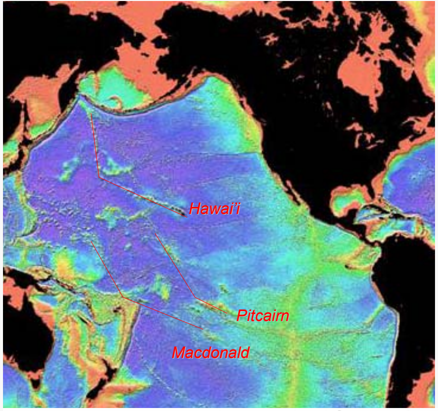
Ocean Islands and Plume Magmatism

Wilson p. 245-285

- **In this lecture:**
  - **Definition, ideas, distribution of "Hotspots"**
  - **Crustal structure**
  - **Partial melting**
  - **Petrography, mineralogy**
  - **Major elements, shallow level crystallization of OIB**
  - **Trace element, isotopic composition of OIB**
  - **Integrated petrologic model**



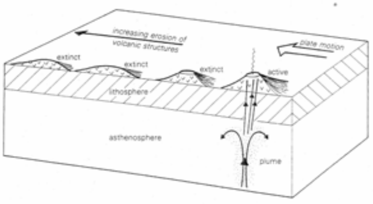


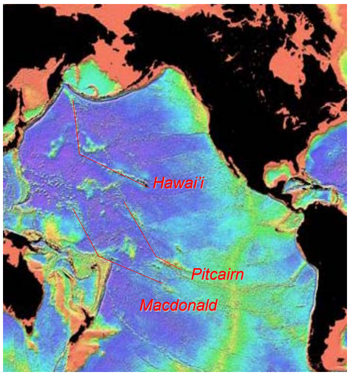
Figure 9.3 Hotspot model for the generation of linear volcanic island chains.

What are "Hot Spots" ?

Most igneous activity concentrated at plate margins

10% within plate interiors

Small seamounts vs. immense ocean Islands



"Hot spot" model of Wilson (1963)

Observations

Linear chains of volcanic islands in Pacific

Age progression established through K-Ar dating

Model

1. **Fixed magma source, or "hot spot" in mantle over which oceanic plate moves**
2. **Surface volcanism fed by mantle plume**
3. **Volcanes carried away from plume center, magma supply cut off**
4. **Forms chains of volcanoes parallel to direction of sea floor spreading**

Explains most, but not all intraplate volcanism (rifting + extension important)

Upwelling deep mantle plume hypothesis of Morgan (1972)

1. **Secondary mode of mantle convection to plate tectonics**
2. **Plumes arise from base heating within a boundary layer**
3. **Source of Plumes?** ***Controversial***

From 670 km seismic discontinuity?

From CMB ? If so, this is a major mode of mantle convection!

Do plumes incorporate recycled crust, or tap undisturbed primordial mantle ?

Where are “Hot Spots” ?

122 Hot spots active over the last 10 Ma

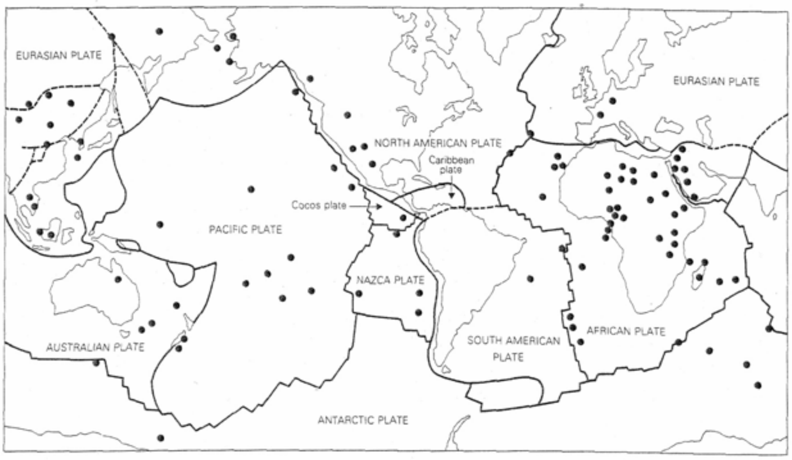
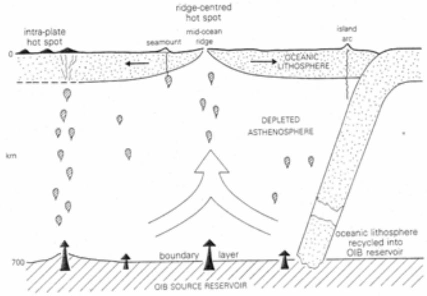


Figure 9.4 Distribution of hot spots within the oceanic and continental plates (after Burke & Wilson 1976, p. 37).

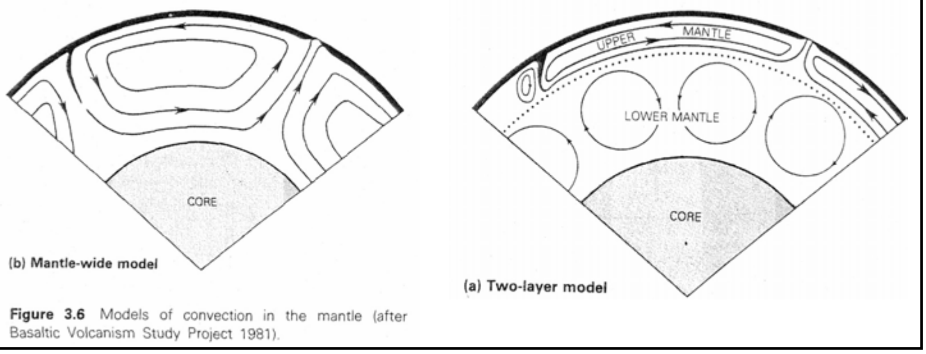
The Big Question: Where do Plumes Originate ?



Origin at 670 km boundary layer ?
layered mantle convection

vs.

Origin at CMB?
whole mantle convection



(b) Mantle-wide model

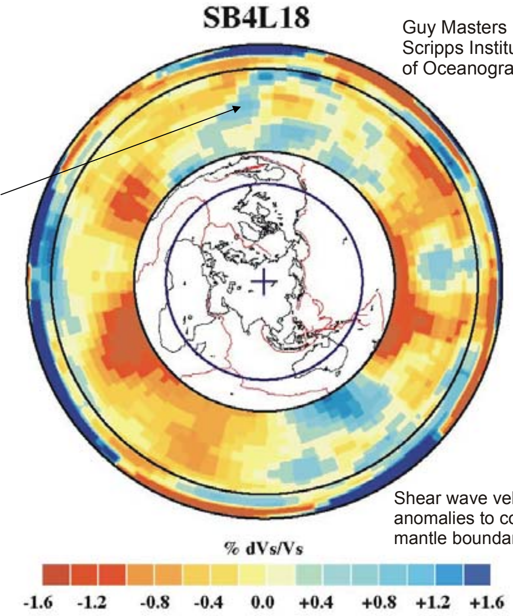
(a) Two-layer model

Figure 3.6 Models of convection in the mantle (after Basaltic Volcanism Study Project 1981).

The Big Question: Where do Plumes Originate ?

Slice through the center of the Earth. The cut of the slice is along the great circle that is marked by the blue circle in the center of the plot. One of the most prominent features is a seismically fast slab-like anomaly that extends from the surface beneath the Continental US well throughout the whole mantle. This is thought to be the image of the subducted Farallon plate.

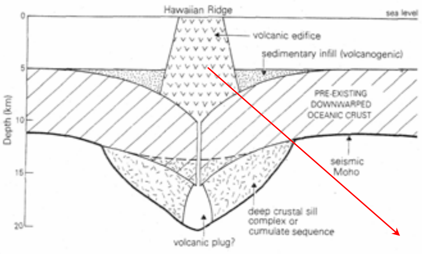
Other marked features include two large slow anomalies under Africa and the central Pacific Ocean that originate at the CMB (core-mantle boundary)and extend well up into the lower mantle. Also prominent are the seismically fast continental shields in the upper mantle: the South and West African Cratons, the southern extension of the Canadian Shield and the Australian Shield. Mid-ocean ridges are associated with slow anomalies in the upper mantle. The black circle marks the 670km discontinuity between upper and lower mantle.



Guy Masters
Scripps Institute
of Oceanography

Shear wave velocit
anomalies to core-
mantle boundary

Crustal structure, magma plumbing system



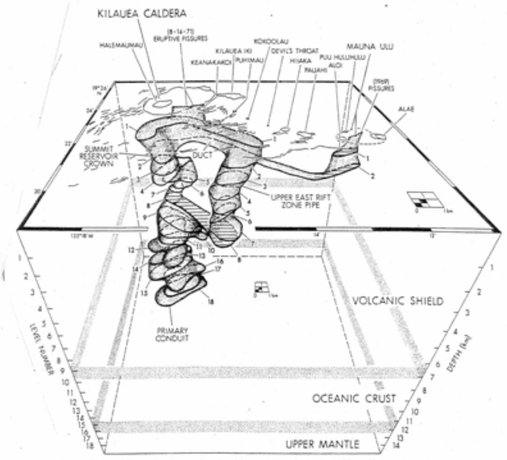


Figure 43. Perspective view northward and downward into the interior of Kilauea Volcano, from Ryan and others (1981). Magma conduits are defined by zones of earthquake hypocenters that surround them over periods of several years. Numbers on magma conduits represent horizontal sections at depths corresponding to the level-number scale on left side.

Seismic evidence

Gravity profile

- **low density volcanic complex**
- **requires high density "root"**
  - **may be ultramafic cumulates?**

Crustal magma reservoirs

- **defined by earthquake hypocenters**
- **shallow reservoir extends down 14 km to primary conduit/feeder dike**

Partial melting processes

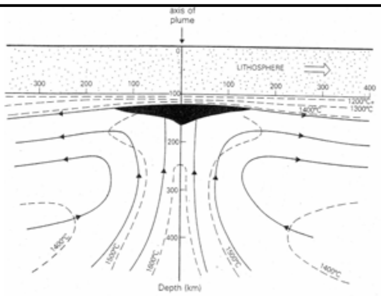
Decompression melting similar to MORB

Main constraints from experimental petrology

Tholeiitic basalt: extract melt <15 kbar

Alkali olivine basalt: extract melt 15-25 kbar

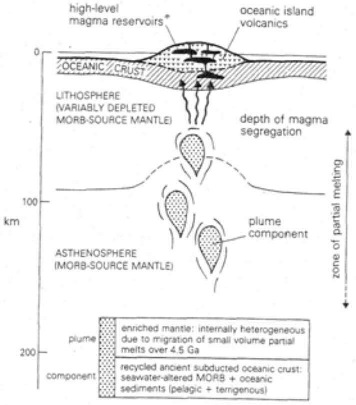
Alkali basalt: extract > 25 kbar



Need to know

1. Composition of primary basalt
2. Mineralogy of mantle source
3. Degree of melting
4. Melting mechanism
   (batch/fractional; modal/non-modal)
5. Depth of melting and melt segregation
6. Importance of mixing different mantle sources
   (plume vs. depleted upper mantle vs. lithosphere)

Crustal contamination is not severe,
near primary magmas may erupt



Magma series, crystallization, mixing

Two magma series:

Tholeiitic and Alkaline

Two Alkaline differentiation trends

under- and over-saturated wrt SiO_2

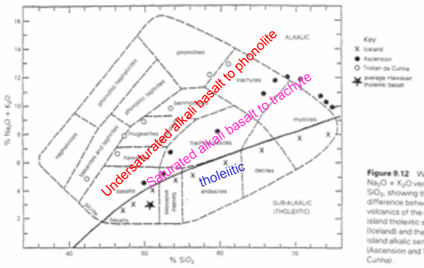


Figure 9.12 Weight % $Na_2O + K_2O$ versus wt.% SiO_2, showing the difference between volcanics of the oceanic island tholeiitic series (Iceland) and the oceanic island alkalic series (Ascension and Tristan da Cunha).

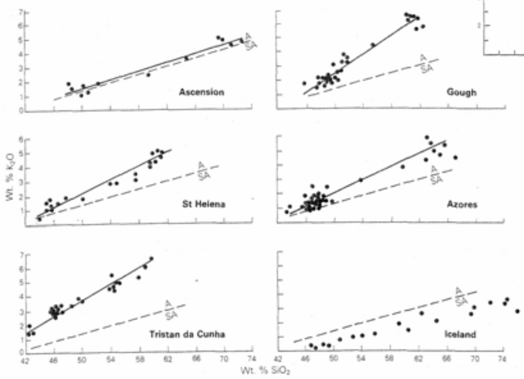


Figure 9.13 Weight.% K_2O versus wt.% SiO_2 for volcanic suites from Atlantic oceanic islands. The dashed line divides tholeiitic (sub-alkalic) and alkalic suites (after Middlemost 1975). Data sources: Ascension, Harris (1983); St Helena, Baker (1969); Tristan da Cunha, Baker *et al.* (1964); Iceland, Carmichael (1964); Gough, Le Roex (1985); Azores, White *et al.* (1979).

Mineralogy of ocean island basalts

Contrasts With MORB

Oceanic Tholeiites vs. Alkali Basalts

Mantle xenoliths

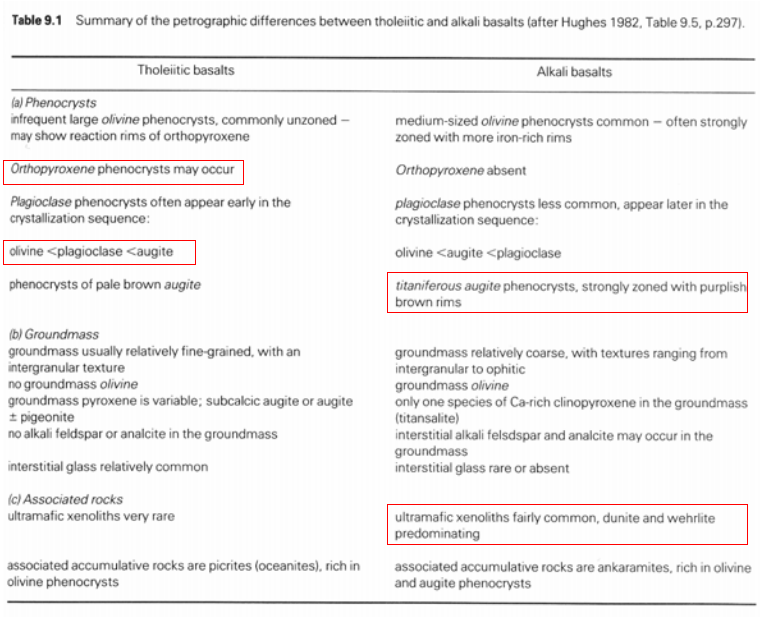


Table 9.1 Summary of the petrographic differences between tholeiitic and alkali basalts (after Hughes 1982, Table 9.5, p.297).

Tholeiitic basalts	Alkali basalts
(a) Phenocrysts	
infrequent large *olivine* phenocrysts, commonly unzoned – may show reaction rims of orthopyroxene	medium-sized *olivine* phenocrysts common – often strongly zoned with more iron-rich rims
Orthopyroxene phenocrysts may occur	*Orthopyroxene* absent
Plagioclase phenocrysts often appear early in the crystallization sequence:	*plagioclase* phenocrysts less common, appear later in the crystallization sequence:
olivine <plagioclase <augite	olivine <augite <plagioclase
phenocrysts of pale brown *augite*	*titaniferous augite* phenocrysts, strongly zoned with purplish brown rims
(b) Groundmass	
groundmass usually relatively fine-grained, with an intergranular texture no groundmass *olivine* groundmass pyroxene is variable; subcalcic augite or augite ± pigeonite no alkali feldspar or analcite in the groundmass	groundmass relatively coarse, with textures ranging from intergranular to ophitic groundmass *olivine* only one species of Ca-rich clinopyroxene in the groundmass (titansalite) interstitial alkali felsdspar and analcite may occur in the groundmass
interstitial glass relatively common	interstitial glass rare or absent
(c) Associated rocks	
ultramafic xenoliths very rare	ultramafic xenoliths fairly common, dunite and wehrlite predominating
associated accumulative rocks are picrites (oceanites), rich in olivine phenocrysts	associated accumulative rocks are ankaramites, rich in olivine and augite phenocrysts

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Major and trace element composition of magmas

Compare Hawaiian tholeiites and alkali basalts to MORB

Elevated LILEs

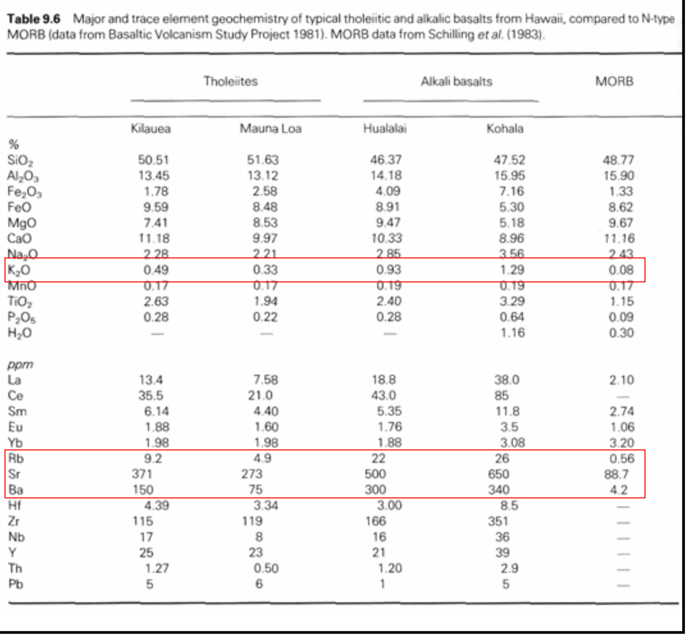


Table 9.6 Major and trace element geochemistry of typical tholeiitic and alkalic basalts from Hawaii, compared to N-type MORB (data from Basaltic Volcanism Study Project 1981). MORB data from Schilling *et al.* (1983).

	Tholeiites		Alkali basalts		MORB
	Kilauea	Mauna Loa	Hualalai	Kohala	
%					
SiO_2	50.51	51.63	46.37	47.52	48.77
Al_2O_3	13.45	13.12	14.18	15.95	15.90
Fe_2O_3	1.78	2.58	4.09	7.16	1.33
FeO	9.59	8.48	8.91	5.30	8.62
MgO	7.41	8.53	9.47	5.18	9.67
CaO	11.18	9.97	10.33	8.96	11.16
Na_2O	2.28	2.21	2.85	3.56	2.43
K_2O	0.49	0.33	0.93	1.29	0.08
MnO	0.17	0.17	0.19	0.19	0.17
TiO_2	2.63	1.94	2.40	3.29	1.15
P_2O_5	0.28	0.22	0.28	0.64	0.09
H_2O	—	—	—	1.16	0.30
ppm					
La	13.4	7.58	18.8	38.0	2.10
Ce	35.5	21.0	43.0	85	—
Sm	6.14	4.40	5.35	11.8	2.74
Eu	1.88	1.60	1.76	3.5	1.06
Yb	1.98	1.98	1.88	3.08	3.20
Rb	9.2	4.9	22	26	0.56
Sr	371	273	500	650	88.7
Ba	150	75	300	340	4.2
Hf	4.39	3.34	3.00	8.5	—
Zr	115	119	166	351	—
Nb	17	8	16	36	—
Y	25	23	21	39	—
Th	1.27	0.50	1.20	2.9	—
Pb	5	6	1	5	—

Magma series, crystallization, mixing

Fractional crystallization in crustal plumbing systems of Oliv + Cpx + Mt + (Plag)

= Linear variations in Major and Trace element Harker diagrams

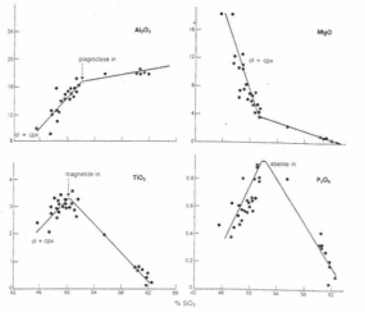


Figure 9.16 Weight % Al_2O_3, TiO_2, MgO and P_2O_5 versus %SiO_2 for volcanic rocks from Gough (data from Le Roex 1985).

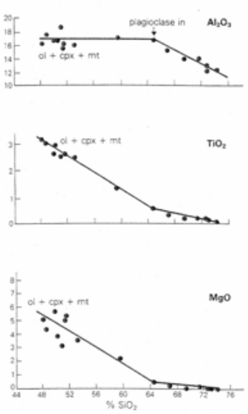


Figure 9.15 Variation of wt.% Al_2O_3, TiO_2 and MgO versus % SiO_2 for volcanic rocks from Ascension (data from Harris 1983).

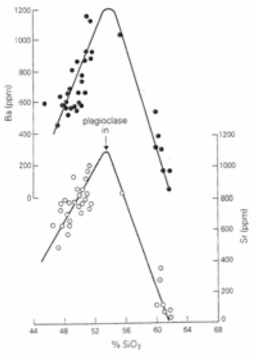


Figure 9.17 Variation of Ba and Sr (ppm) versus wt.% SiO_2 for the Gough Island volcanic suite (data from Le Roex 1985).

Incompatible trace element composition of magmas

LREE, LILE enrichment is distinctive

Ocean Island tholeiites similar to EMORB

suggests similar components

Ocean Island alkaline lavas distinct from MORB

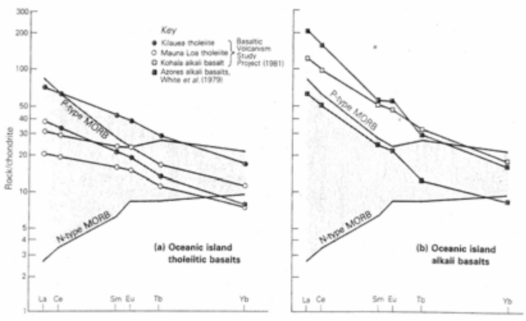


Figure 9.21 Chondrite-normalized REE abundances. Shown for comparison are typical N- and P-type MORB REE patterns

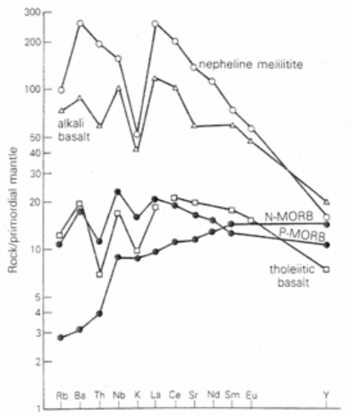


Figure 9.22 Incompatible element abundances, normalized to primordial mantle values (Sun 1980), for typical tholeiitic and alkali basalts and a melilite nephelinite from Hawaii. Shown for comparison are patterns for N- and P-type MORB (Sun 1980). Data from Basaltic Volcanism Study Project (1981) and Clague & Frey (1982).

Radiogenic isotope composition of magmas

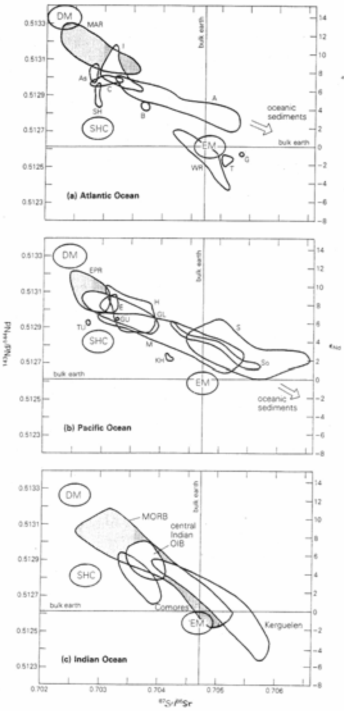
Sr-Nd isotope array of OIBs

At least 3, perhaps more mantle source end-member components:

1. Depleted mantle (DM)
2. Crustal sediment (modern or ancient?)

or

3. Primordial bulk earth modified > 1Ga by melting (EM)
4. Saint Helena (SHC)



Key

MAR	Mid-Atlantic Ridge
I	Iceland
As	Ascension
C	Canary Islands
SH	St Helena
B	Bouvet
A	Azores
G	Gough
T	Tristan da Cunha
WR	Walvis Ridge
EPR	East Pacific Rise
H	Hawaiian Islands
KH	Koolau, Hawaii
E	Easter Island
GL	Galapagos
GU	Guadaloupe
TU	Tubuaii (Australes)
M	Marquesas
S	Samoa
So	Society Islands

The Central Indian OIB field includes data for the following islands; Marion – Prince Edward, Crozet, Amsterdam, St Paul, Reunion, Rodriguez and Mauritius

Major source components identified

DM	depleted mantle (source of N-type MORB)
EM	enriched mantle
SHC	St Helena component

Figure 9.23 ^{143}Nd/^{144}Nd versus ^{87}Sr/^{86}Sr for MORB and oceanic-island basalts (after Staudigel *et al.* 1984, and Hamelin *et al.* 1986). Data for the Marquesas and Tubuaii from Vidal *et al.* (1984).

Radiogenic isotope composition of magmas

Pb isotope array of OIBs

Require recycling of continental crust into the mantle:

Pb is highly depleted in DM, enriched in continental sediment. *why?*

Pb isotope ratios greatly different for DM and and Plume source mantle

Mixing of DM and SHC (Plume) sources explains most Pb isotope variation

NHRL defined by MAR + EPR basalt

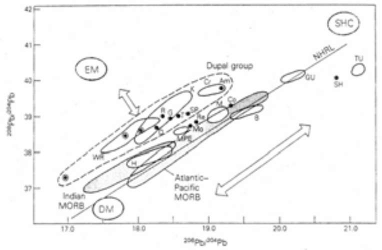
DUPAL anomaly requires 3rd component

Positve deviation from NHRL in ^{208}Pb/^{204}Pb

Band centered on 30-40 °S

3 possibly 4 sources:

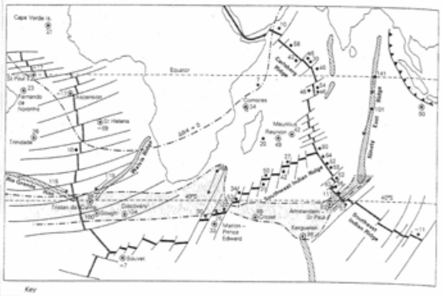
DM + EM (lower mantle) + SHC (crust?)



Key

Am	Amsterdam
Re	Reunion
R	Raratonga
Mo	Mauritius
Co	Comores
MPE	Marion – Prince Edward
SP	St Paul
K	Kerguelen
Cr	Crozet
⊛	Indian MORB with Dupal characteristics

Figure 9.26 ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb for MORB and oceanic island basalts from the Atlantic, Pacific and Indian oceans. Abbreviations as in Figures 9.23 & 25. The dashed line separates the field of oceanic islands with a distinct Dupal signature (after Hamelin & Allègre (1985) with additional data from Hart (1984) and Vidal et al. (1984)). Open arrows indicate two component mixing vectors.



Key

▨	zone of maximum Dupal anomaly (Δ8/4 > 80)	•	MORB
▩	aseismic ridges	⊛	OIB

Figure 9.28 Detailed map of the Δ8/4 anomaly for MORB and OIB from the South Atlantic and Indian oceans. Older samples have arrows leading from them pointing in the direction of their original location. Data from Dupré & Allègre (1983), Hart (1984), Hamelin & Allègre (1985) and Hamelin et al. (1986).

Petrogenetic model, General

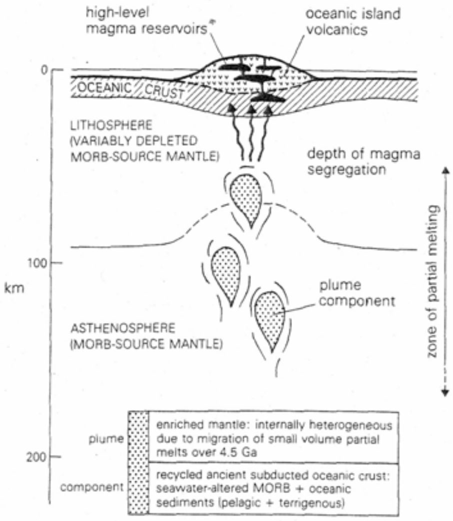
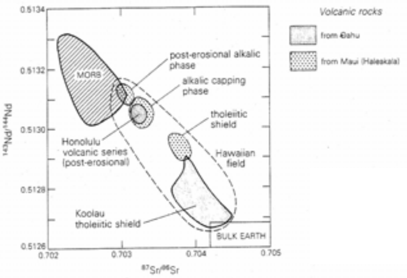


Figure 9.32 Detailed model for OIB petrogenesis.

Petrogenetic model, Hawaii

Transition from voluminous tholeiitic shield stage, to small volume alkaline cap lavas



Figre 9.33 ^{143}Nd/^{144}Nd versus ^{87}Sr/^{86}Sr for Hawaii basalts to show the change in isotopic composition betwe the tholeiitic shield-building stage and the post-erosion alkalic stage. On Oahu, volcanics of the Koolau tholeiit shield are overlain by the post-erosional Honolulu Volcan Series. Data from Chen & Frey (1985) and Stille *et al.* (198

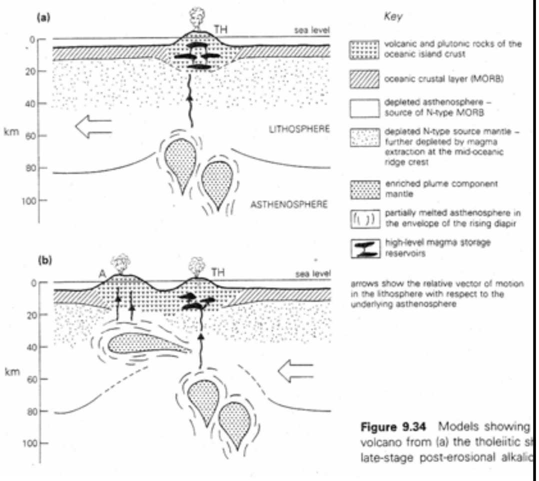


Figure 9.34 Models showing volcano from (a) the tholeiitic s late-stage post-erosional alkalic