Isotope Geochemistry

- Isotopes do not fractionate during partial melting or fractional crystallization processes. So they will reflect the characteristics of the mantle source
- OIBs, which sample a great expanse of oceanic mantle in places where crustal contamination is minimal, provide incomparable evidence for the nature of the mantle

Isotopes used as tracers in mantle geochemistry

Parent nuclide	**Daughter nuclide**	**Tracer ratio (radiogenic/nonradiogenic)**
^{87}Rb	^{87}Sr	$^{87}Sr/^{86}Sr$
^{147}Sm	^{143}Nd	$^{143}Nd/^{144}Nd$
^{235}U	^{207}Pb	$^{207}Pb/^{204}Pb$
^{238}U	^{206}Pb	$^{206}Pb/^{204}Pb$
^{232}Th	^{208}Pb	$^{208}Pb/^{204}Pb$
^{40}K	^{40}Ar	$^{40}Ar/^{36}Ar$
^{176}Lu	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	^{187}Os	$^{187}Os/^{188}Os$

Mantle Reservoirs

Key

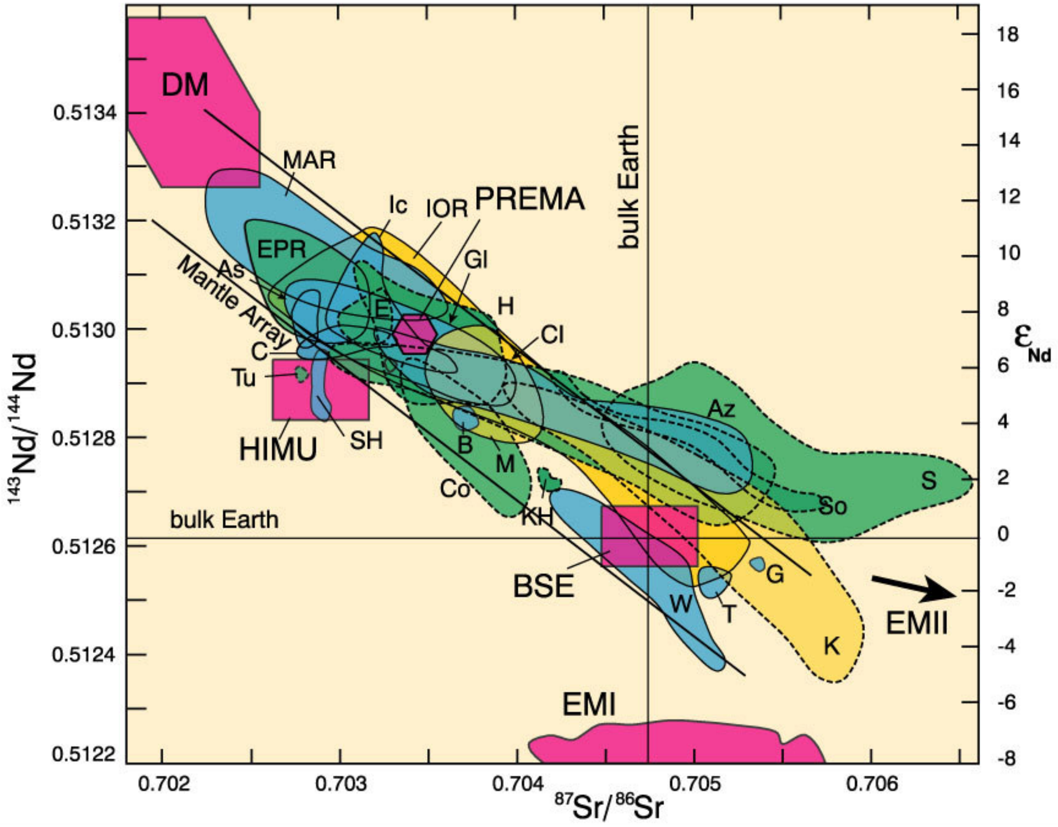
Mantle Reservoirs: 🟥

BSE	Bulk Silicate Earth
EMI	Enriched Mantle I
EMII	Enriched Mantle II
DM	Depleted Mantle
HIMU	High μ Mantle
PREMA	Prevalent Mantle

🟦	Atlantic Islands	———
🟩	Pacific Islands	- - - - - -
🟨	Indian Ocean Islands	----------

As	Ascension	
Az	Azores	
B	Bouvet	
C	Canary Is.	
CI	Central Indian*	
E	Easter Is.	
EPR	East Pacific Rise	🟩
G	Gough	
Gl	Galapagos	
Gu	Guadaloupe	
H	Hawaii	
Ic	Iceland	
IOR	Indian Ocean Ridge	🟨
K	Kerguelen	
KH	Koolau, Hawaii	
M	Marqueseas	
MAR	Mid-Atlantic Ridge	🟦
S	Samoa	
SH	St. Helena	
So	Society Is.	
T	Tristan da Cunha	
Tu	Tubaii	
W	Walvis	

* includes: Amsterdam, Crozet, Marion-Prince Edward, Mauritius, Reunion, and Rodriguez.



Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

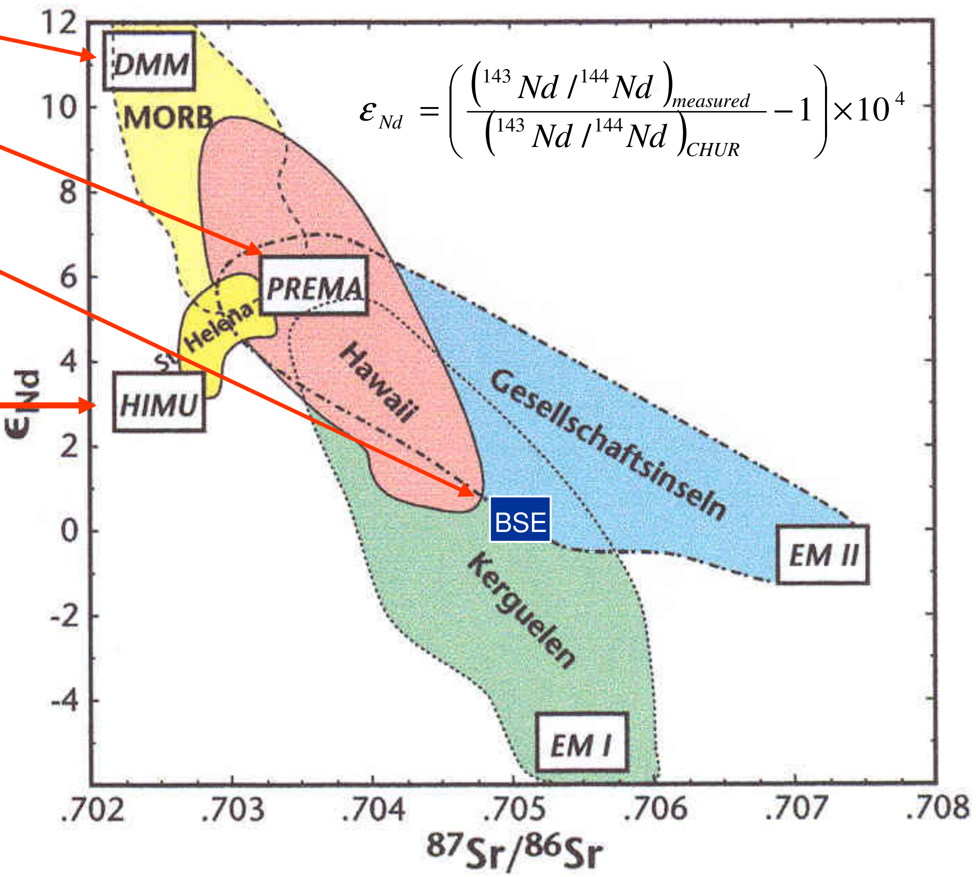
Mantle Reservoirs

DM (Depleted Mantle) =
N-MORB source

PREMA (PREvalent MAntle)

BSE (Bulk Silicate Earth) or the
Primary Uniform Reservoir

HIMU (high-μ, μ = $^{238}U/^{204}Pb$)

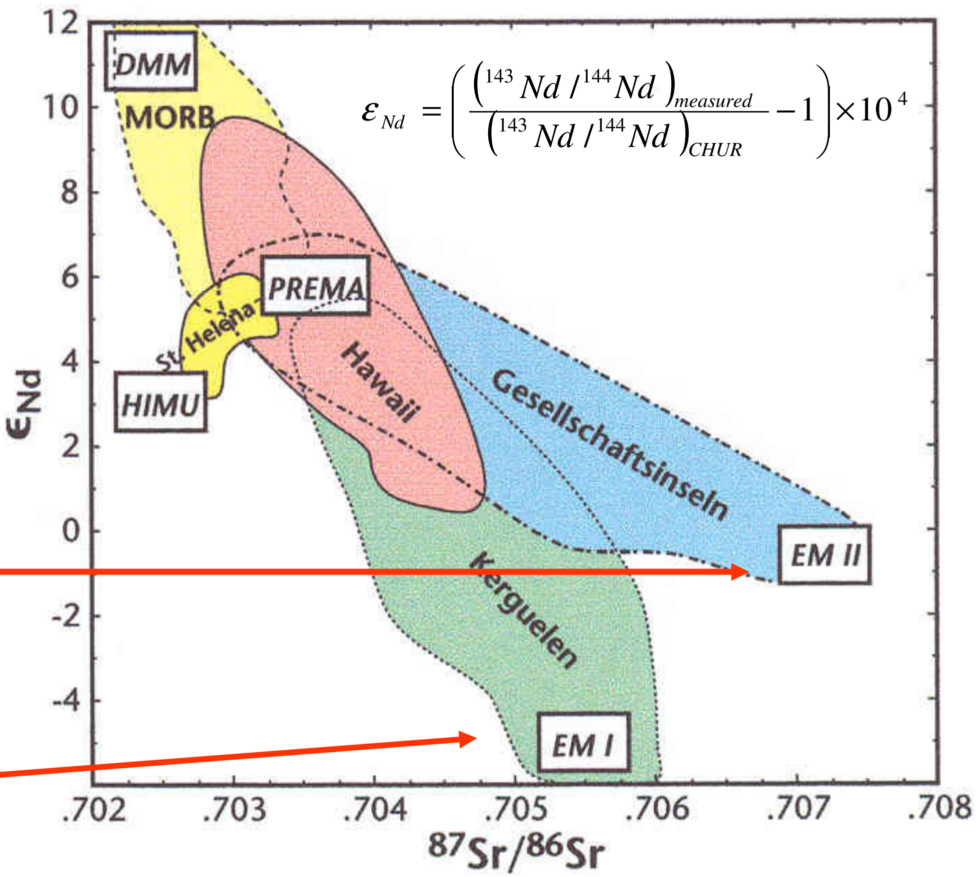


$$\varepsilon_{Nd} = \left(\frac{\left({}^{143}Nd/{}^{144}Nd \right)_{measured}}{\left({}^{143}Nd/{}^{144}Nd \right)_{CHUR}} - 1 \right) \times 10^{4}$$

Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

Mantle Reservoirs

The high Sr ratios in EM I and EM II also require a high Rb content and a similarly long time to produce the excess ^{87}Sr. This signature correlates well with continental crust (or sediments derived from it). Oceanic crust and sediment are other likely candidates for these reservoirs



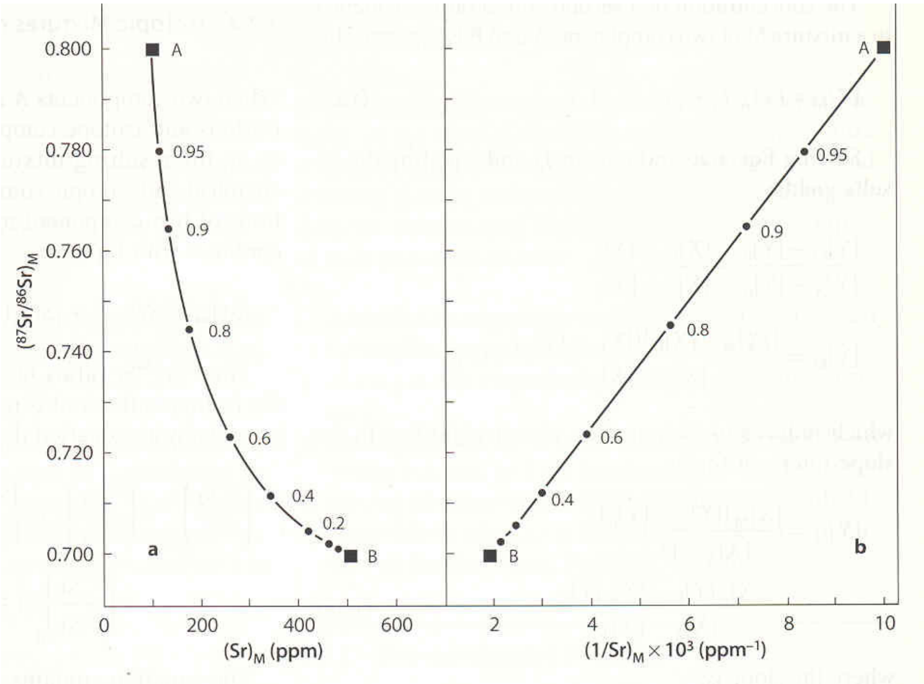
$$\varepsilon_{Nd} = \left(\frac{\left(^{143}Nd/^{144}Nd\right)_{measured}}{\left(^{143}Nd/^{144}Nd\right)_{CHUR}} - 1 \right) \times 10^{4}$$

EM-II = enriched mantle-2
^{87}Sr/^{86}Sr well above any reasonable mantle sources

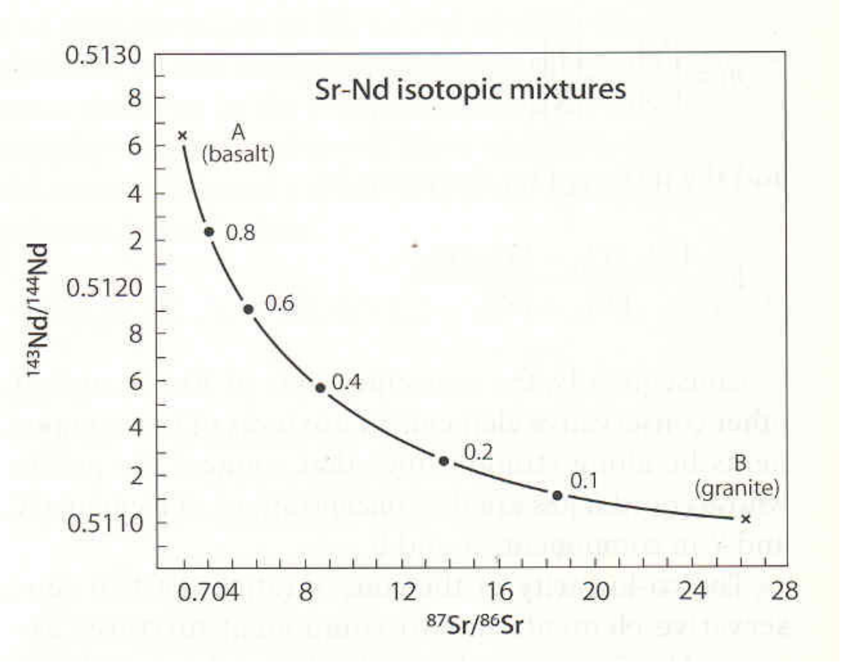
EM I = enriched mantle-1 has low ^{87}Sr/^{86}Sr (near primordial) and very low ^{143}Nd/^{144}Nd

Binary mixtures

Sr	500 ppm	100 ppm
$^{87}Sr/^{86}Sr$	0.7	0.8



$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_M = \frac{0.8\times100\times0.9+0.7\times500(1-0.9)}{100\times0.9+500(1-0.9)} = 0.764$$



G. Faure, 1986, 2001

The isotope geology of Pb

Pb produced by radioactive decay of U & Th

$^{238}U \rightarrow {}^{206}Pb$

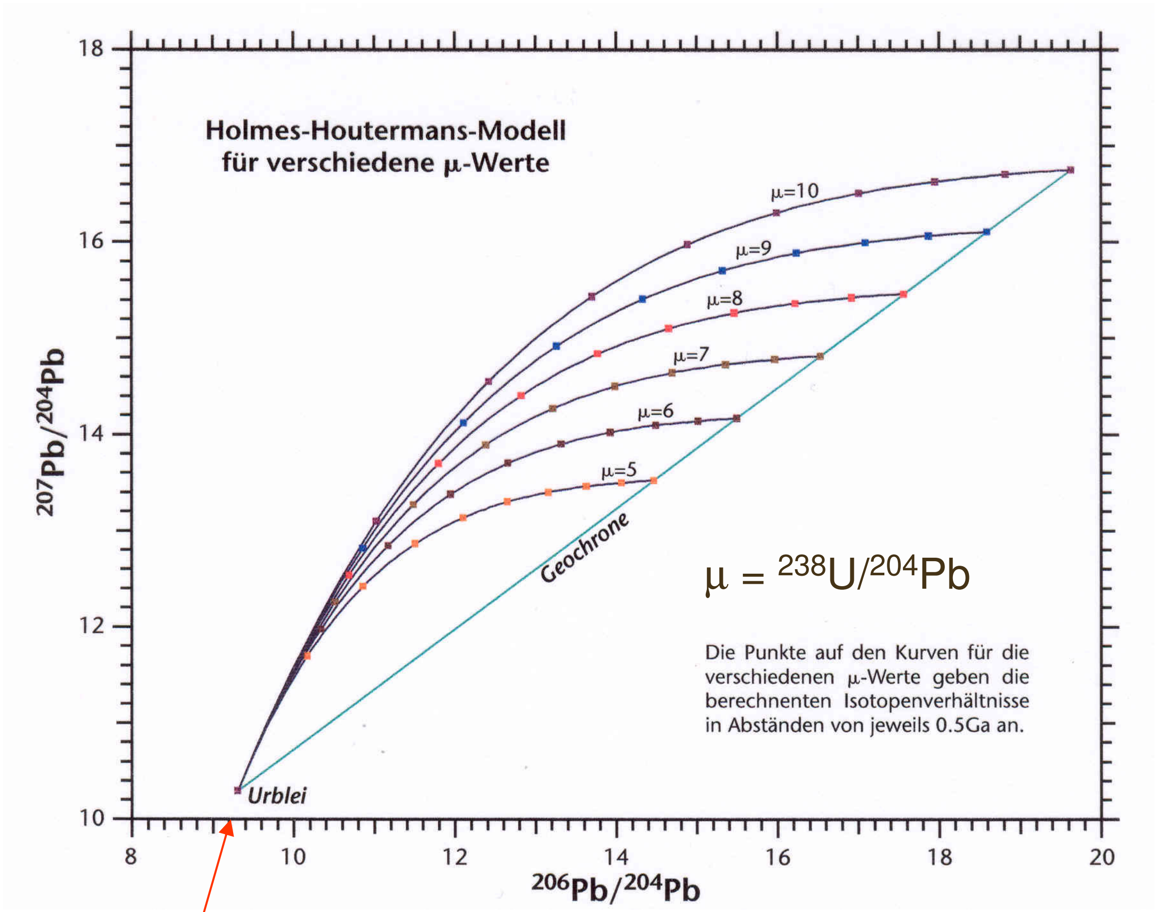
$^{235}U \rightarrow {}^{207}Pb$

$^{232}Th \rightarrow {}^{208}Pb$

^{204}Pb is non-radiogenic

so, increase of $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$,
due to U and Th decay

The isotope geology of Pb



$\mu = {}^{238}U/{}^{204}Pb$

$$\left(\frac{^{206}Pb}{^{204}Pb}\right)_t = a_0 + \mu(e^{\lambda_1 T} - e^{\lambda_1 t})$$

$$\left(\frac{^{207}Pb}{^{204}Pb}\right)_t = b_0 + \frac{\mu}{137.88}(e^{\lambda_2 T} - e^{\lambda_2 t})$$

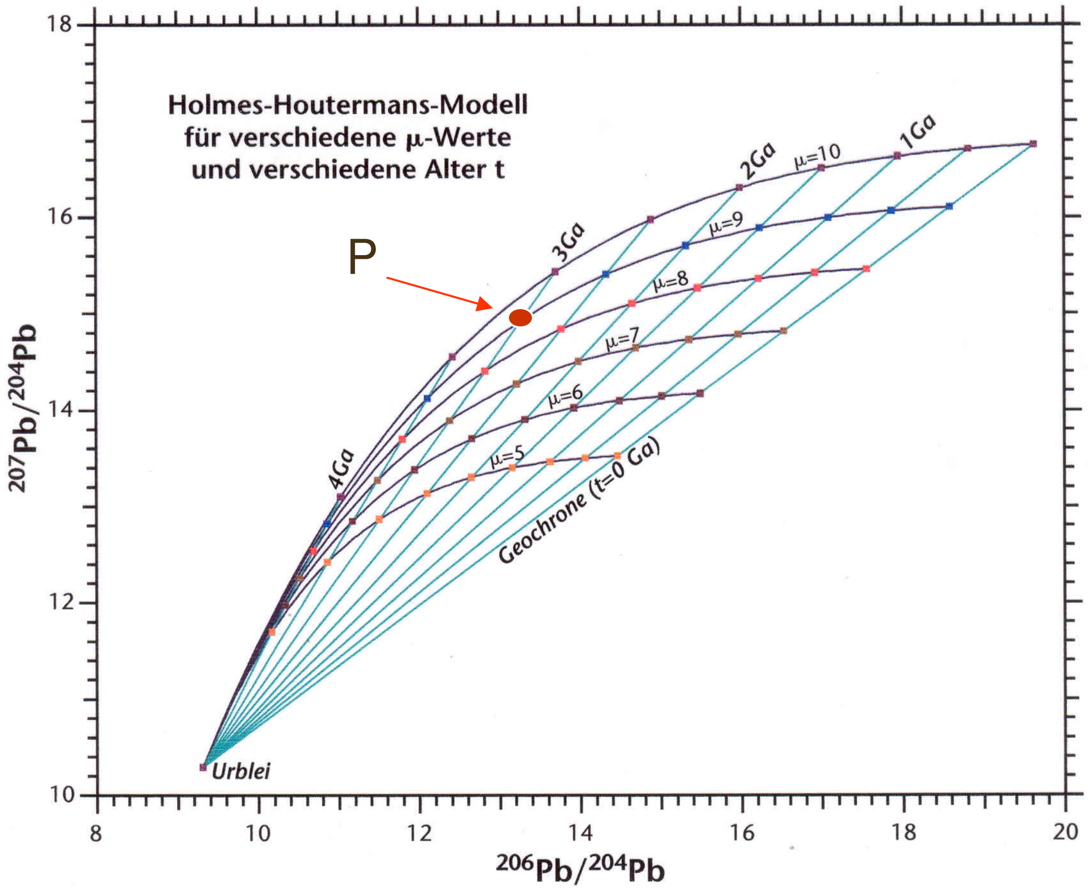
$$\left(\frac{^{206}Pb}{^{204}Pb}\right)_i = a_0 = 9.30$$

$$\left(\frac{^{207}Pb}{^{204}Pb}\right)_i = b_0 = 10.29$$

Primeval lead

(Isotope ratios of Pb in troilite of the iron meteorite Canyon Diablo)

The isotope geology of Pb

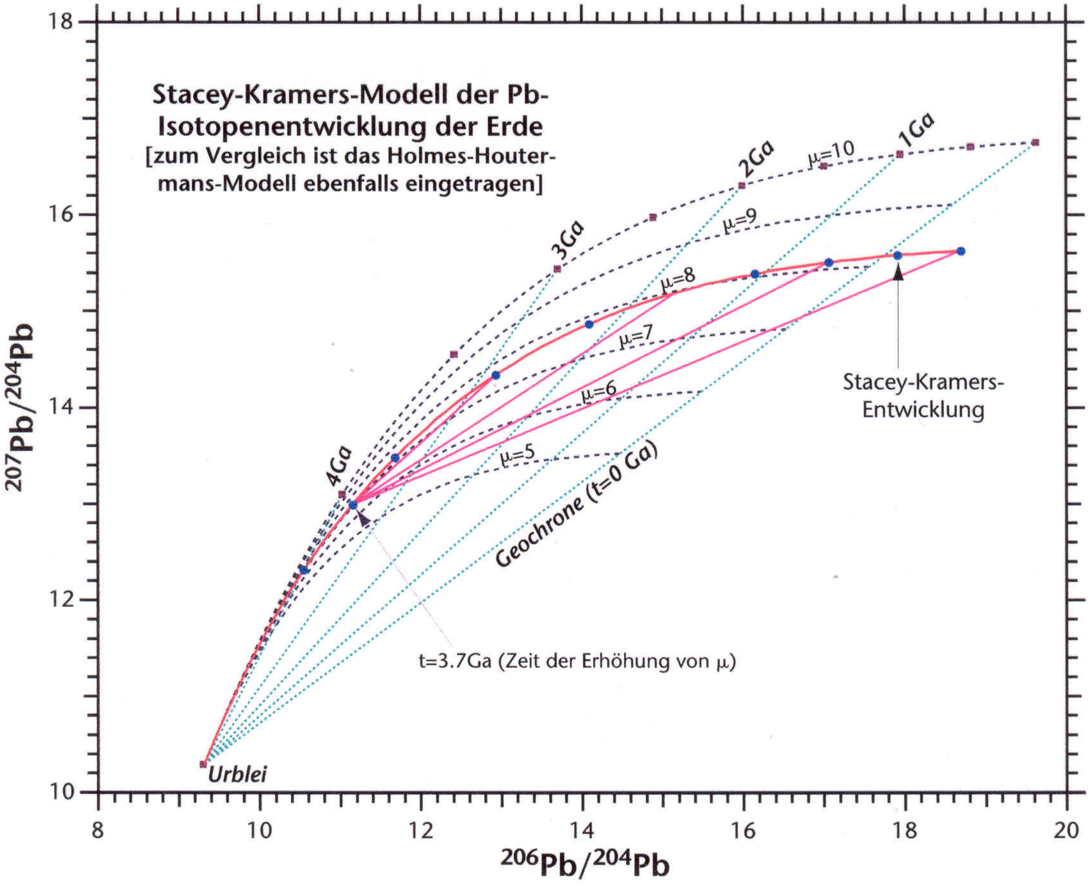


$$\left(\frac{{}^{206}Pb}{{}^{204}Pb}\right)_t = a_0 + \mu\left(e^{\lambda_1 T} - e^{\lambda_1 t}\right)$$

$$\left(\frac{{}^{207}Pb}{{}^{204}Pb}\right)_t = b_0 + \frac{\mu}{137.88}\left(e^{\lambda_2 T} - e^{\lambda_2 t}\right)$$

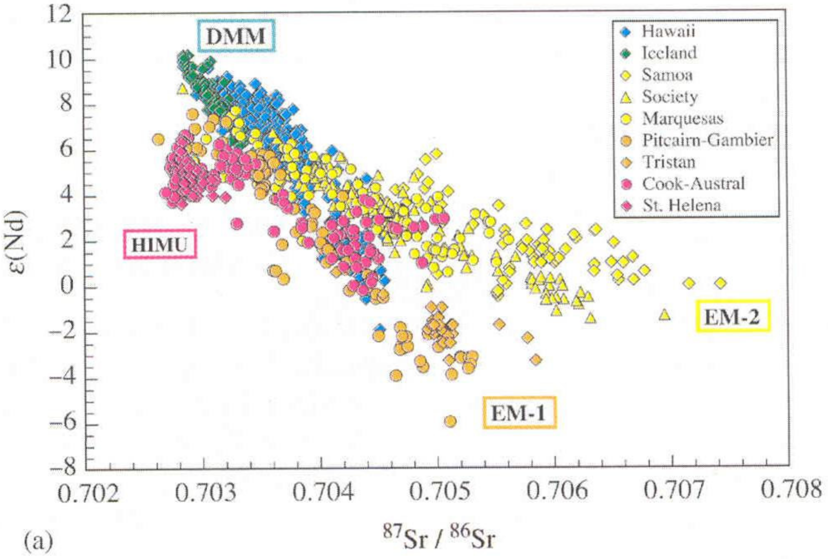
The straight lines are isochrons for selected values of t. Point P: ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb ratios of a lead mineral (e.g. galena that was withdrawn 3x10^9 years ago from a source region with a present μ-value of 9.

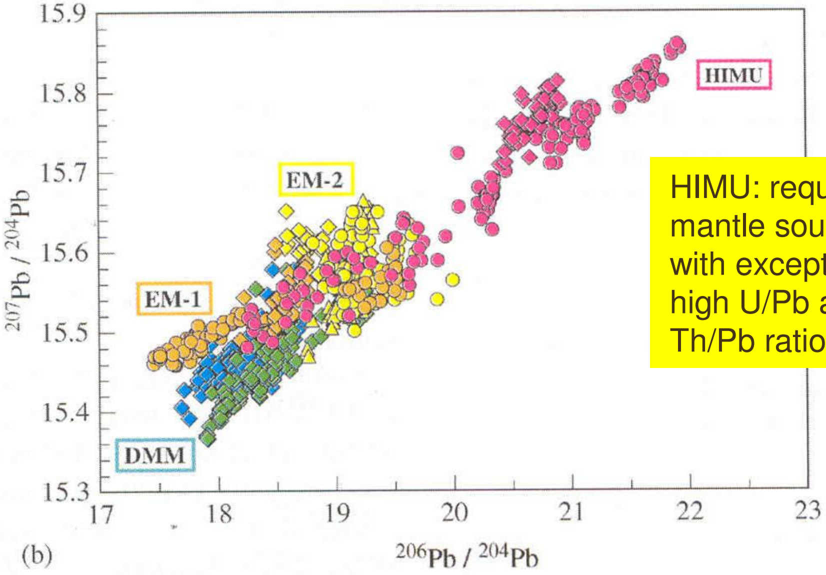
The isotope geology of Pb



Two-stage Pb evolution model of Stacey & Kramers (1975)

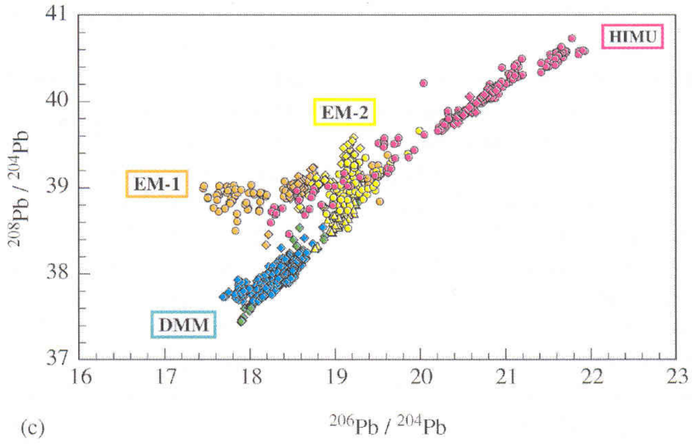
In this model Pb evolves from primordial isotope ratios between 4.6 and 3.7 Ga in a reservoir with a μ-(^{238}U/^{204}Pb) value of 7.2. At 3.7 Ga the μ-value of the reservoir was changed by geochemical differentiation to 9.7.

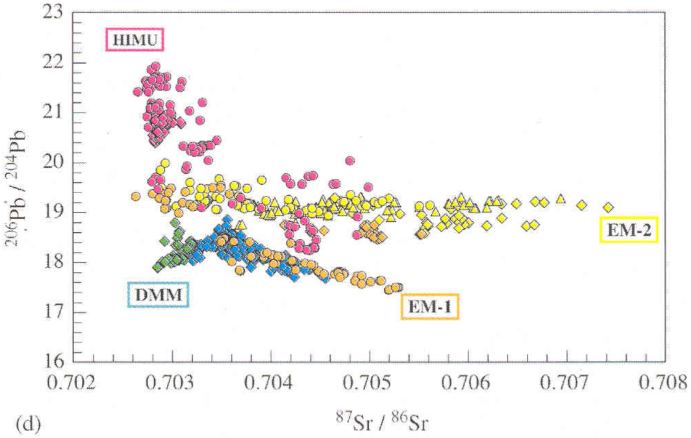


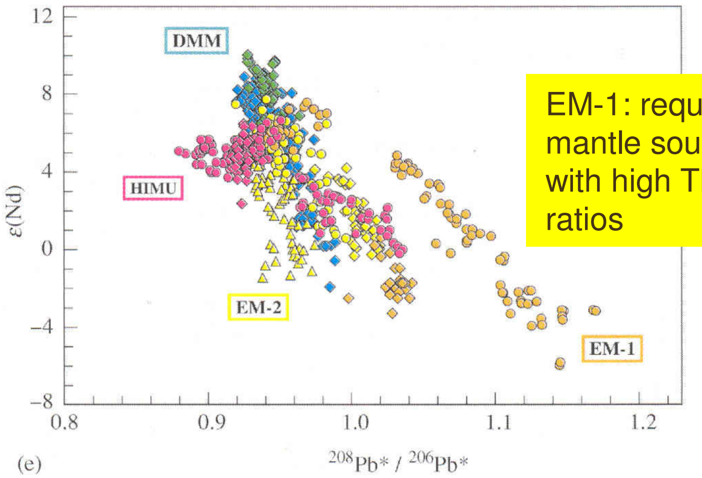


HIMU: requires mantle sources with exceptionally high U/Pb and Th/Pb ratios

Hofmann (2003) Treatise on Geochemistry, Vol. 2: The mantle and core.





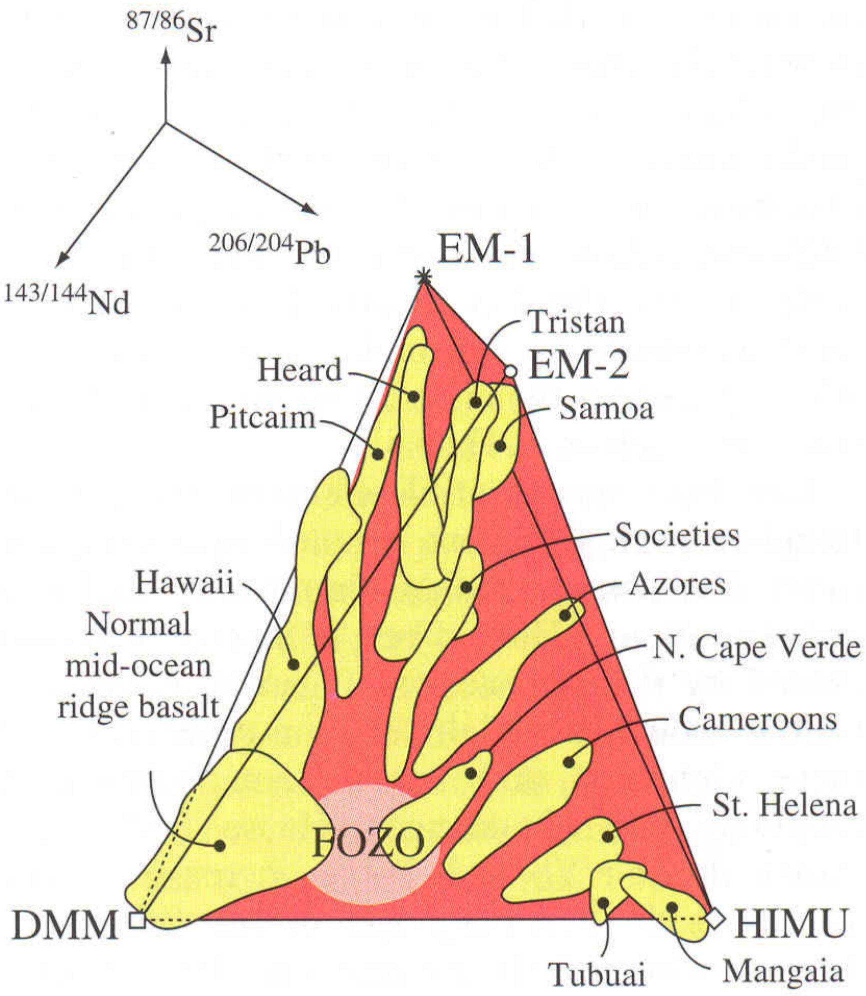


EM-1: requires mantle sources with high Th/U ratios

Mantle isotope tetrahedron

Hart et al. (1992)
Science 256

FOZO (for focal zone): material from the lower mantle that is present as a mixing component in all deep-mantle plumes



Mantle reservoirs/flavors

- Isotopically enriched reservoirs (EM-1, EM-2, and HIMU) are too enriched for any known mantle process, and they correspond to crustal rocks and/or sediments

- **HIMU** – (enriched in ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb, depleted in ^{87}Sr/^{86}Sr)

  Origin: a) recycled oceanic crust, which has lost alkalis (Rb) and Pb during alteration and subduction

  b) metasomatically enriched oceanic lithosphere

- **EM-1** (slightly enriched in ^{87}Sr/^{86}Sr, but not in Pb, very low ^{143}Nd/^{143}Nd)

  Origin: a) recycling of delaminated subcontinental lithosphere

  b) recycling of subducted ancient pelagic sediment (because of their high Th/U and low (U,Th)/Pb ratios)

- **EM-2** (more enriched, especially in ^{87}Sr/^{86}Sr and radiogenic Pb

  Origin: a) recycled ocean crust and small amount of subducted sediment

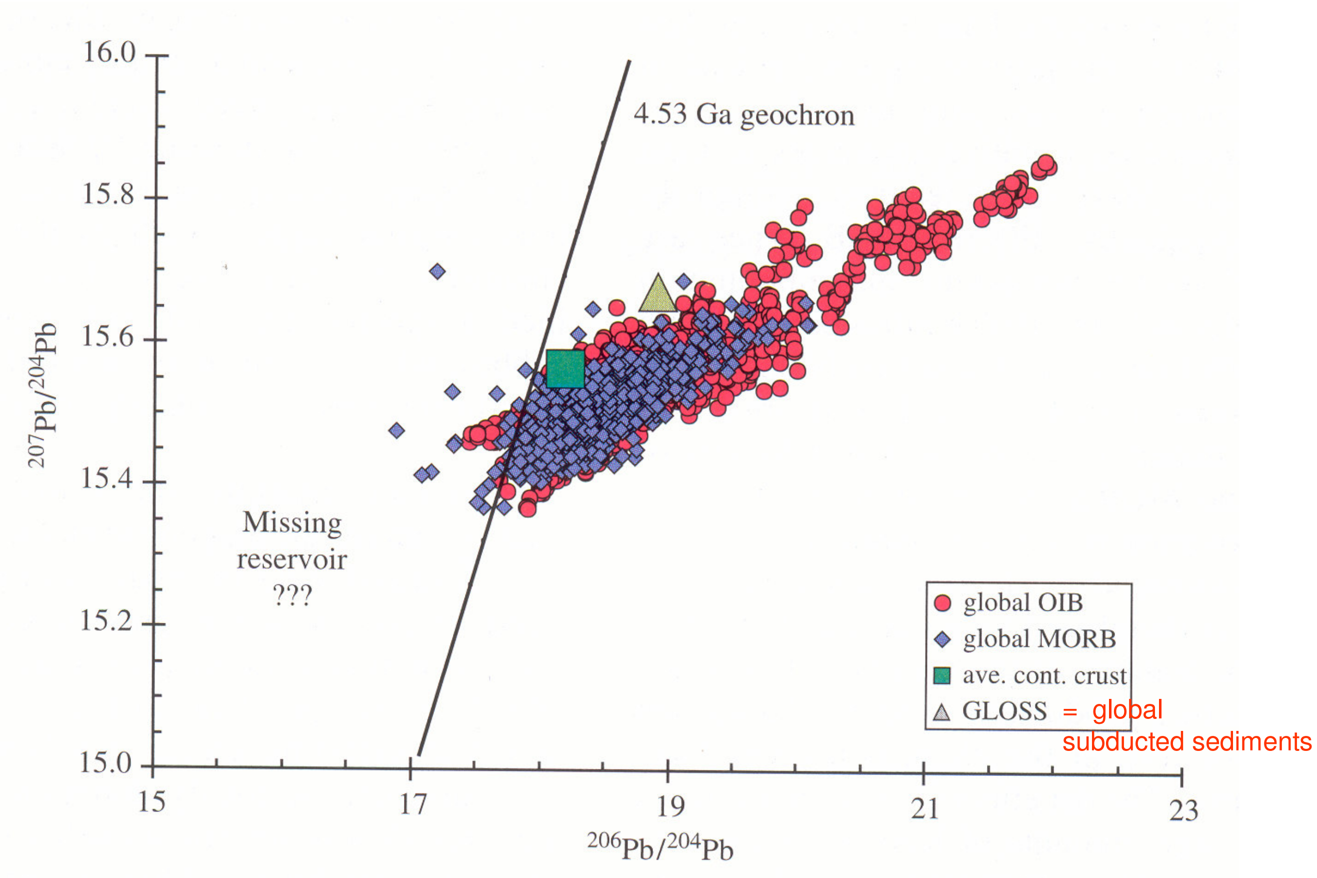
  b) recycling of melt-impregnated oceanic lithosphere

The isotope geology of Pb

- U, Pb, and Th are concentrated in continental crust (high radiogenic daughter Pb isotopes)
- Oceanic crust has elevated U and Th content (compared to the mantle) as well as sediments derived from oceanic and continental crust
- Pb isotopes are a sensitive measure of crustal (including sediment) components in mantle isotopic systems

The lead paradox

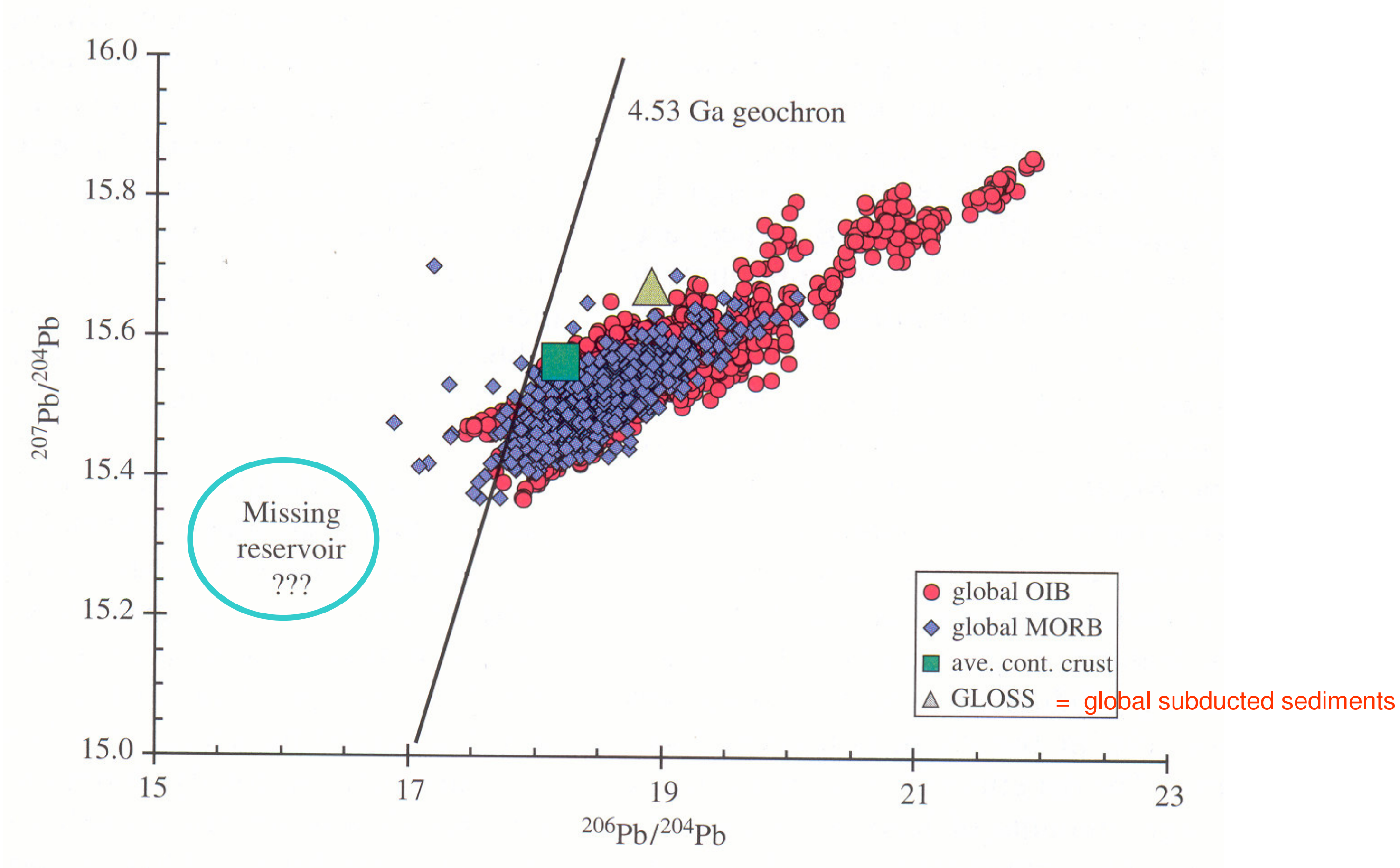
Kruste und Mantel:
komplementär bzgl. Pb-Konzentration – nicht aber bzgl. Isotopie!



Hofmann (2003) :
Treatise on Geochemistry

The fact that MORBs do not plot to the left of the geochron is called the “First Lead Paradox”

The lead paradox

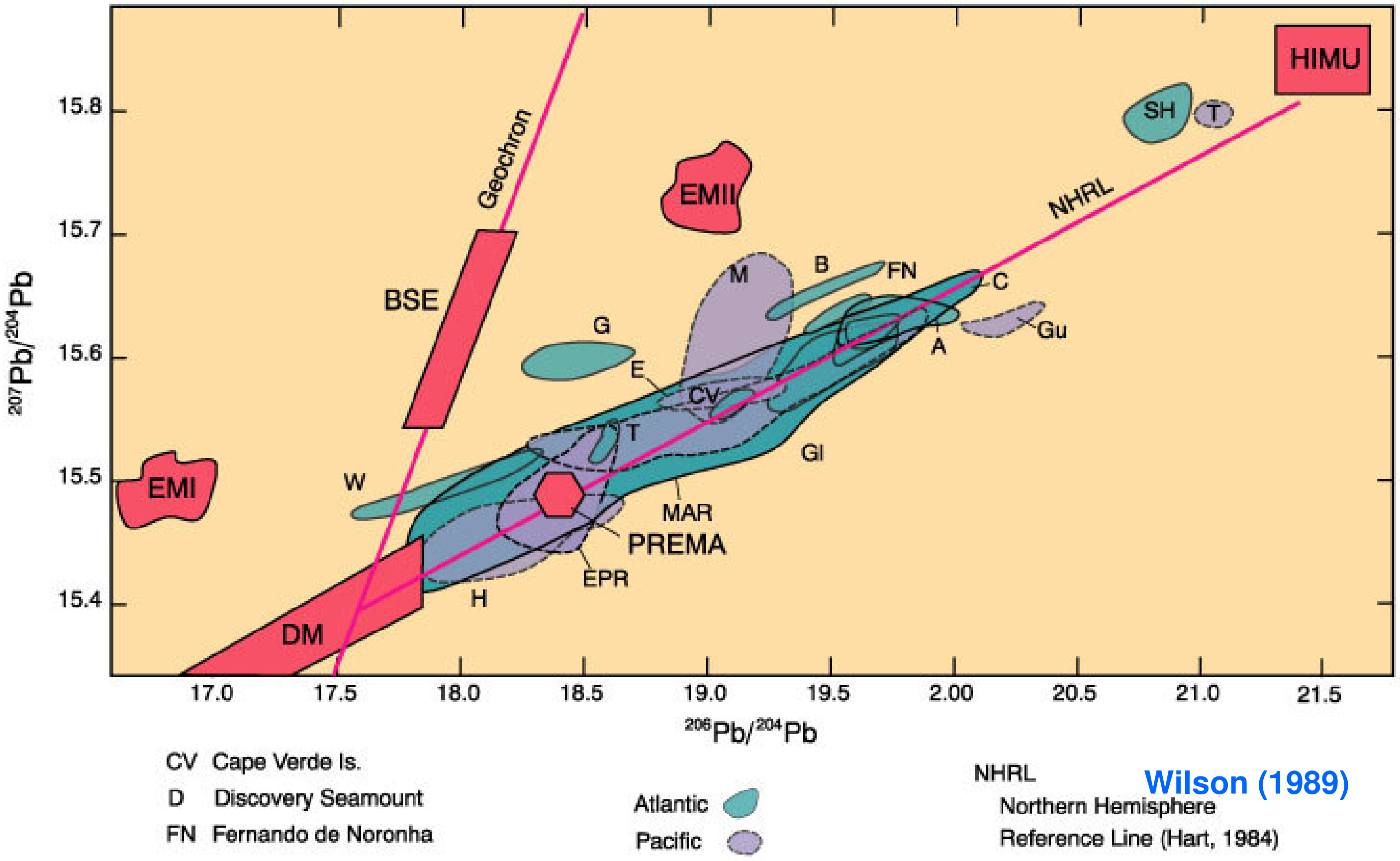


hidden reservoir with Pb isotopes to the left of the geochron

- uptake of lead by the core (“core pumping”)?
- storage of unradiogenic lead in the lower cont. crust or subcont. lithosphere?

Ave. oceanic and cont. crust close to geochron
→ little net fractionation of U/Pb during crust-mantle differentiation

Pb isotope geochemistry

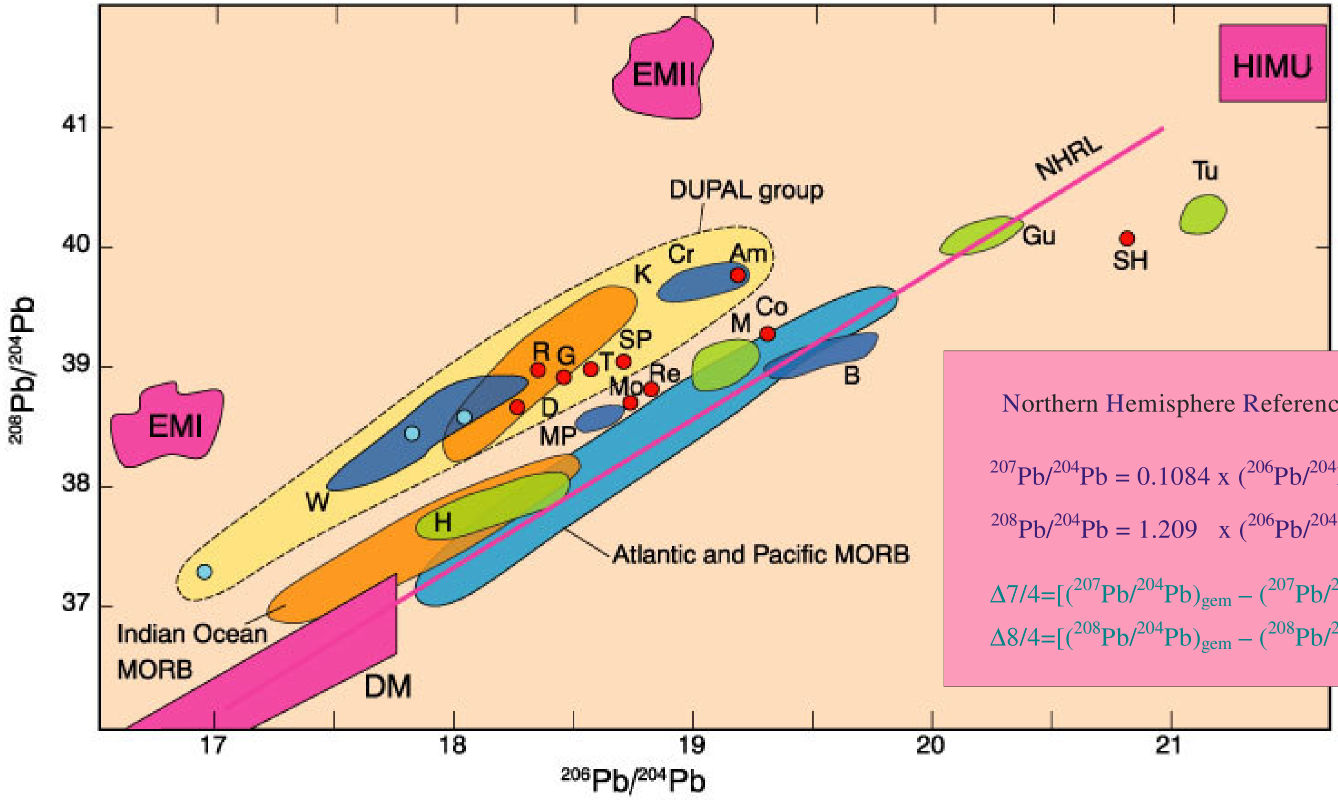


Wilson (1989)

The $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ data, especially from the northern hemisphere form a linear mixing line between DM and HIMU, a line called the **Northern Hemisphere Reference Line (NHRL)**

Pb isotope geochemistry

Data from Hamelin and Allègre (1985), Hart (1984), Vidal et al. (1984)



Am	Amsterdam	MP	Marion-Pr. Edward	SP	St. Paul
Cr	Crozet	R	Raratonga	●	Indian Ocean MORB with DUPAL characteristics
Mo	Mauritius	Re	Reunion		

Northern Hemisphere Reference Lines (NHRL)

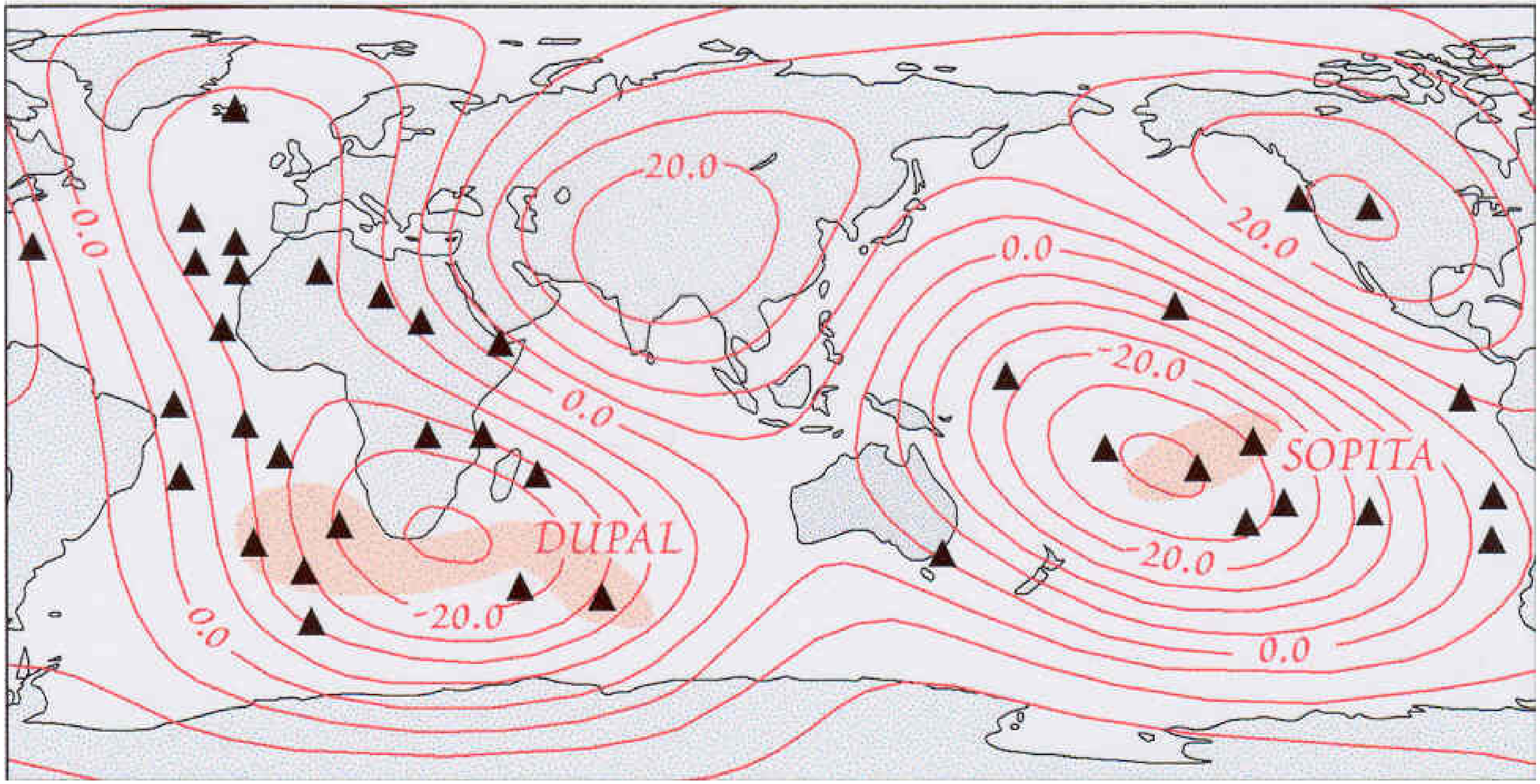
$^{207}Pb/^{204}Pb = 0.1084 \times (^{206}Pb/^{204}Pb) + 13.491$

$^{208}Pb/^{204}Pb = 1.209 \times (^{206}Pb/^{204}Pb) + 15.627$

$\Delta 7/4 = [(^{207}Pb/^{204}Pb)_{gem} - (^{207}Pb/^{204}Pb)_{NHRL}] \times 100$

$\Delta 8/4 = [(^{208}Pb/^{204}Pb)_{gem} - (^{208}Pb/^{204}Pb)_{NHRL}] \times 100$

Pb isotope geochemistry



Hart (1984)

DUPAL = DUPre & ALlegre

SOPITA = SOuth Pacific Isotopic and Thermal Anomaly