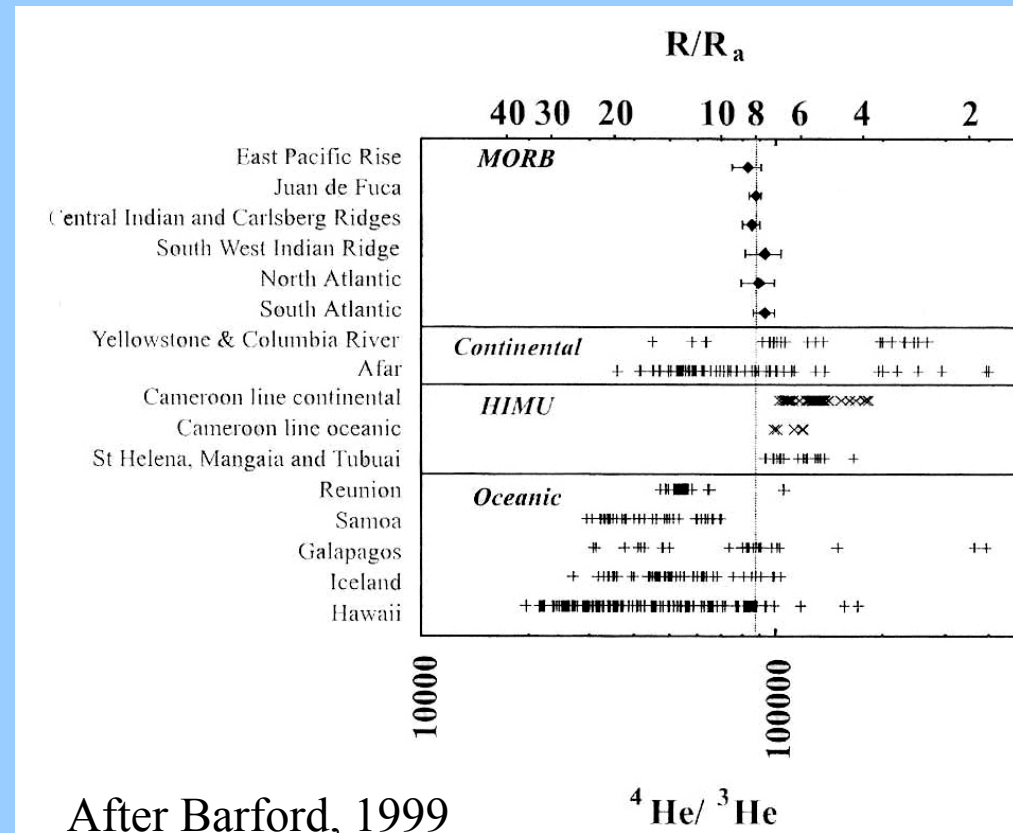
# Histogram of He isotope ratios in mid-ocean ridge basalts (MORBs)

- $^3\text{He}/^4\text{He}$  ratios reported relative to the atmospheric ratio of  $1.39 \times 10^{-6}$
- 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



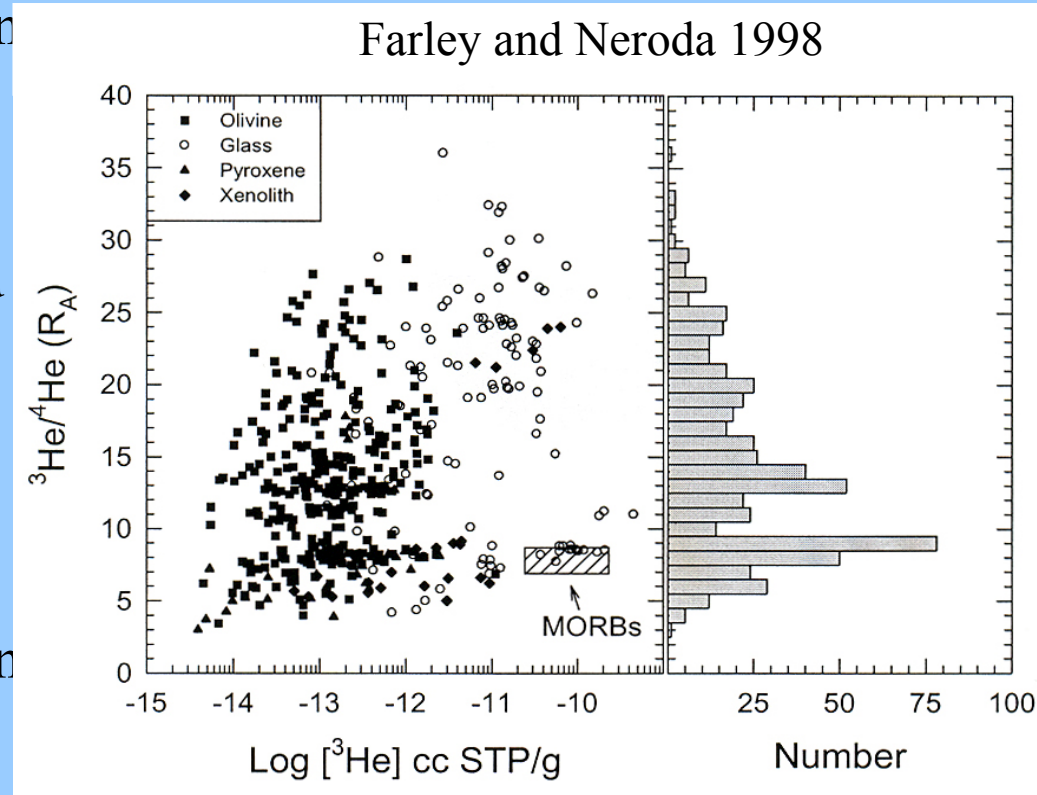
# Comparison of He isotope ratios from selected MORs, OIBs, and continental hotspots

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



# 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



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

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

# Geochemistry of Ne

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

# Ne isotopic composition of mantle derived rocks

Less degassed ← → More degassed

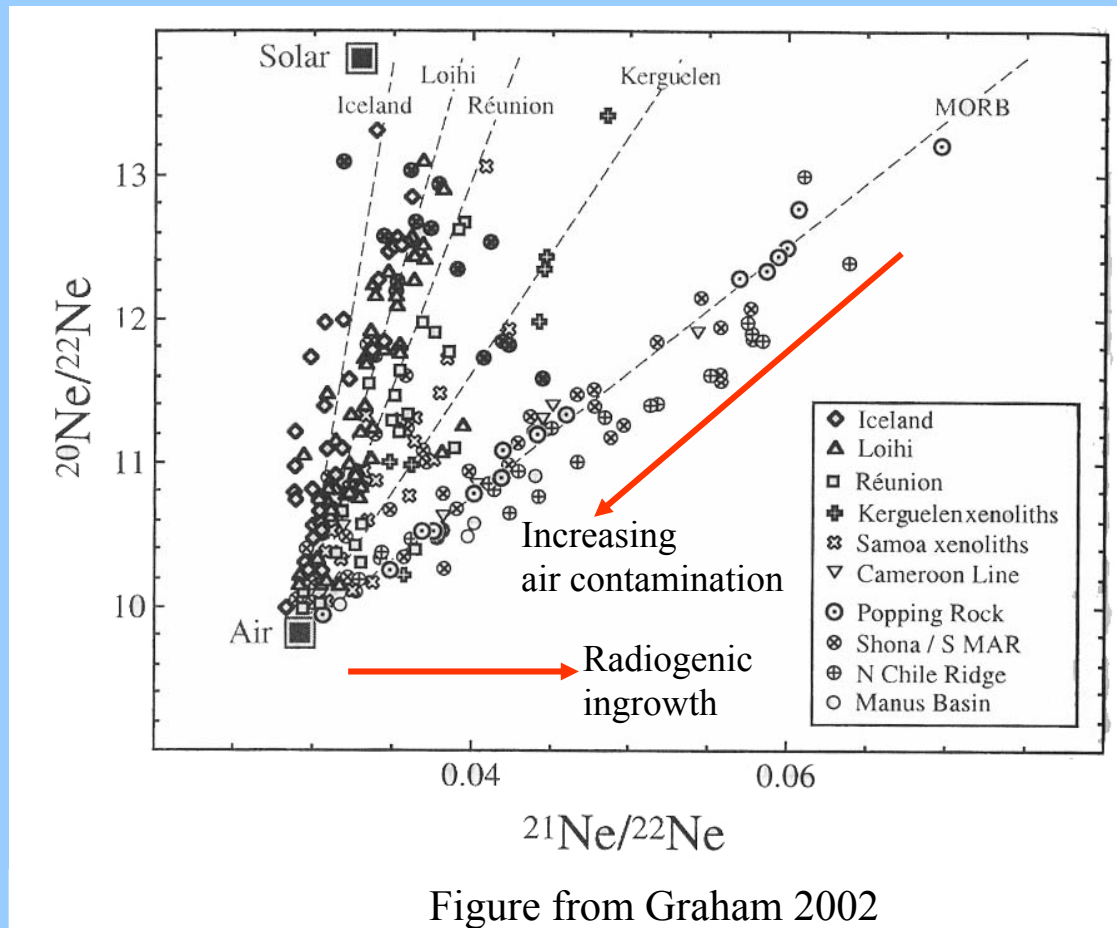
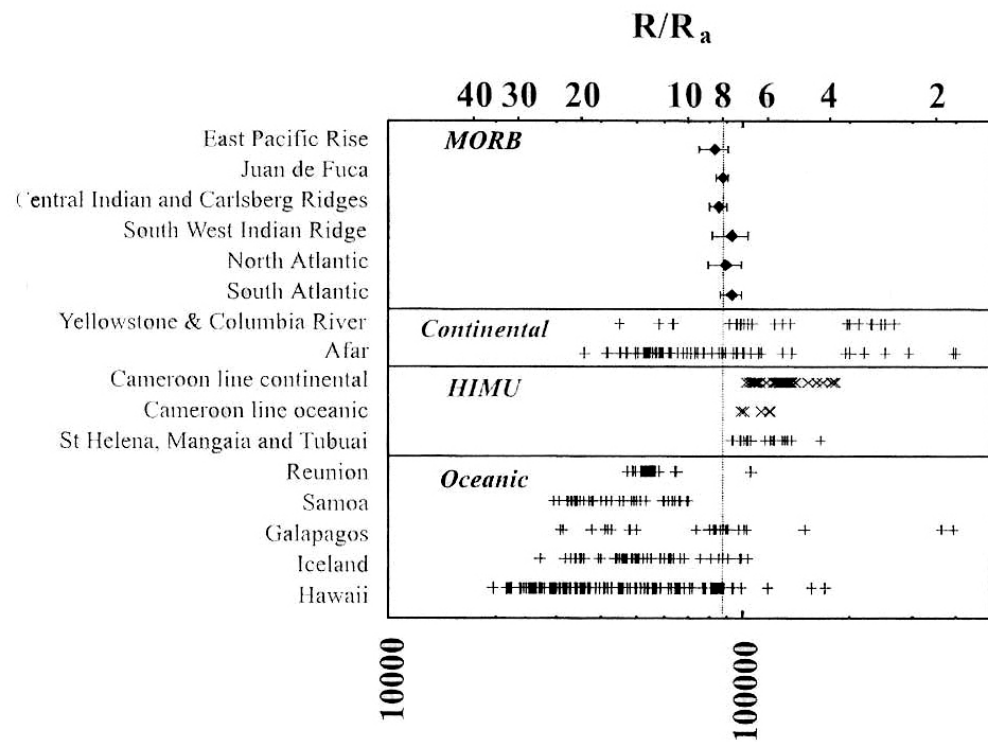


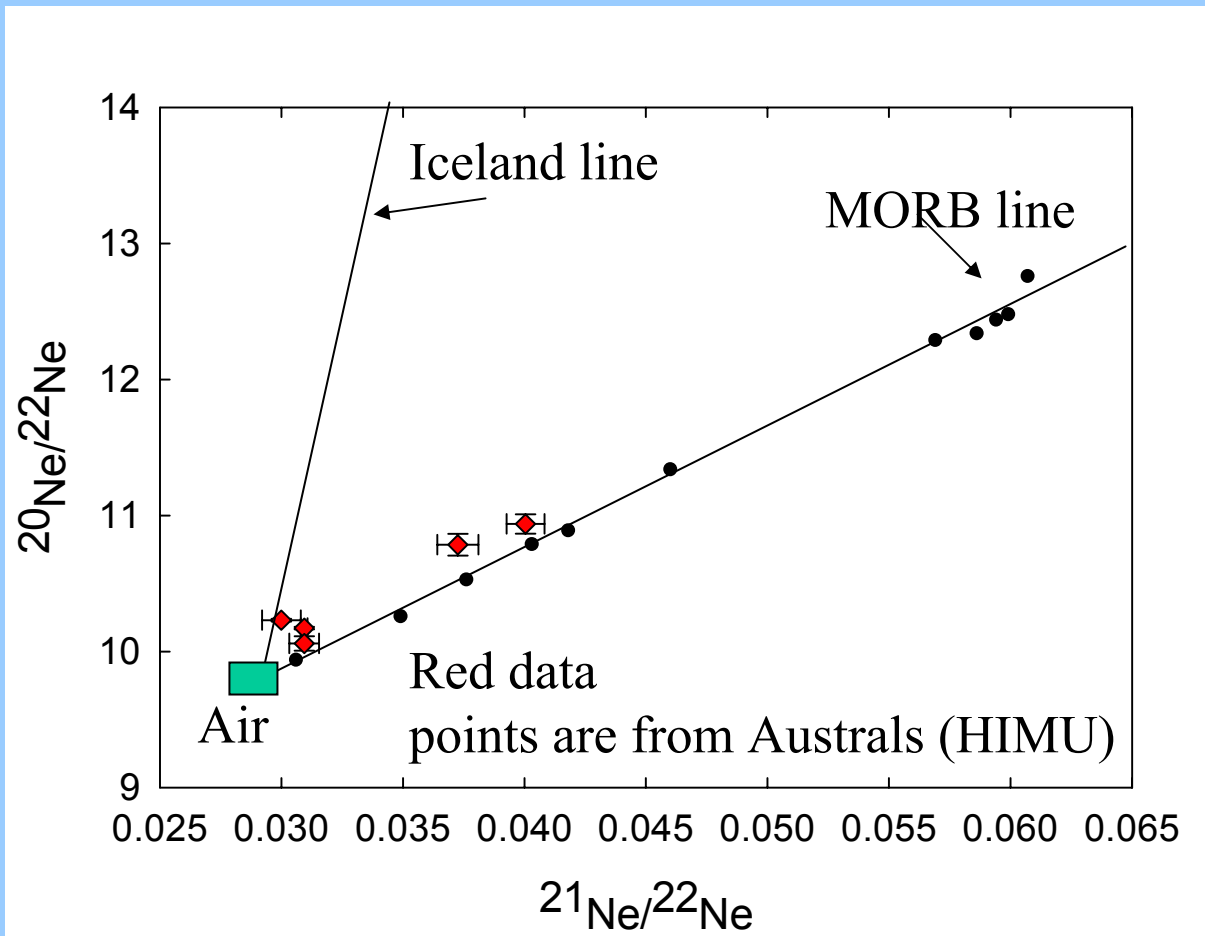
Figure from Graham 2002

- Mantle  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio is fixed;  $^{21}\text{Ne}/^{22}\text{Ne}$  varies because of radiogenic ingrowth and varying degrees of degassing
- Different ocean islands have distinct  $^{21}\text{Ne}/^{22}\text{Ne}$  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



After Barford, 1999

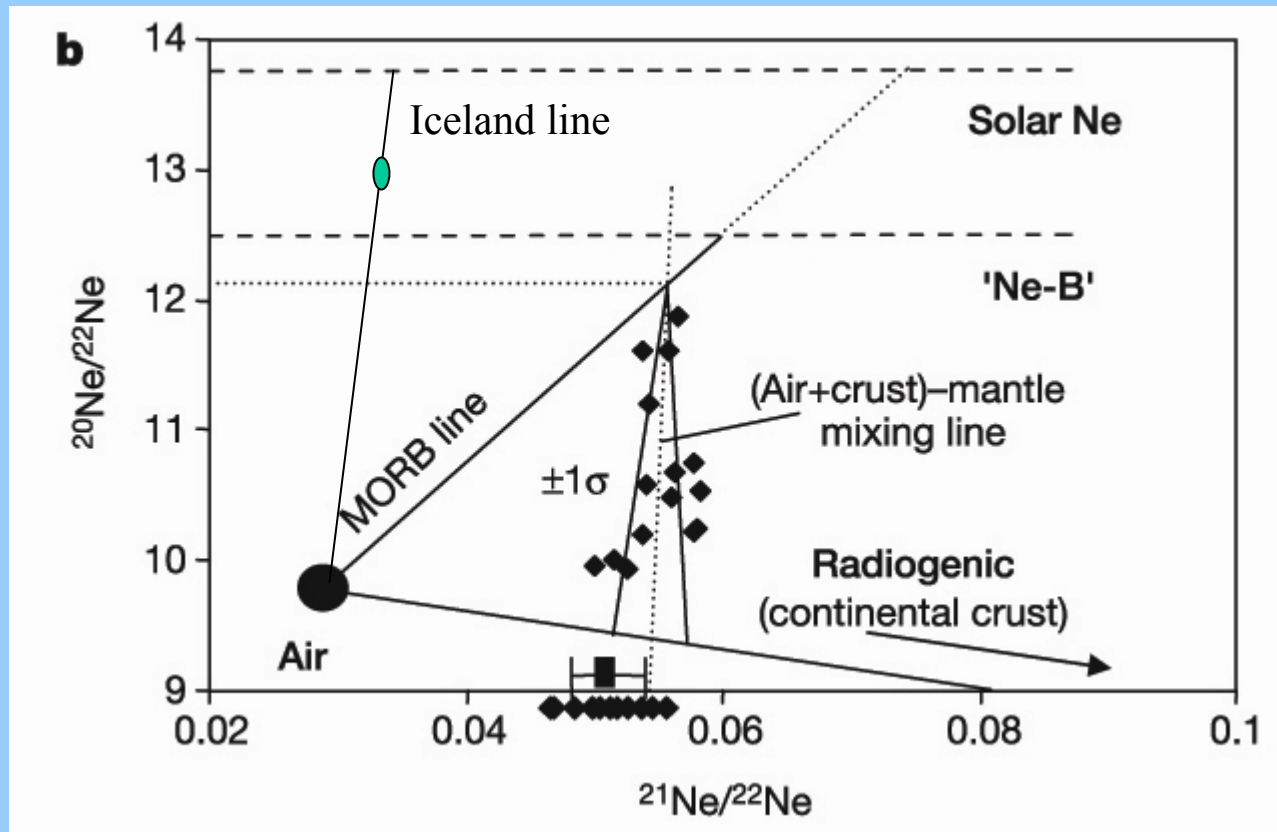
$^4\text{He}/^3\text{He}$



HIMU Ne isotopic signature is not more radiogenic than MORBs  
Mukhopadhyay and Parai (in prep)



# Neon composition in the convective mantle



Ballentine et al., 2005

# Geochemistry of Ar

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

# Geochemistry of Ar

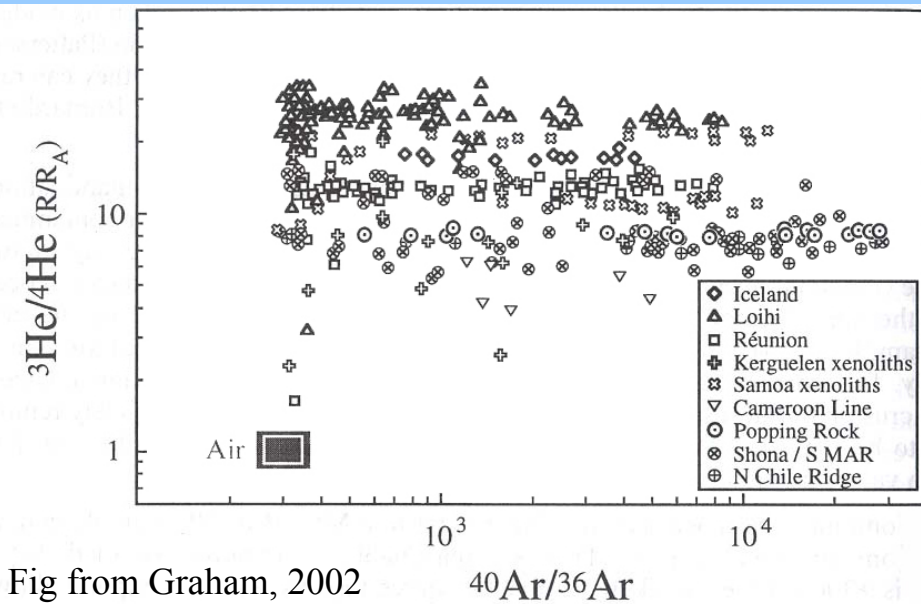
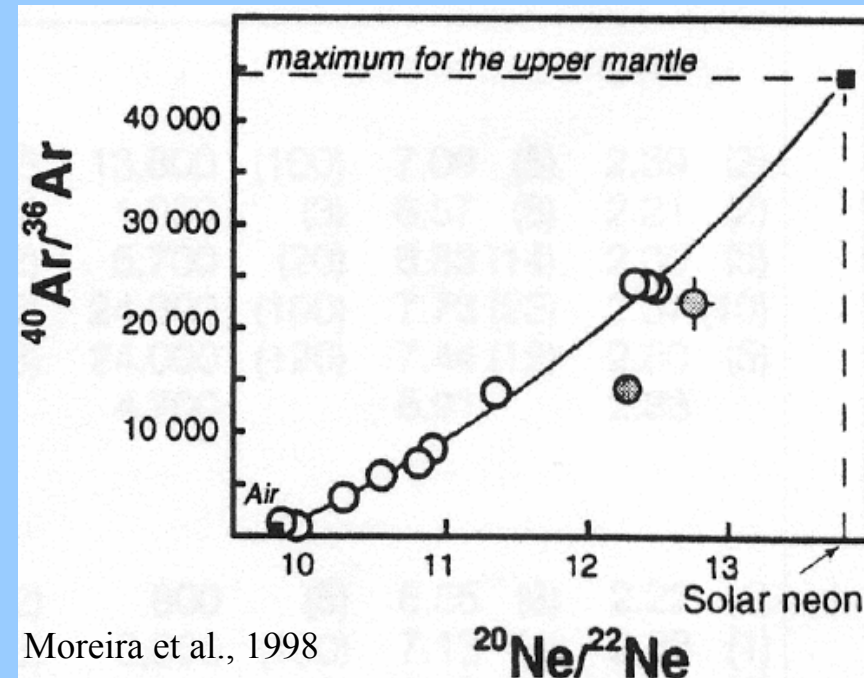


Fig from Graham, 2002

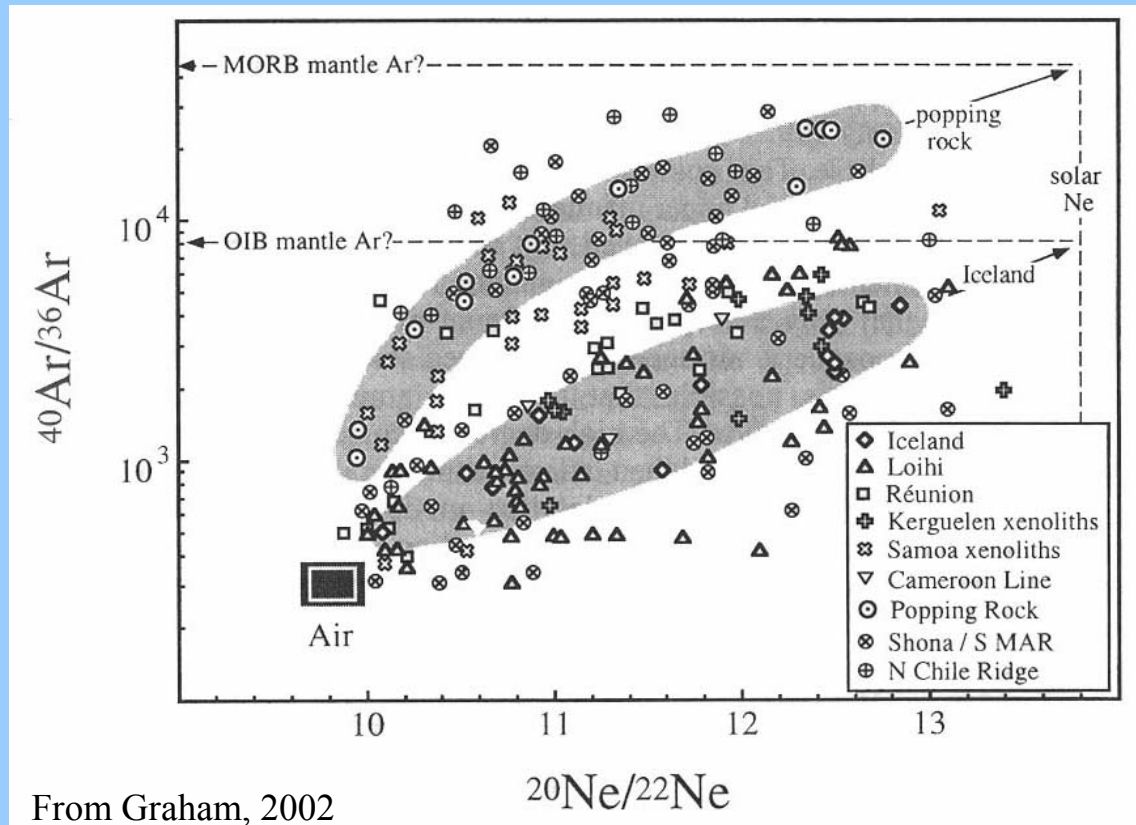
- 1% Ar in the atmosphere
- Significant air contamination for Ar
- Even when  $^3\text{He}/^4\text{He}$  ratios are as high as  $30 R_A$ ,  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios can be atmospheric

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



Moreira et al., 1998

# Geochemistry of Ar



- MORB mantle  $^{40}\text{Ar}/^{36}\text{Ar}$  values are  $\sim 40,000$
- OIBs have lower  $^{40}\text{Ar}/^{36}\text{Ar}$  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. 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

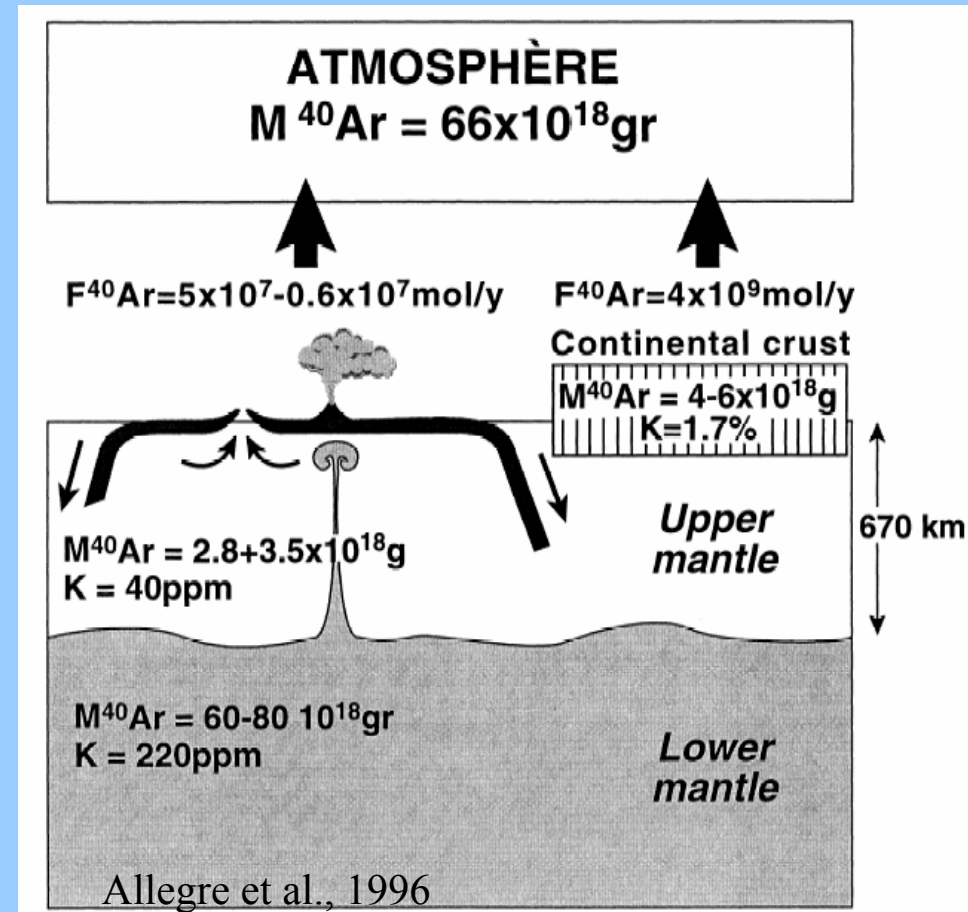
- K content of Earth derived from the K/U ratio of 12700 in MORBs and U content of 20-22.5 ppb
- Implied K content of bulk Earth is 250-285 ppm
- Total  $^{40}\text{Ar}$  produced over Earth history =  $140\text{-}156 \times 10^{18} \text{ g}$
- $^{40}\text{Ar}$  in the atmosphere =  $66 \times 10^{18}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

$63\text{-}80 \times 10^{18}$  of  $^{40}\text{Ar}$  has to be in the mantle

# Evidence for undegassed reservoir: The missing Argon problem

## Constraints from $^{40}\text{Ar}$ flux

- $^4\text{He}$  flux at ridge =  $9.46 \times 10^7$  moles/yr
- $^4\text{He}/^{40}\text{Ar}$  ratio in MORBs 2-15  
 $\Rightarrow$   $^{40}\text{Ar}$  flux  $0.63\text{--}5 \times 10^7$  moles/yr
- Mass of oceanic lithosphere passing through ridges =  $5.76 \times 10^{17}$  g/yr  
If MORB mantle representative of entire mantle and if lithosphere completely degassed,  $^{40}\text{Ar}$  content in mantle  $1.4\text{--}1.8 \times 10^{18}$  g  
Lower than the  $63\text{--}81 \times 10^{18}$  g estimated (Allegre et al., 1996) and requires a hidden reservoir for  $^{40}\text{Ar}$

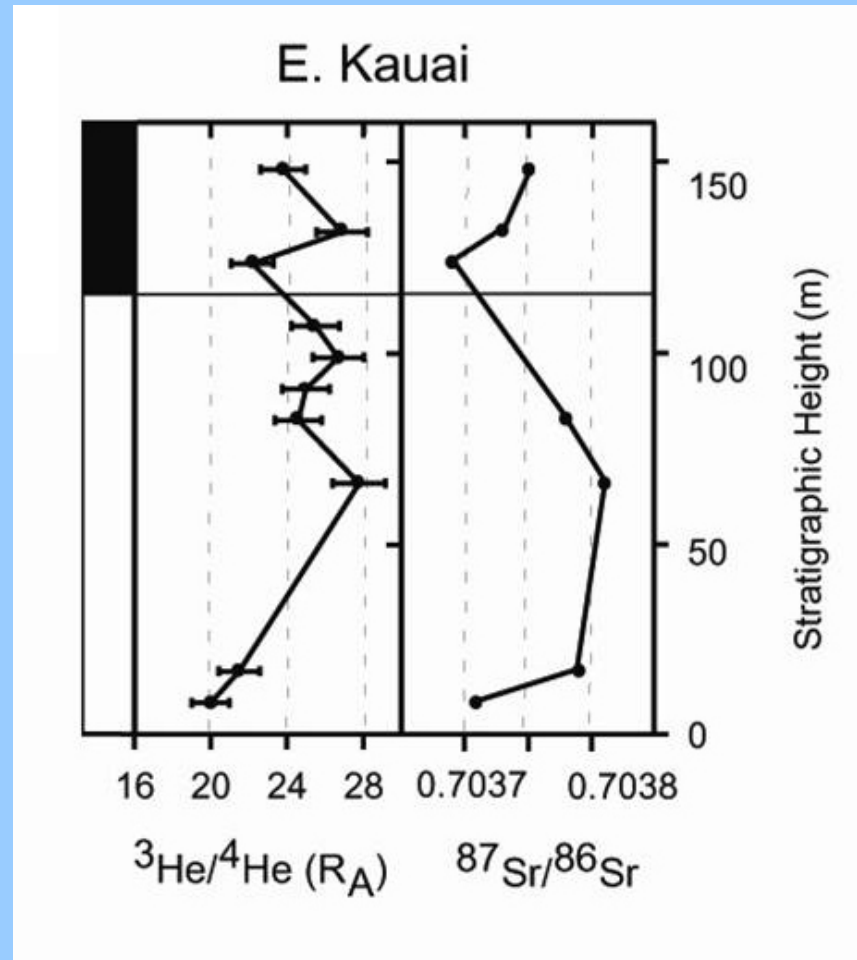
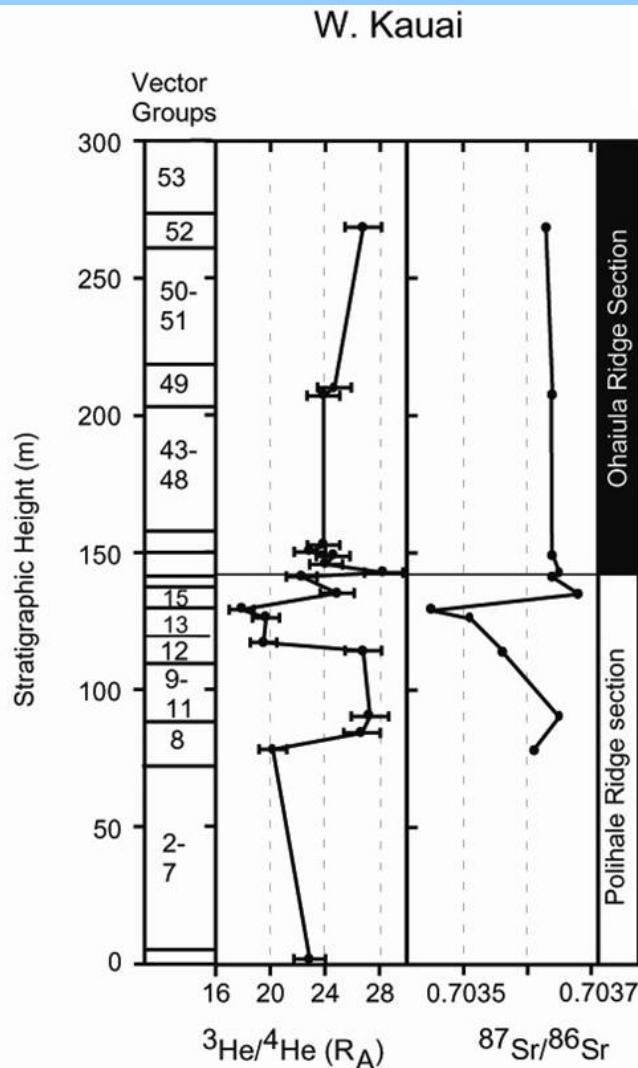


If MORB mantle extends to 670 km,  $0.6\text{--}4.6 \times 10^{18}$  g of  $^{40}\text{Ar}$  in upper mantle and  $59 \times 10^{18}$  g of  $^{40}\text{Ar}$  in the lower mantle, corresponding to a K concentration of about 230ppm; consistent with K content of bulk Earth

# Relationship between He and other lithophile tracers

More depleted ←

→ Less depleted

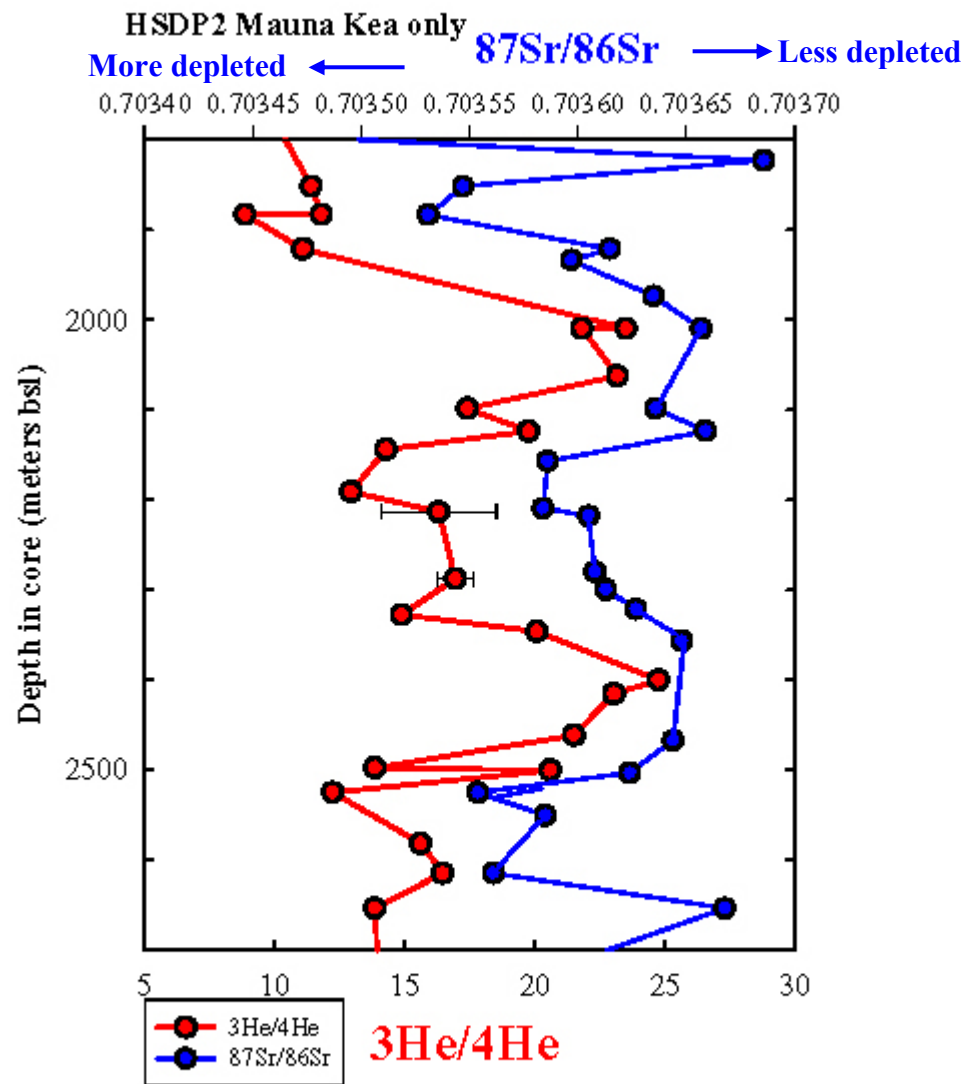


Mukhopadhyay et al (2003)



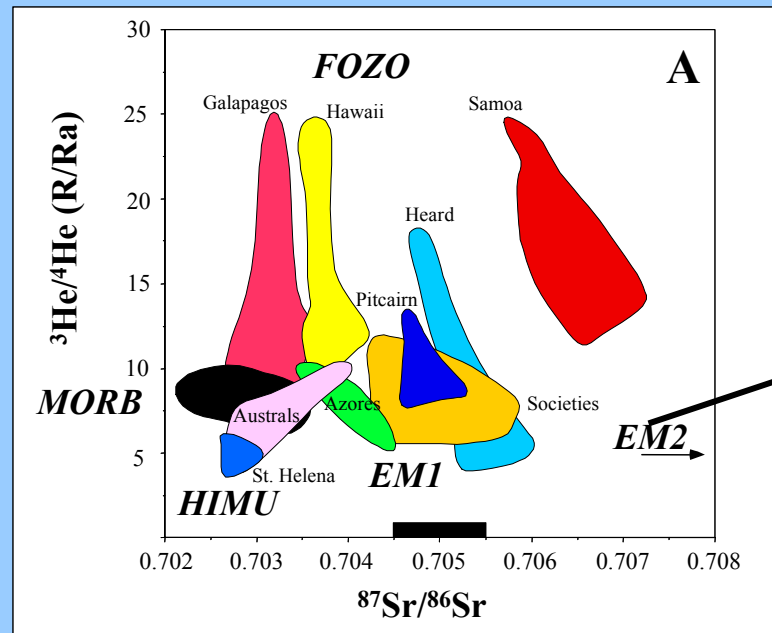
# Relationship between He and other lithophile tracers

- He isotopic variations are strongly coupled to variations in other lithophile tracers (Sr, Nd, Pb)
  - Higher  $^3\text{He}/^4\text{He}$  ratios are associated with *less* depleted  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic signal
- ⇒ high  $^3\text{He}/^4\text{He}$  ratios are indicative of less degassed mantle

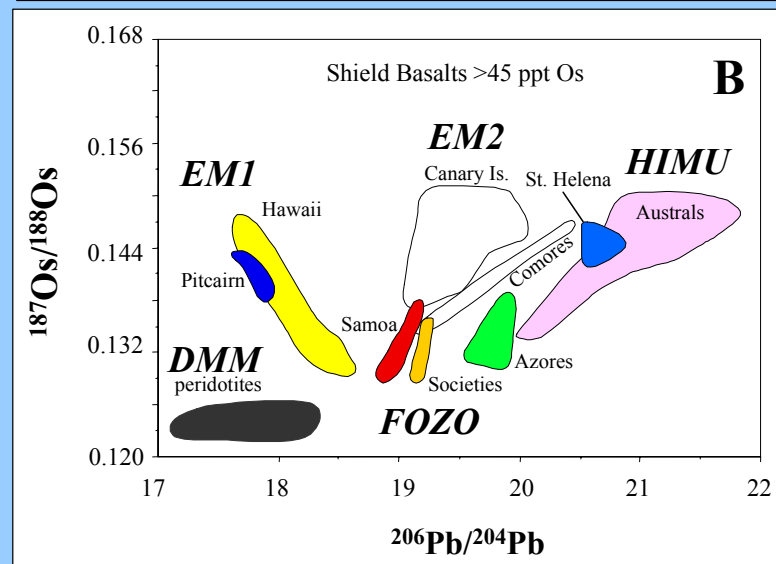


Above data is from the 3 km deep drill hole from Mauna Kea, Hawaii (Kurz et al., 2004)

# Global relationship between He and other lithophile tracers: The wormograms, hartworms, harttubes.....

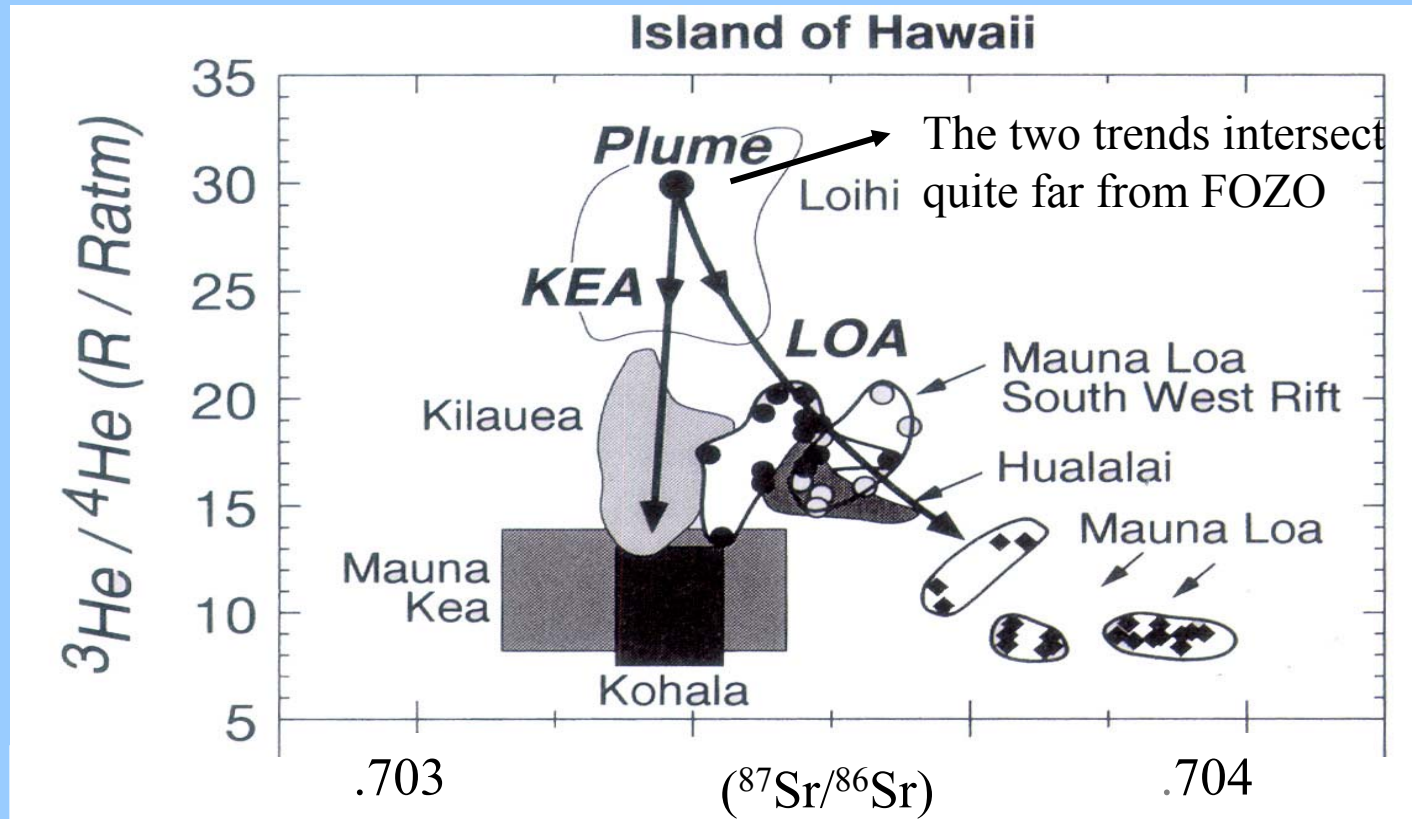


Heavy oxygen  
isotopic composition



Ballentine et al., 2002

Lets look at Hawaii in a little more detail.....



Nothing seems to be mixing with FOZO directly  
Consistent with recent Samoa data (talk to Matt Jackson)

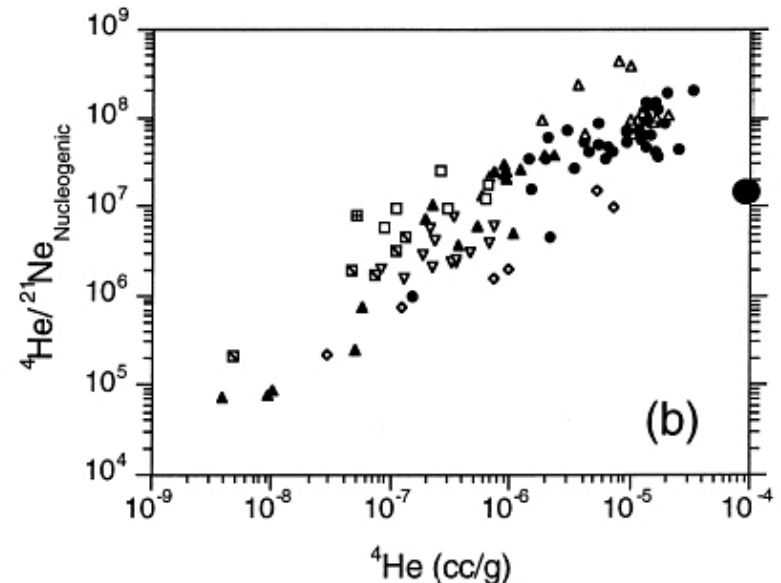
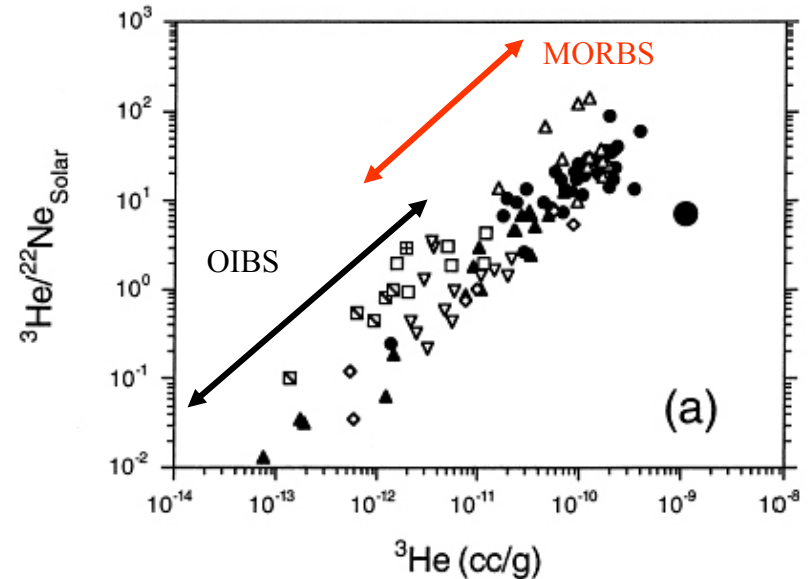
# Global relationship between He and other lithophile tracers

## Inferences:

- High  $^3\text{He}/^4\text{He}$  ratios from a single, relatively undegassed mantle source that is characterized by well defined Sr, Nd, and Pb isotopic composition
- $^3\text{He}/^4\text{He}$  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 has Sr, Nd, Pb isotopic composition that is slightly depleted in comparison to primitive mantle; PHEM is primitive.

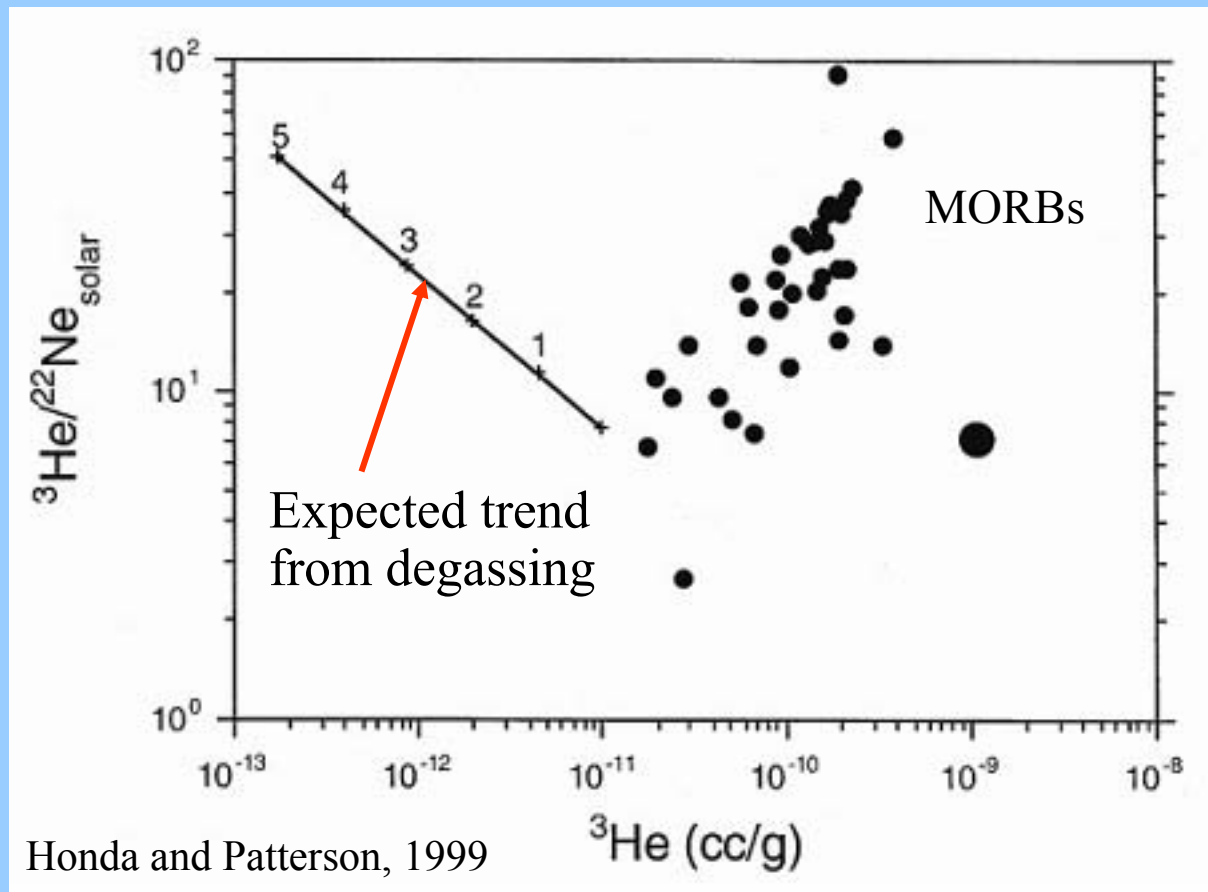
# Noble Gas Concentrations

- 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
- Is such an explanation tenable?



Honda and Patterson, 1999

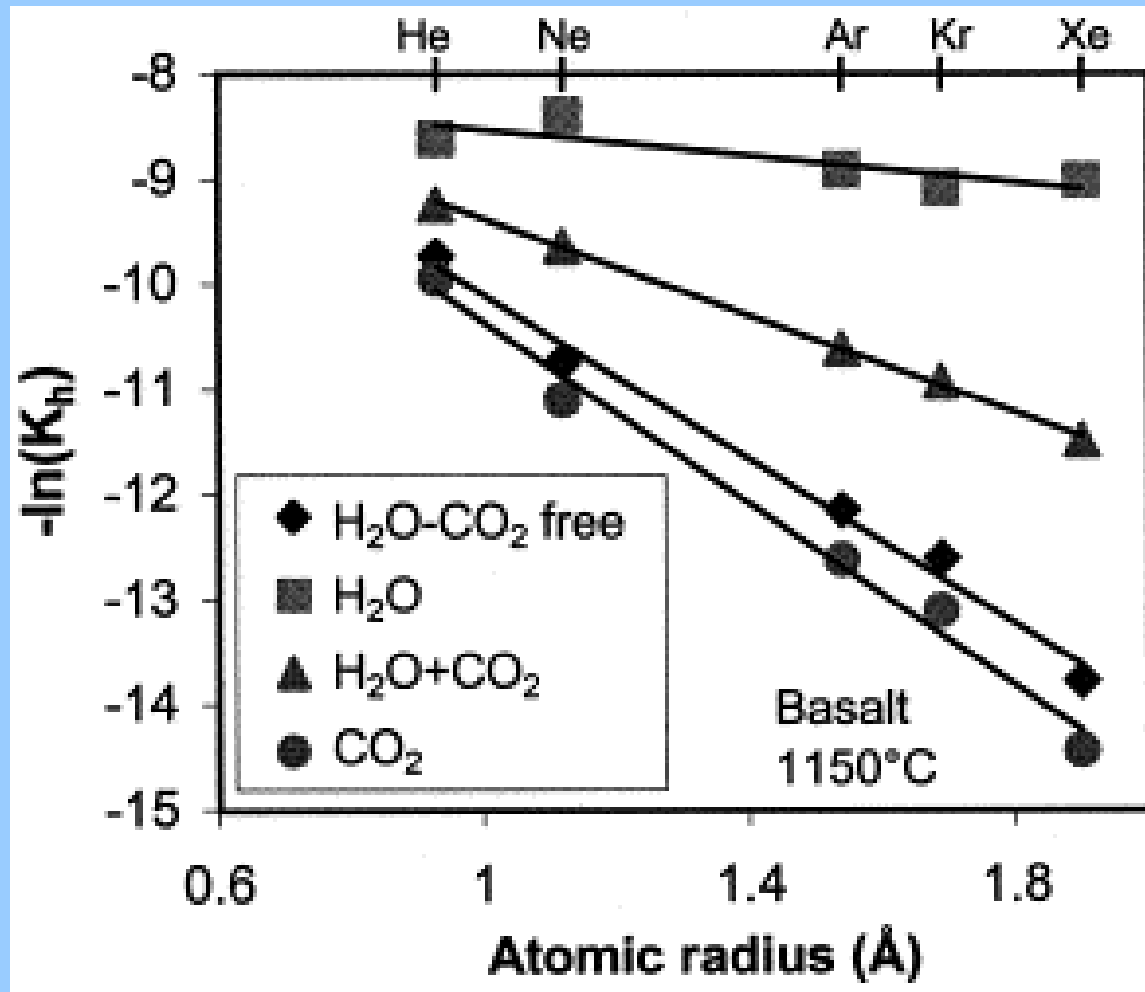
# Noble gas elemental ratios



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.

## Solubility as a function of H<sub>2</sub>O-CO<sub>2</sub>



# Summary statements

- From  $^3\text{He}/^4\text{He}$ ,  $^{21}\text{Ne}/^{22}\text{Ne}$ , and  $^{40}\text{Ar}/^{36}\text{Ar}$  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 reservoir that is less degassed than the MORB source is supported by  $^{40}\text{Ar}$
- Based on correlations between  $^3\text{He}/^4\text{He}$  ratios and other isotopic tracers (Sr, Nd, Pb), the undegassed reservoir has a composition depleted relative to primitive mantle; the depletion is consistent with the inferred  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of  $\sim 8000$  for the OIB source