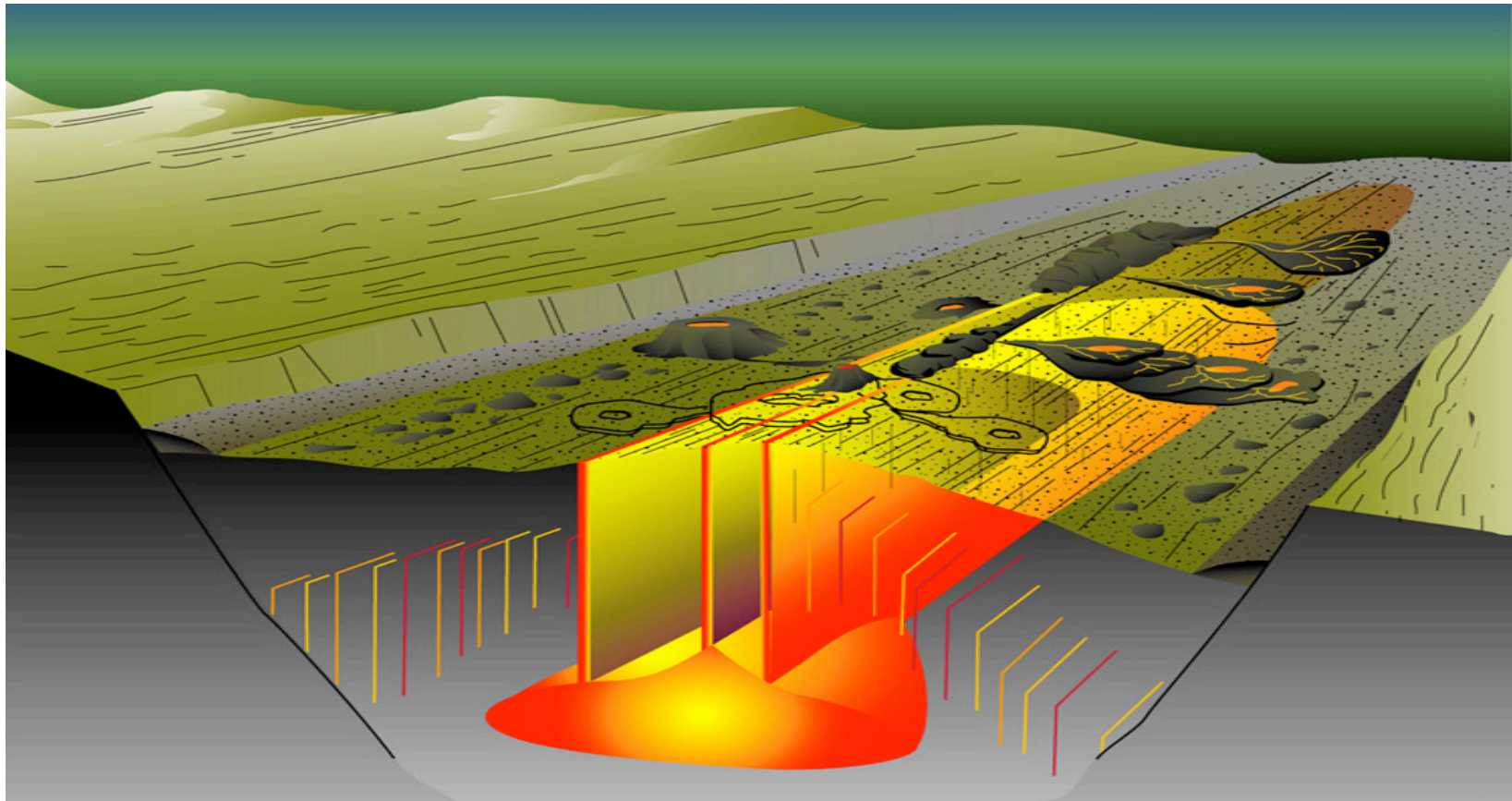


MORB Petrogenesis



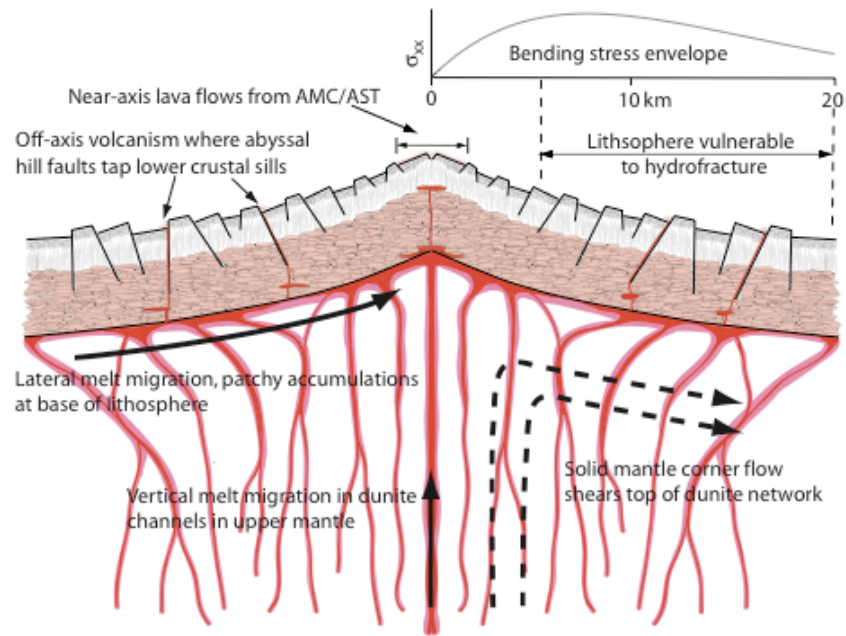
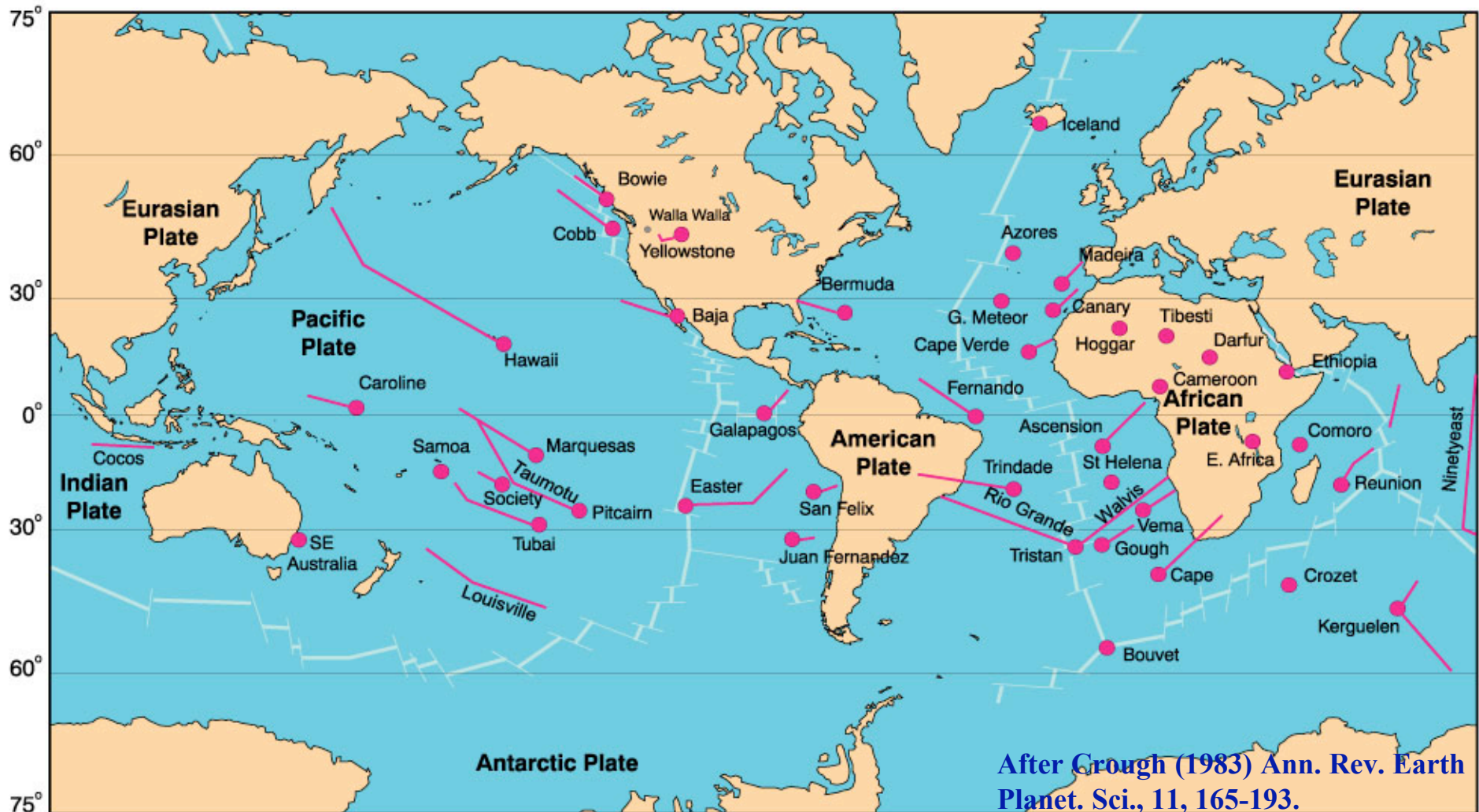


Figure 4. Conceptual illustration of upper mantle and lithospheric processes related to melt delivery and crustal accretion at a fast-spreading mid-ocean ridge.

Ocean Intraplate Volcanism

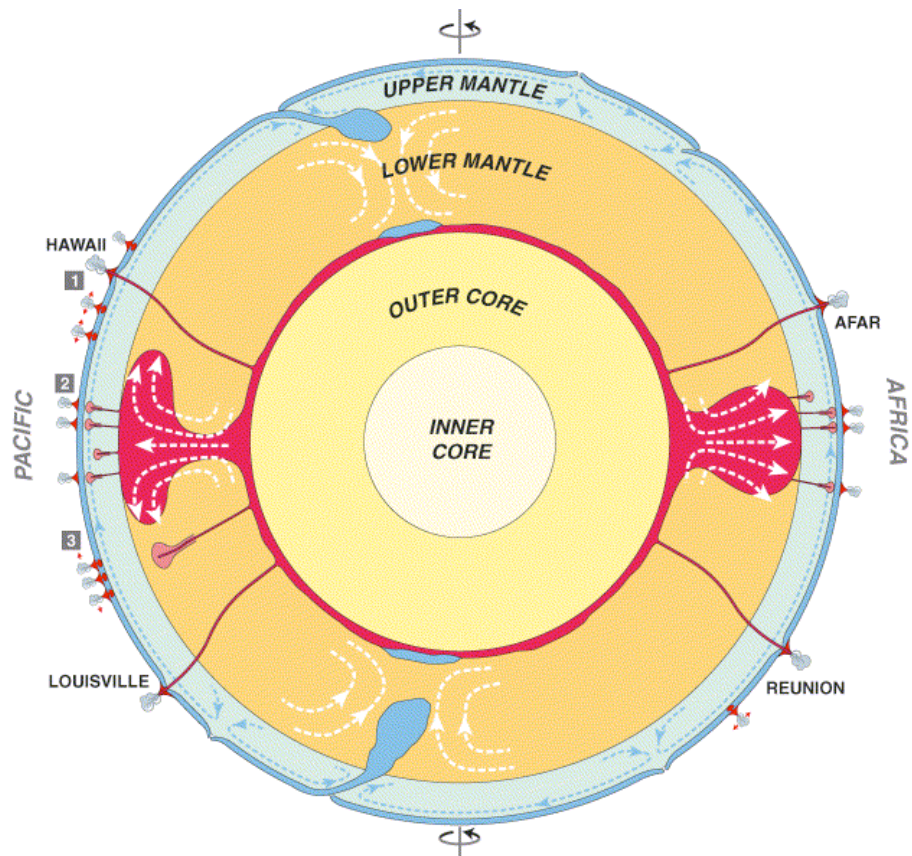
Ocean islands and seamounts

Commonly associated with “hot spots”

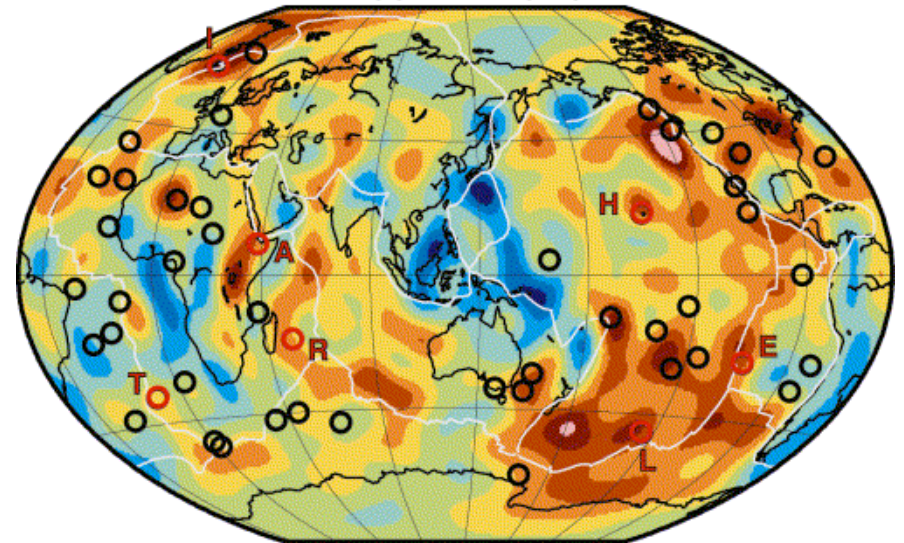


Ocean islands and seamounts

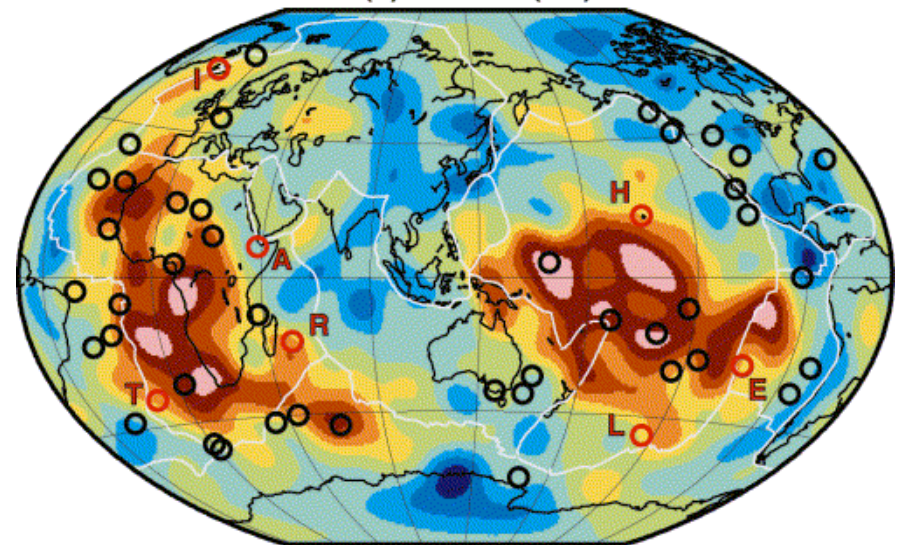
Commonly associated with hot spots



(a) 500 km (2%)



(b) 2850 km (2%)



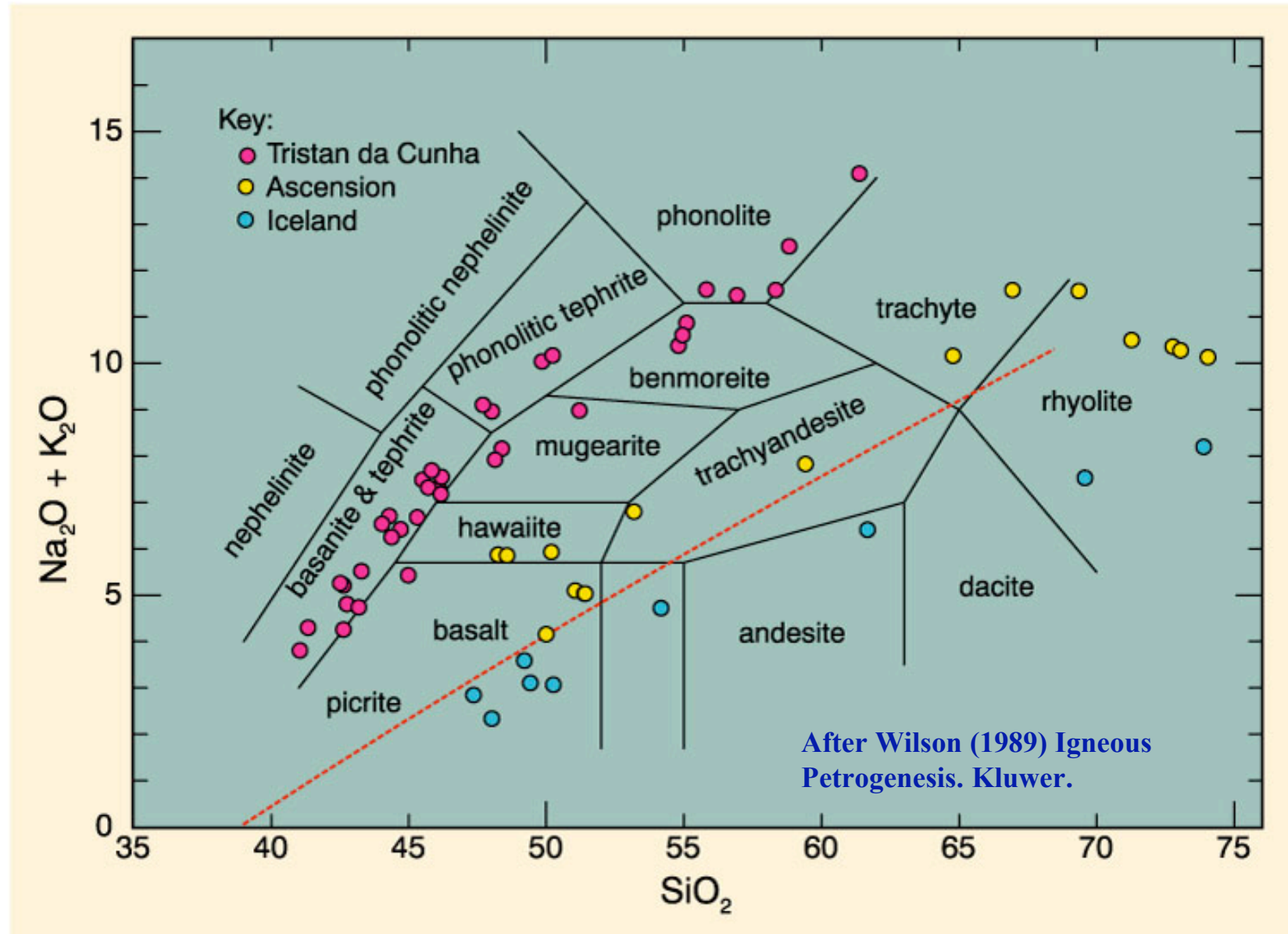
Types of OIB Magmas

Two principal magma series

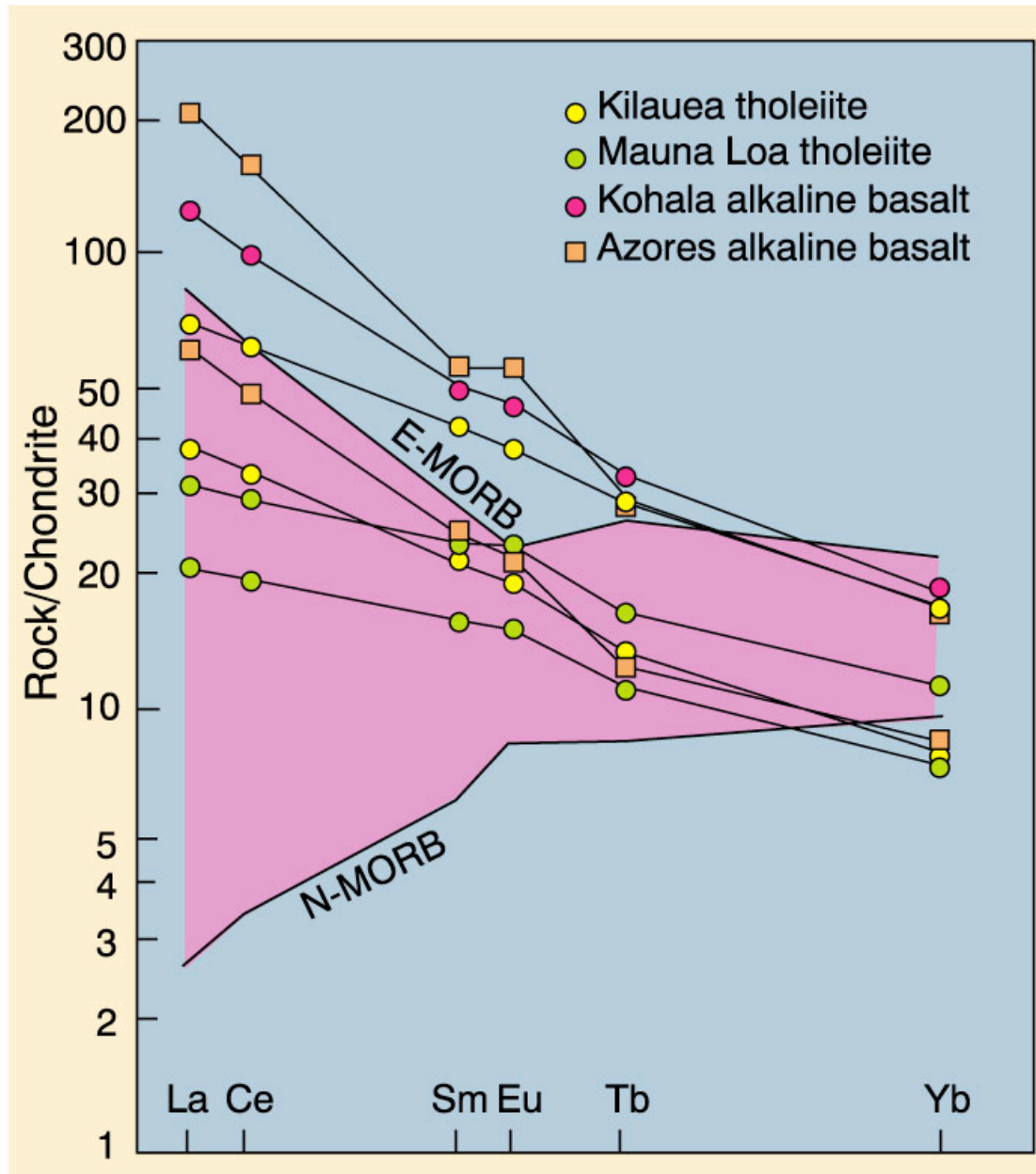
- **Tholeiitic series** (dominant type)
 - ◆ Parental ocean island tholeiitic basalt, or **OIT**
 - ◆ Similar to MORB, but some distinct chemical and mineralogical differences
- **Alkaline series** (subordinate)
 - ◆ Parental ocean island alkaline basalt, or **OIA**
 - ◆ Two principal alkaline sub-series
 - ▲ silica undersaturated
 - ▲ slightly silica oversaturated (less common series)

Evolution in the Series

Tholeiitic, alkaline, and highly alkaline



Trace Elements: REEs



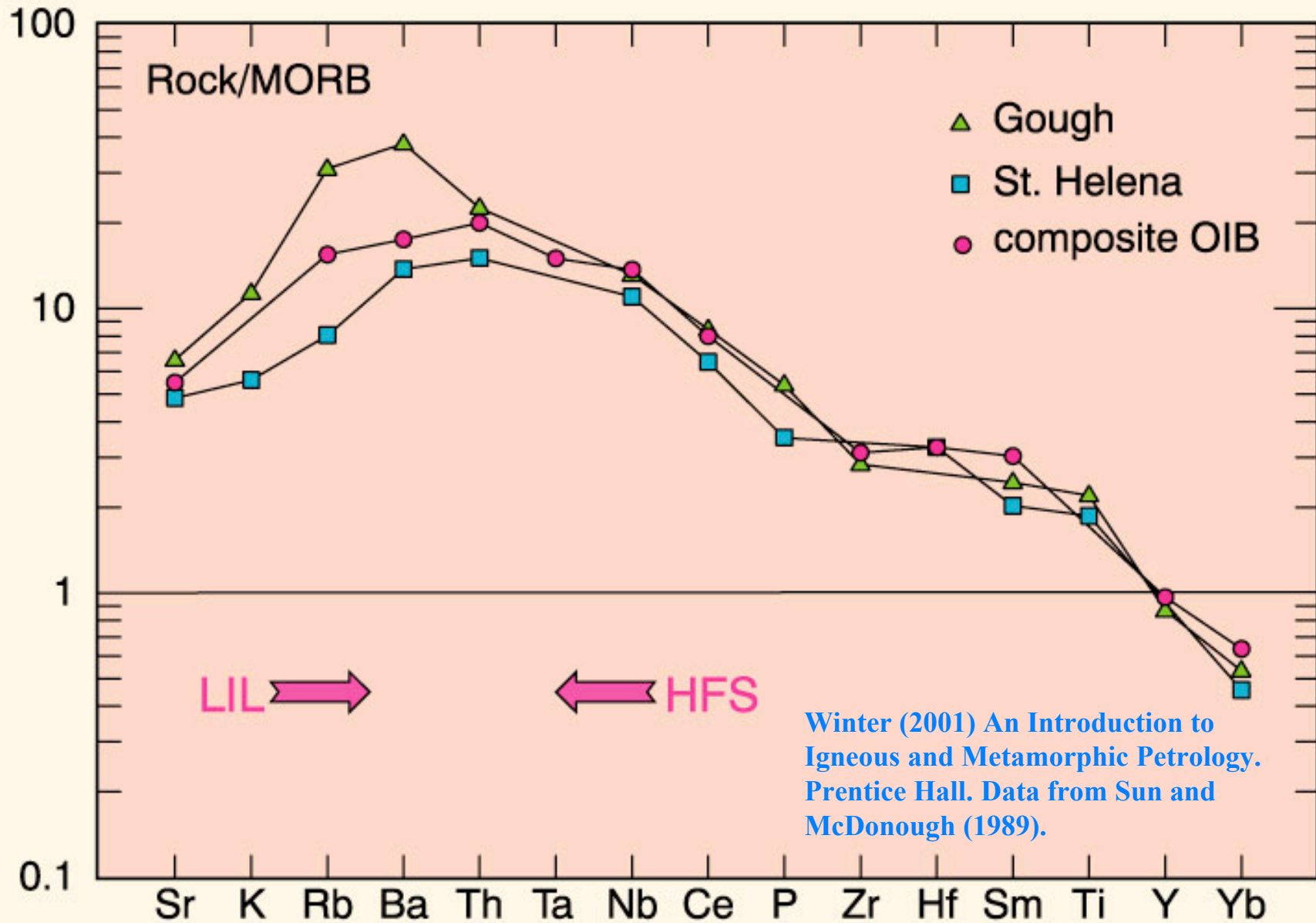
After Wilson (1989)
Igneous Petrogenesis.
Kluwer.

Trace Elements: REEs

La/Yb (REE slope) correlates with the degree of silica undersaturation in OIBs

- ◆ Highly undersaturated magmas: $\text{La/Yb} > 30$
- ◆ OIA: closer to 12
- ◆ OIT: ~ 4
- ◆ (+) slopes \rightarrow E-MORB and all OIBs \neq N-MORB
(-) slope and appear to originate in the lower enriched mantle

MORB-normalized Spider Diagrams



Trace Elements

- The LIL trace elements (K, Rb, Cs, Ba, Pb²⁺ and Sr) are incompatible and are all enriched in OIB magmas with respect to MORBs
- HFS elements (Th, U, Ce, Zr, Hf, Nb, Ta, and Ti) are also incompatible, and are enriched in OIBs > MORBs

Isotope Geochemistry

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

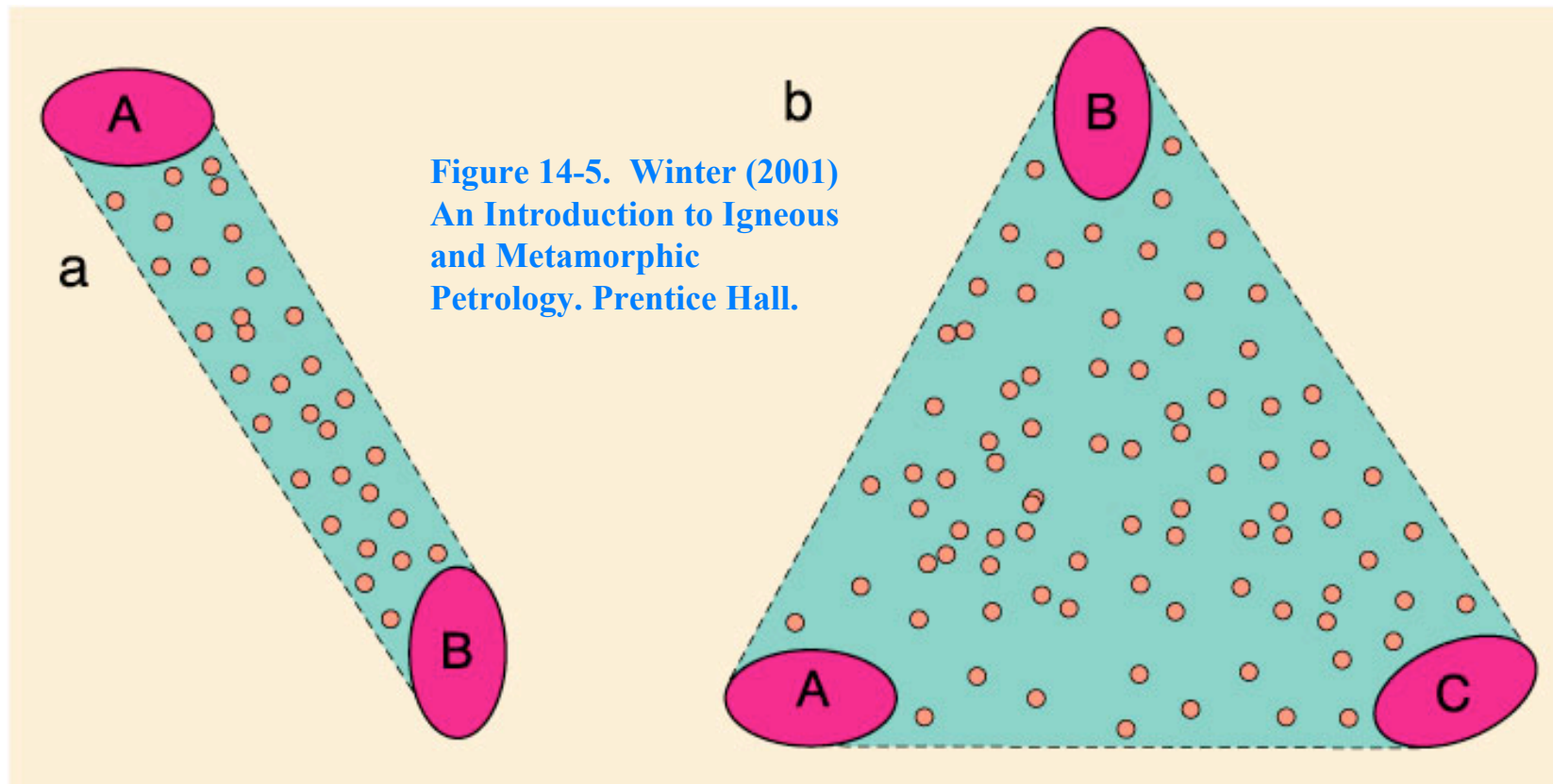
Simple Mixing Models

Binary

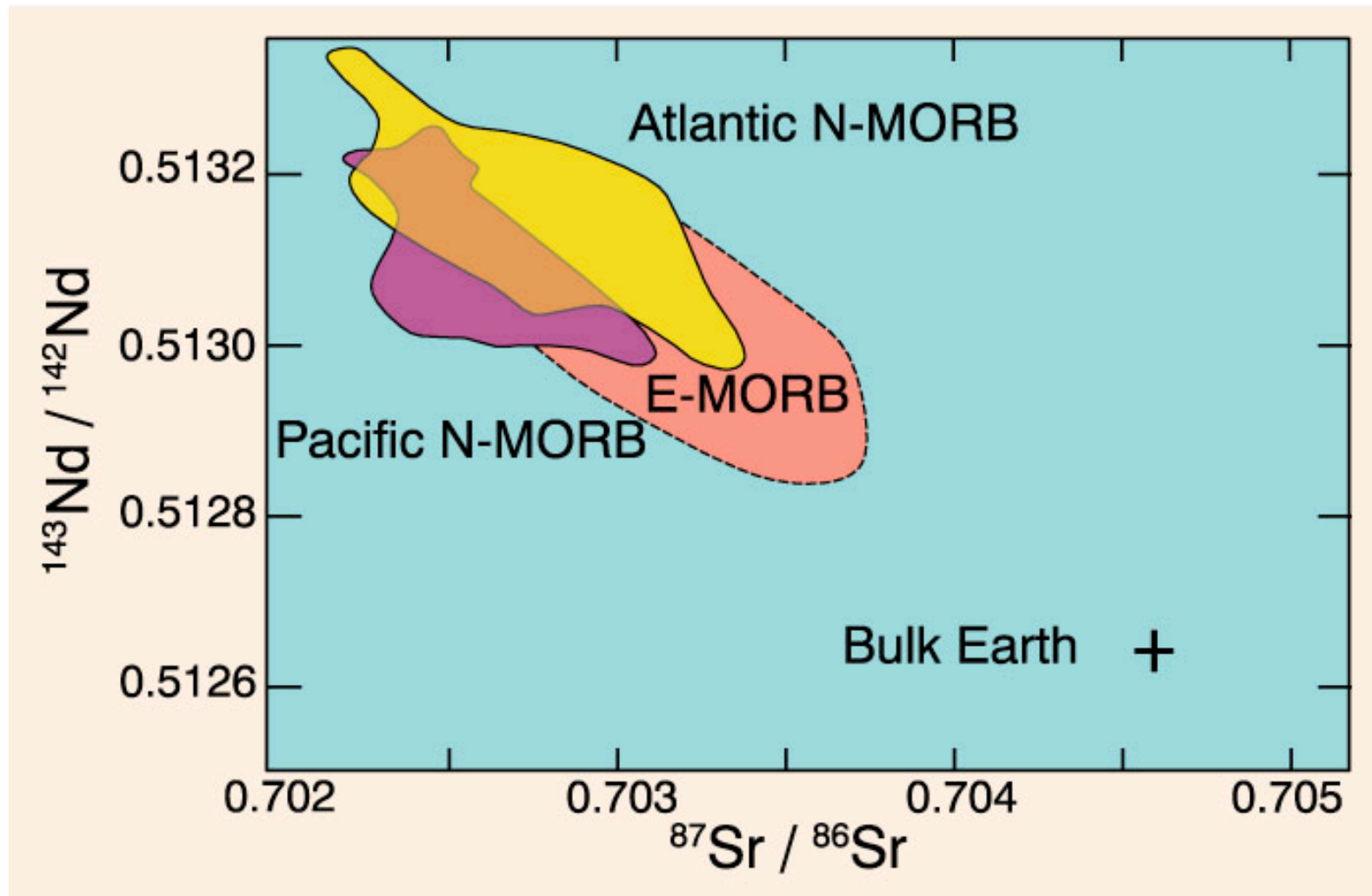
All analyses fall between two reservoirs as magmas mix

Ternary

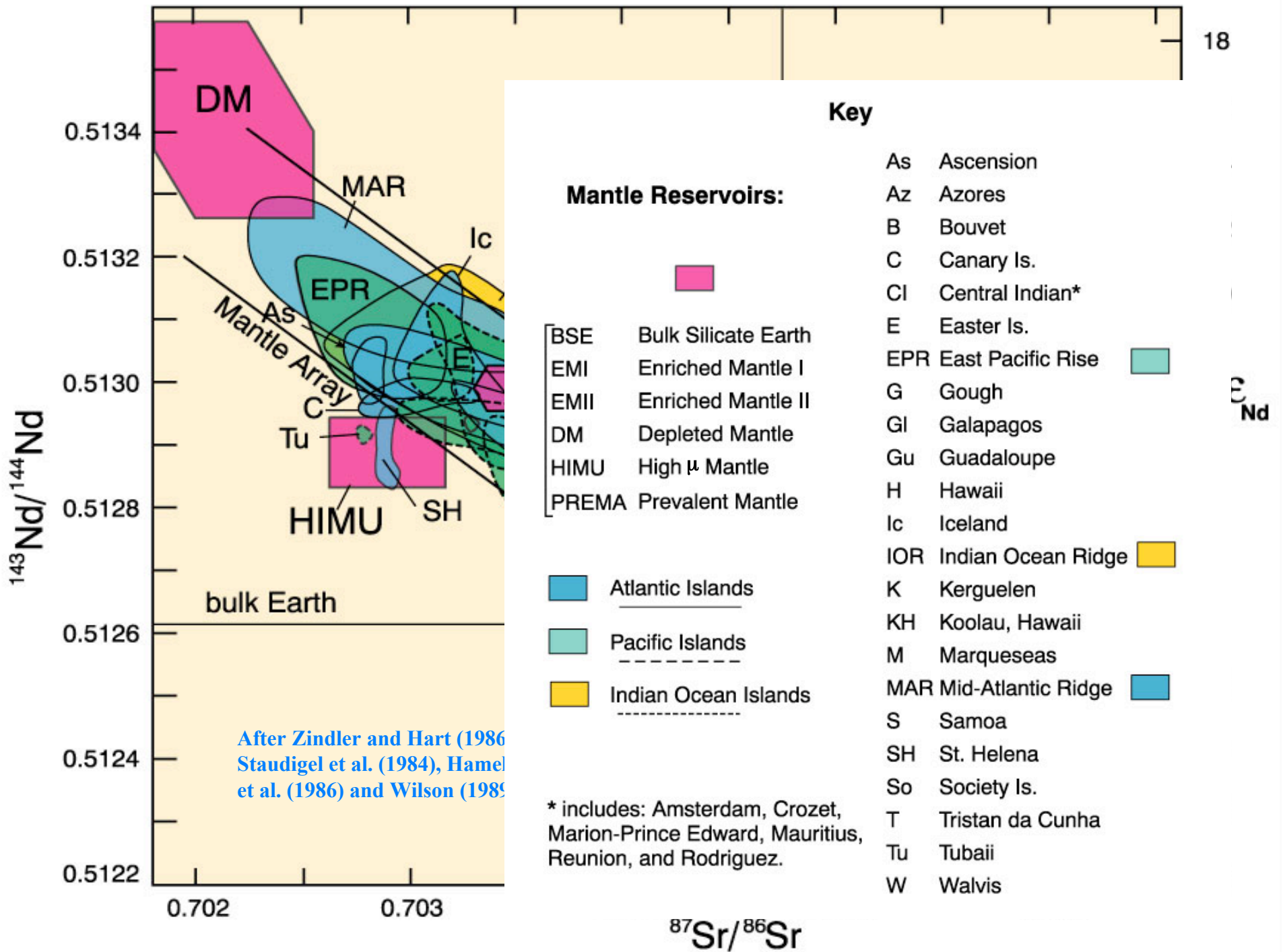
All analyses fall within triangle determined by three reservoirs



Sr - Nd Isotopes



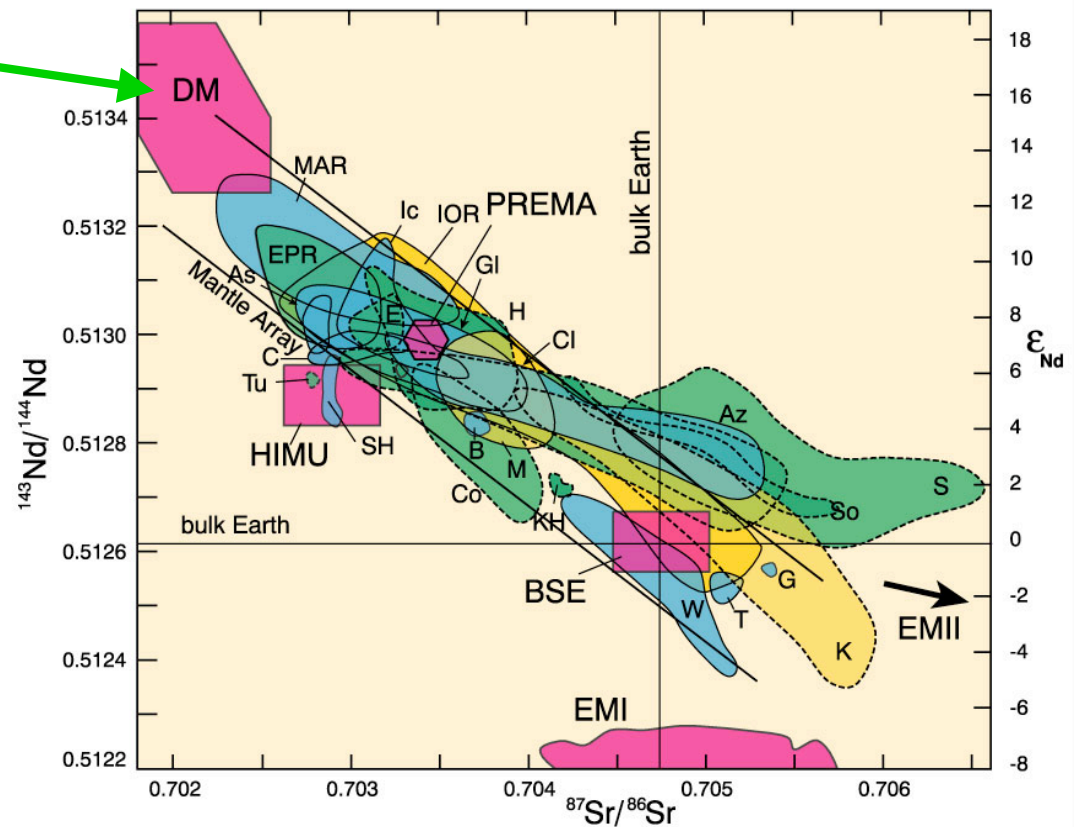
Data from Ito et al. (1987) *Chemical Geology*, 62, 157-176; and LeRoex et al. (1983) *J. Petrol.*, 24, 267-318.



Mantle Reservoirs

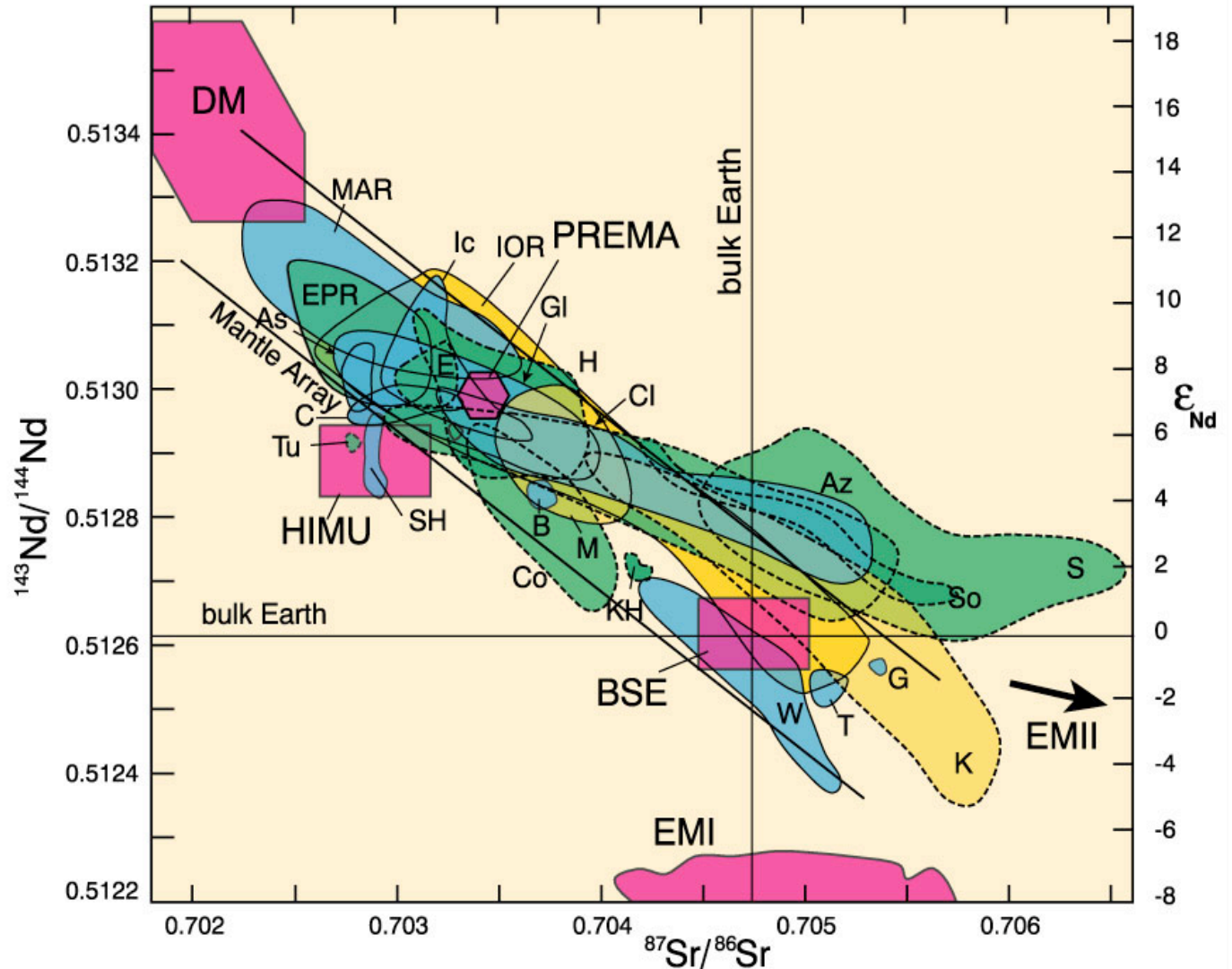
1. DM (Depleted
Mantle) = N-MORB
source

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



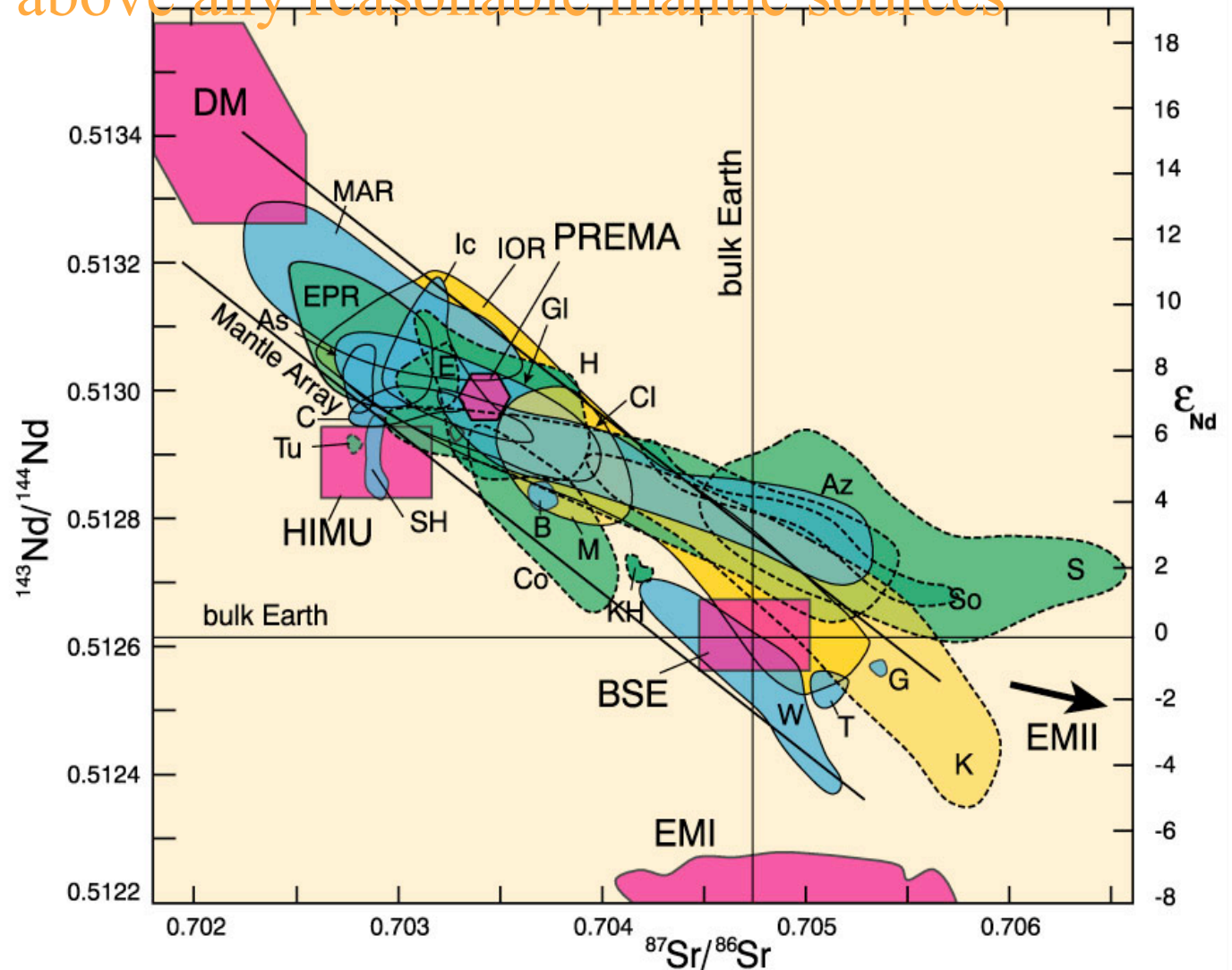
2. BSE (Bulk Silicate Earth) or the Primary Uniform Reservoir

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



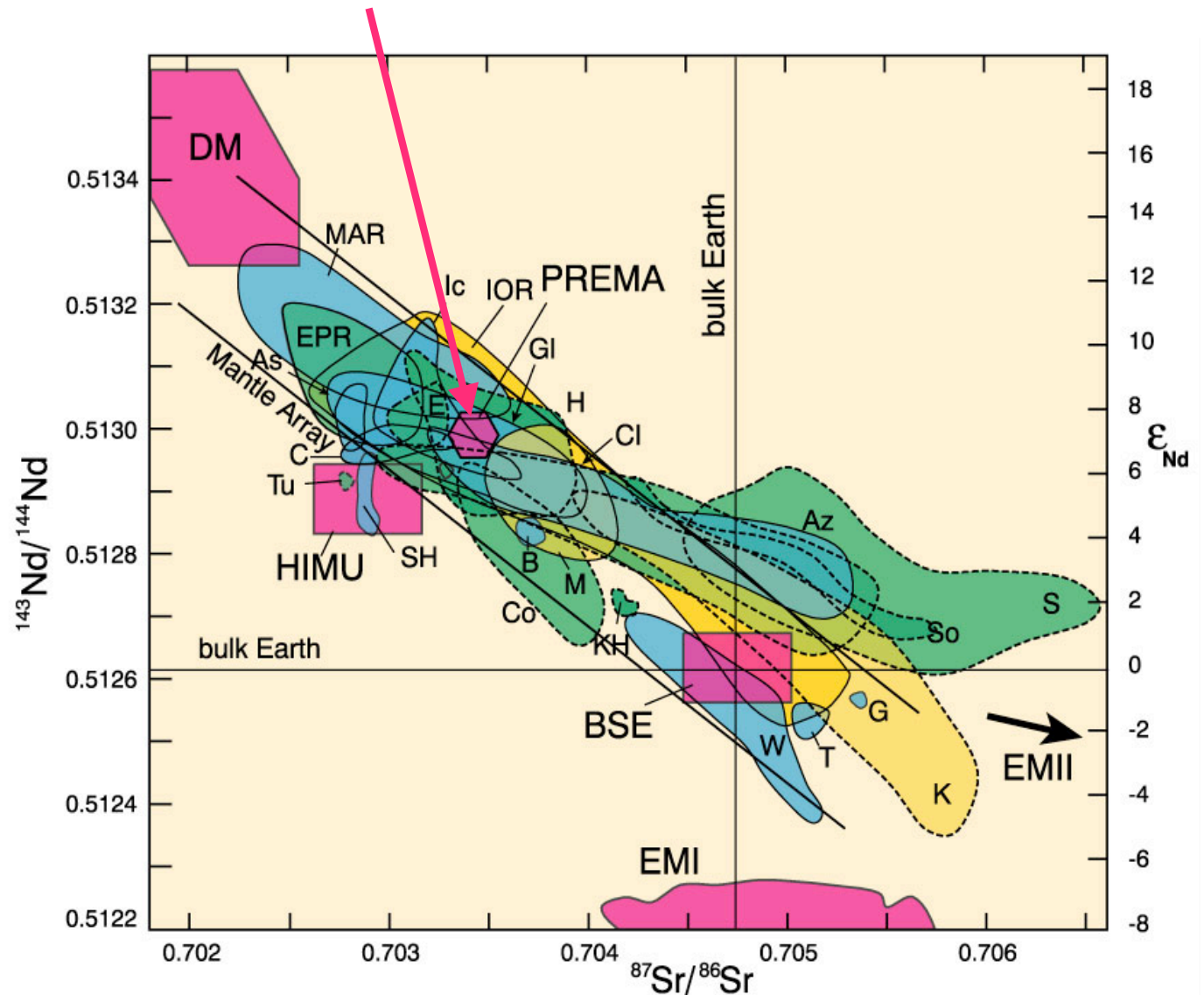
3. **EMI** = enriched mantle type I has lower $^{87}\text{Sr}/^{86}\text{Sr}$ (near primordial)
4. **EMII** = enriched mantle type II has higher $^{87}\text{Sr}/^{86}\text{Sr}$ (> 0.720 , well above any reasonable mantle sources)

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



5. PREMA (PREvalent MAntle)

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



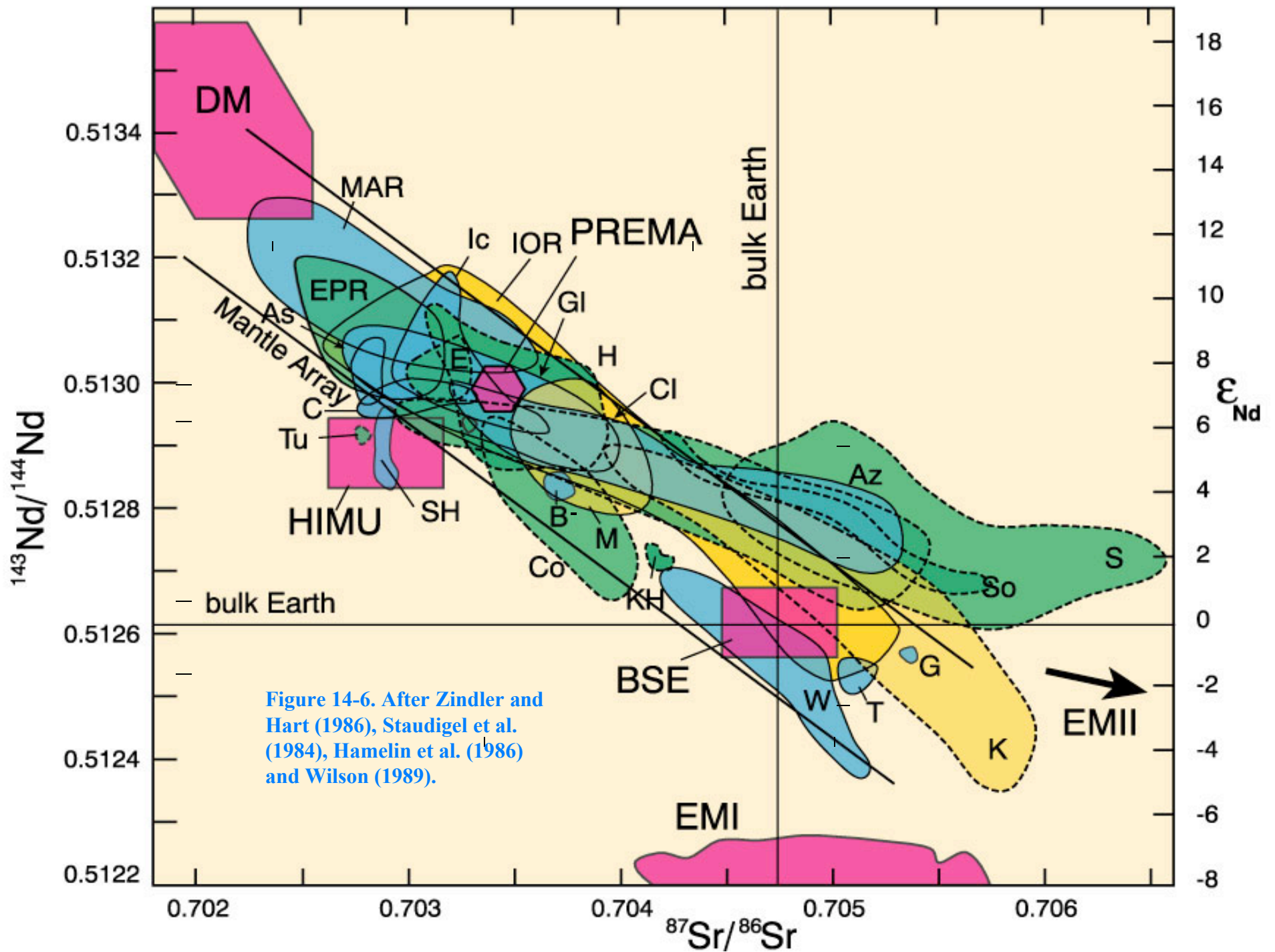


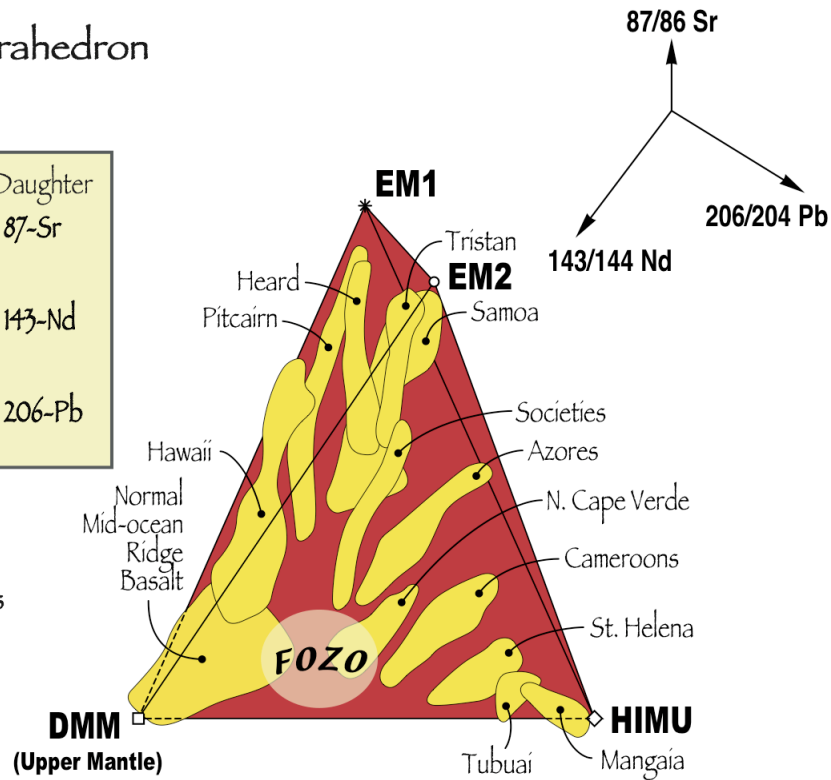
Figure 14-6. After Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

The Mantle Tetrahedron

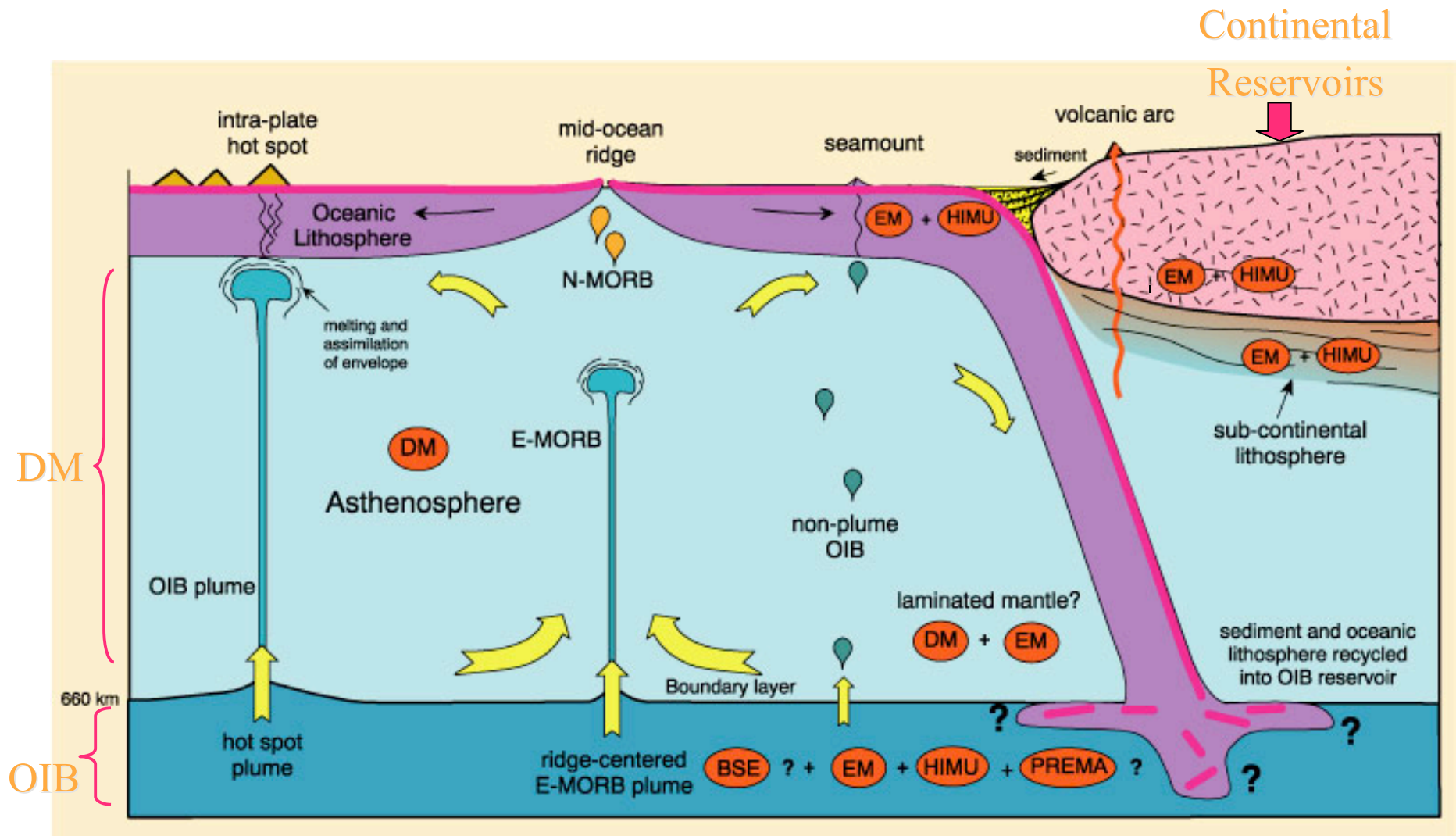
Parent	Daughter
$^{87}\text{-Rb}$	$^{87}\text{-Sr}$
$t_{1/2} = 48.8 \text{ Byr}$	
$^{147}\text{-Sm}$	$^{143}\text{-Nd}$
$t_{1/2} = 106 \text{ Byr}$	
$^{238}\text{-U}$	$^{206}\text{-Pb}$
$t_{1/2} = 4.47 \text{ Byr}$	

-- Observations require:

1. CREATION of reservoirs
2. Long-lived ISOLATION (billions of years)



A Model for Oceanic Magmatism



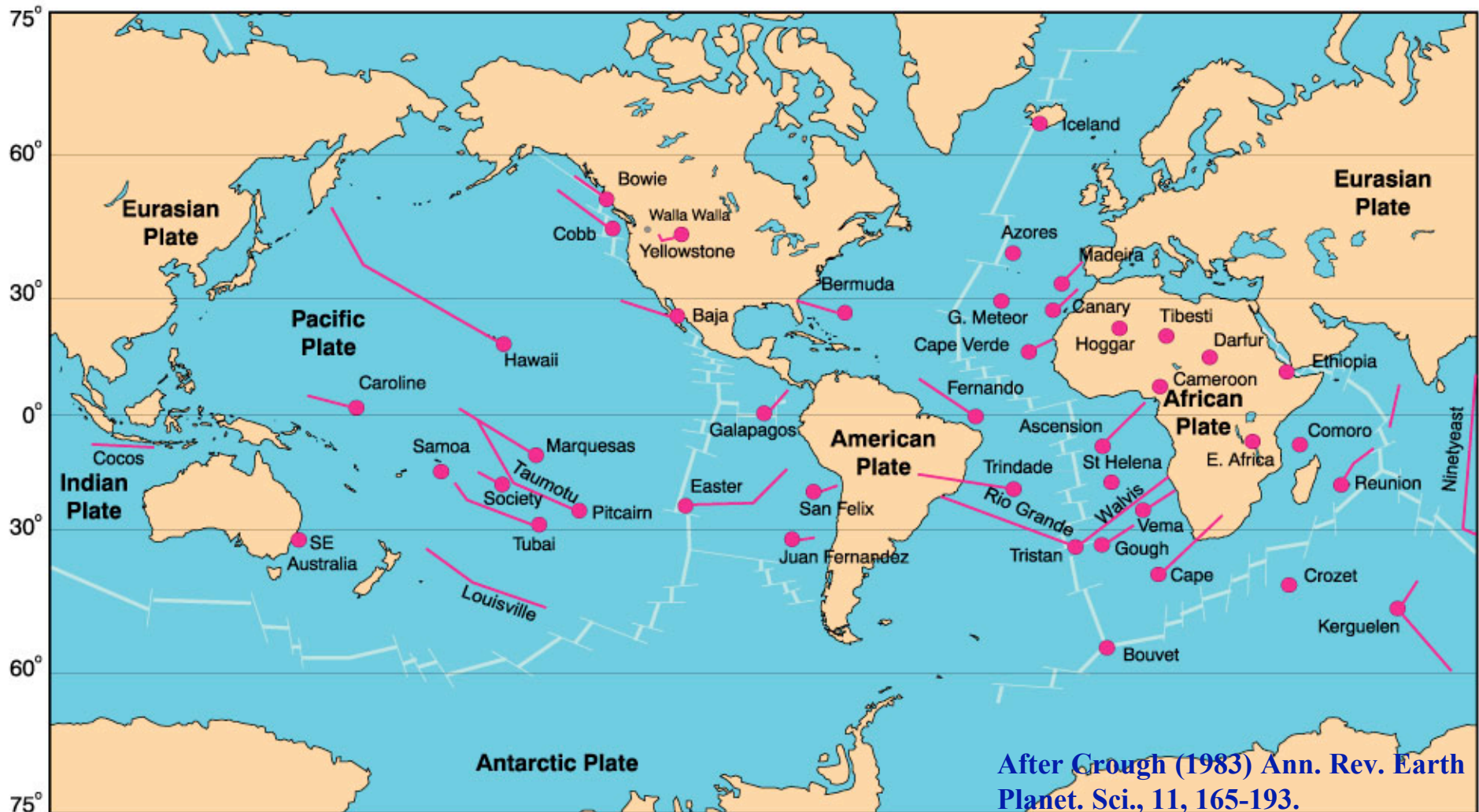
EM and HIMU from crustal sources (subducted OC + CC seds)

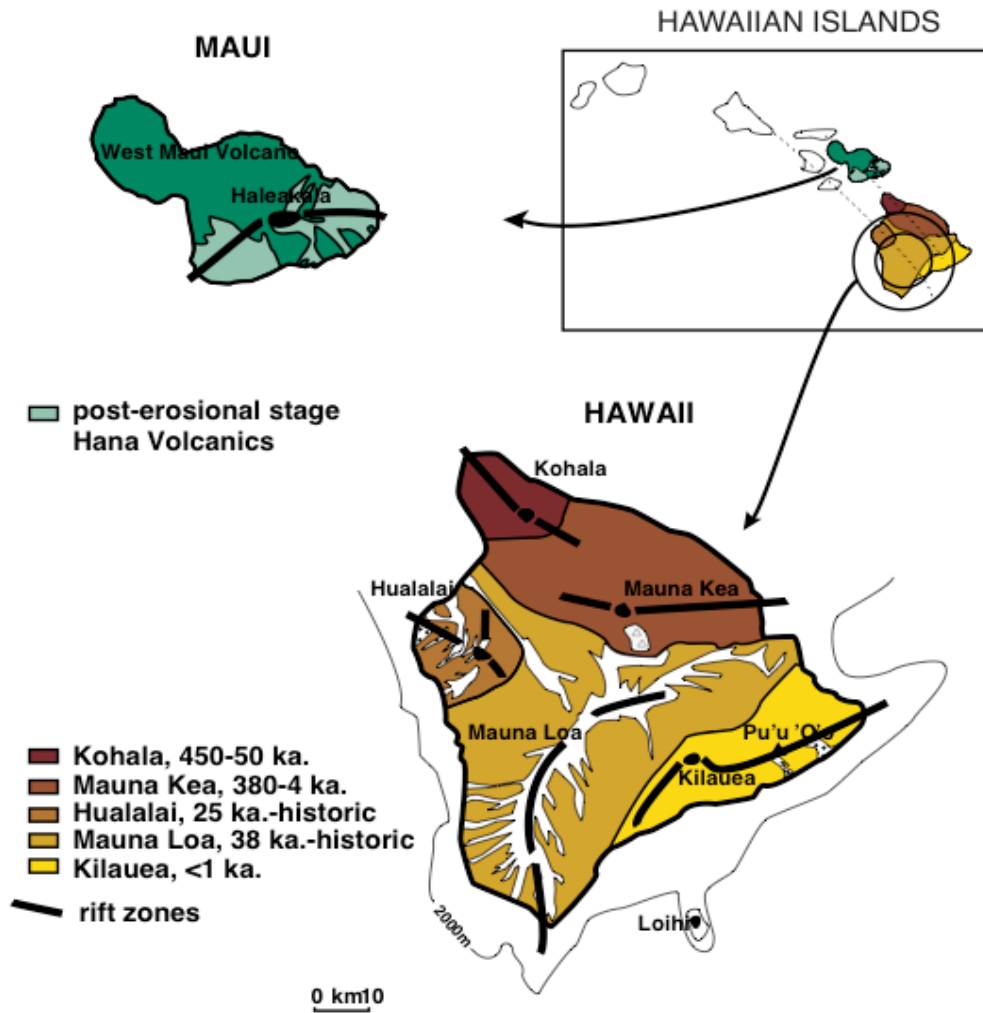
Nomenclature from Zindler and Hart (1986). After Wilson (1989) and Rollinson (1993).

Hawaii

Distinctive Hot Spot Track

Hawaii-Emperor Seamount





Hawaiian Scenario

Cyclic, pattern to the eruptive history

1. Pre-shield-building stage somewhat alkaline and variable
2. Shield-building stage begins with tremendous outpourings of tholeiitic basalts

Hawaiian Scenario

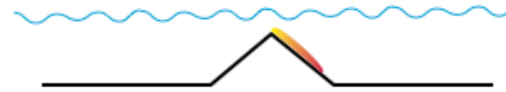
3. Waning activity more **alkaline**, episodic, and violent (Mauna Kea, Hualalai, and Kohala). Lavas are also more diverse, with a larger proportion of differentiated liquids
4. A long period of dormancy, followed by a late, **post-erosional stage**. Characterized by **highly alkaline** and silica-undersaturated magmas, including alkali basalts, nephelinites, melilite basalts, and basanites

4 Stages of Evolution

1. Pre-shield

Loihi

tholeiites,
alkali basalts



2. Shield

Kilauea

Mauna Loa

tholeiites ~99%



3. Post-shield

Mauna Kea

Hualalai

alkali basalts



4. Post-erosional

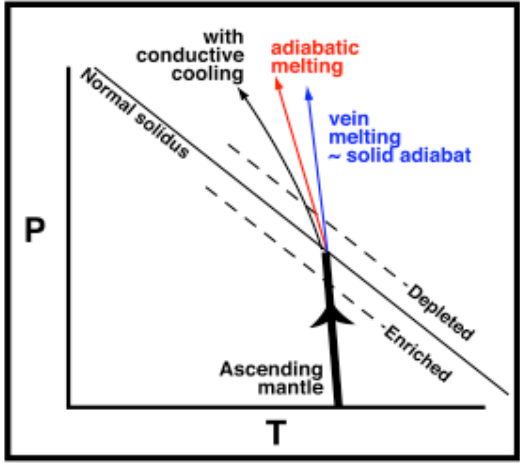
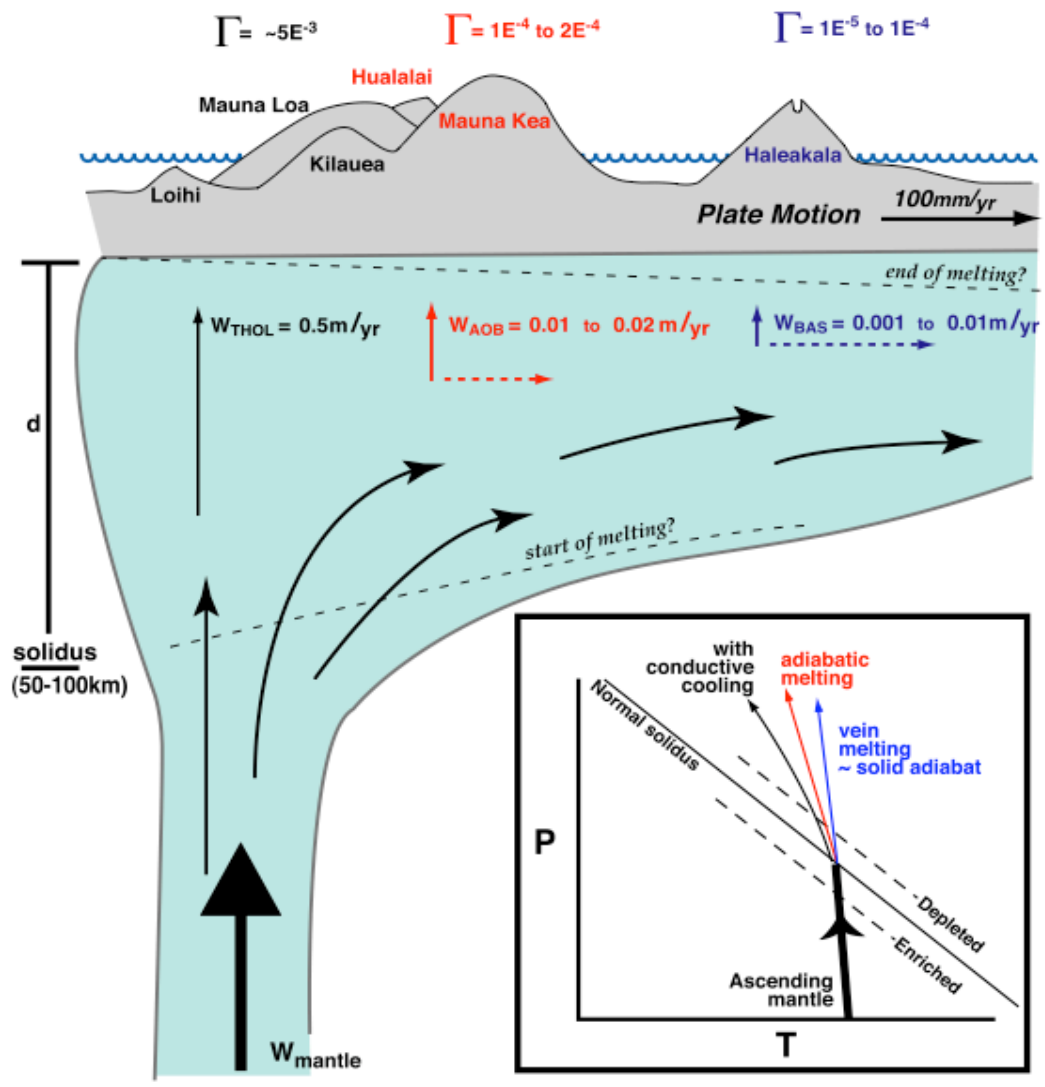
Haleakala

very alkaline basalts

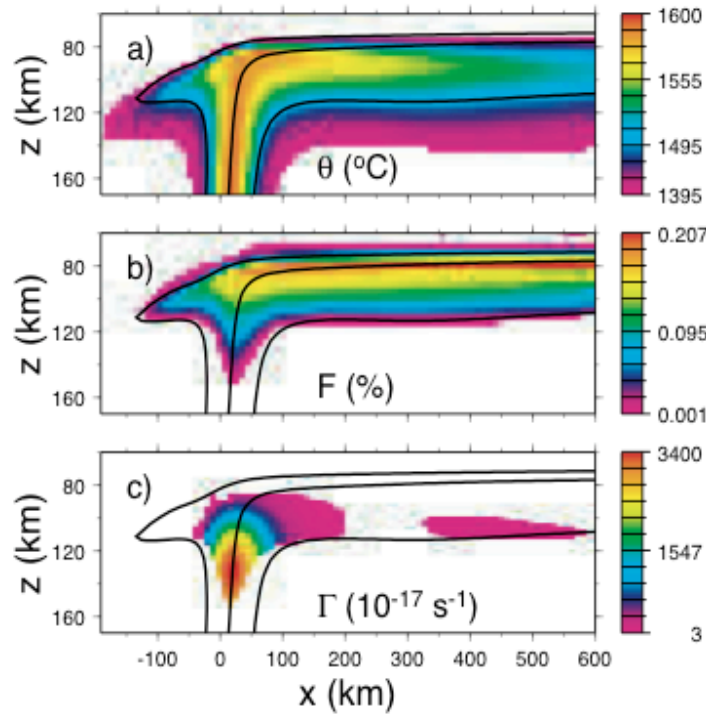


$$\Gamma = W \rho_s \frac{F_{\max}}{d}$$

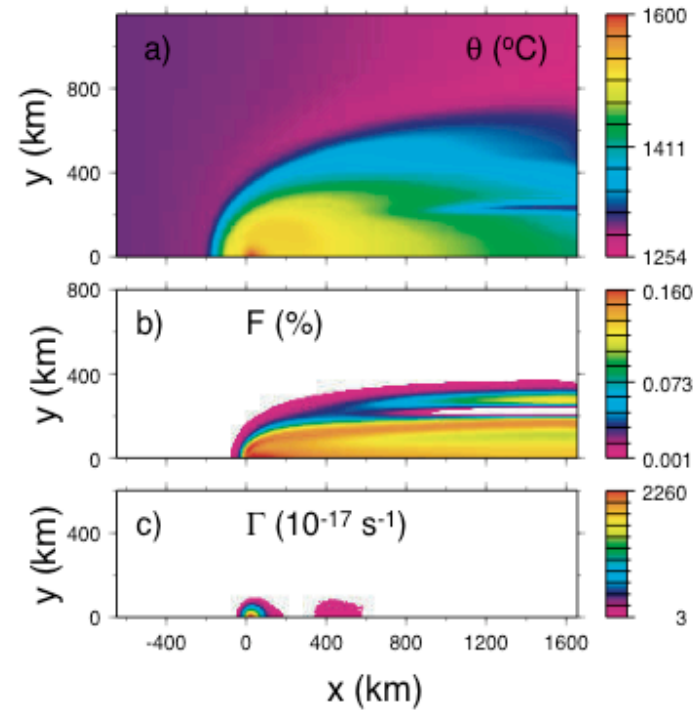
(kg m⁻³ y⁻¹)
%/kbar

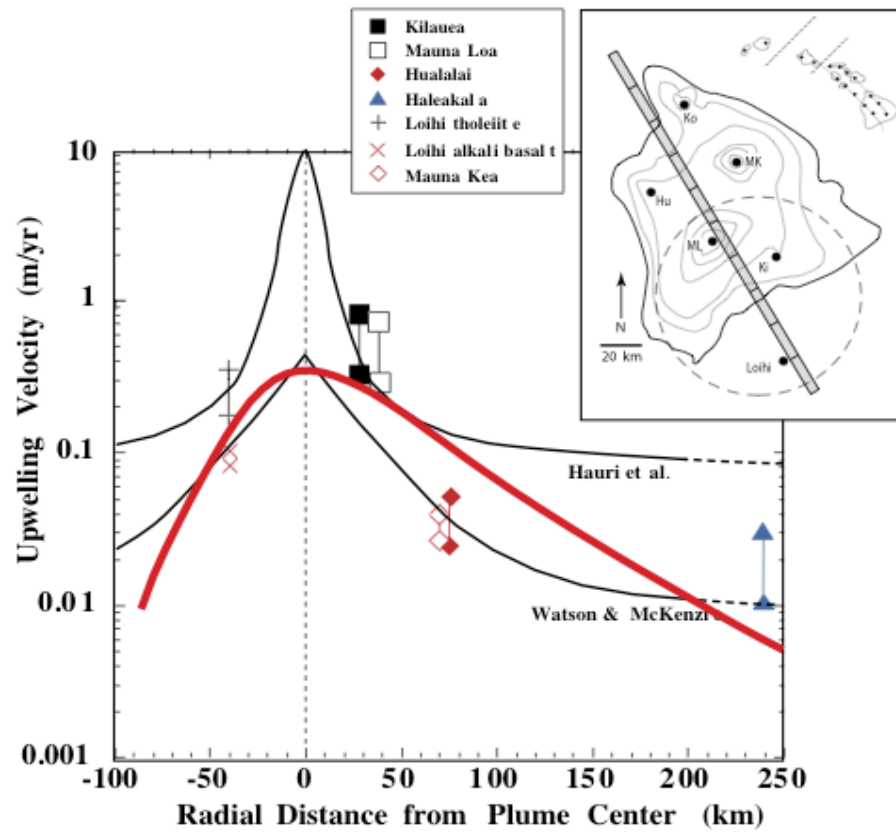


VERTICAL SECTION

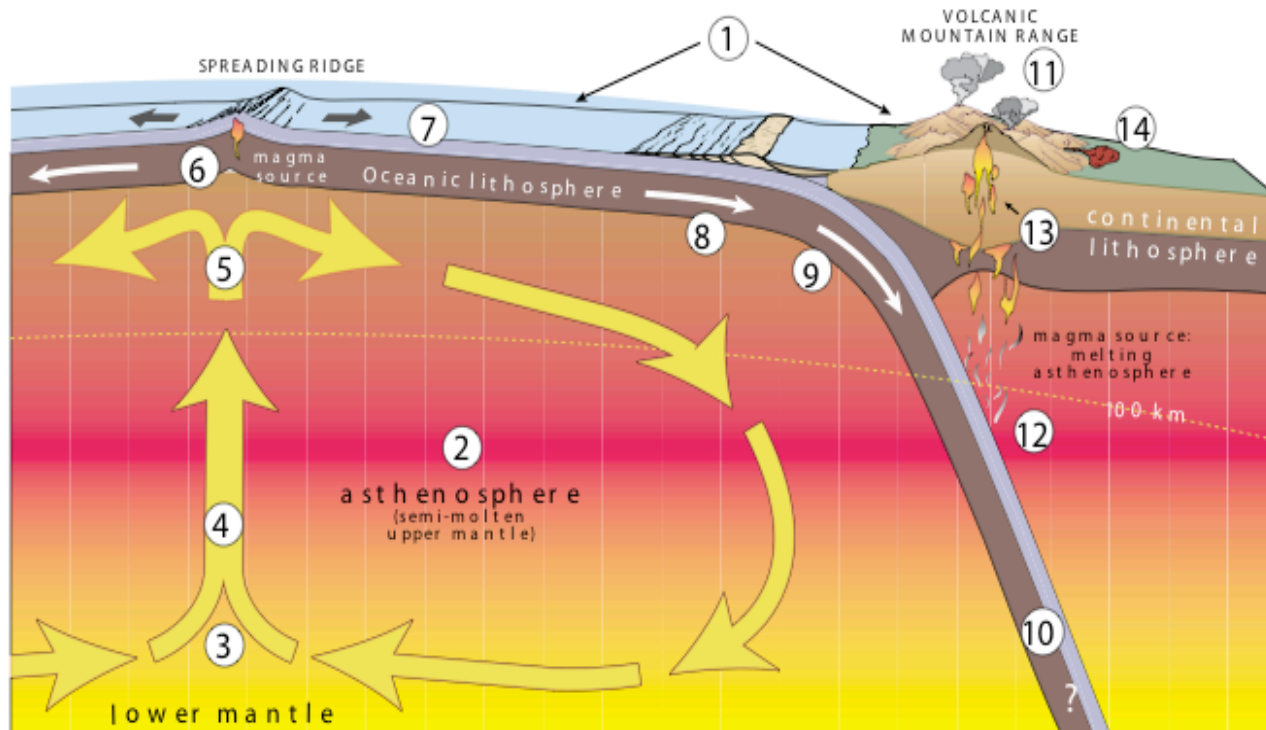


HORIZONTAL SECTION





Island Arc Magmatism

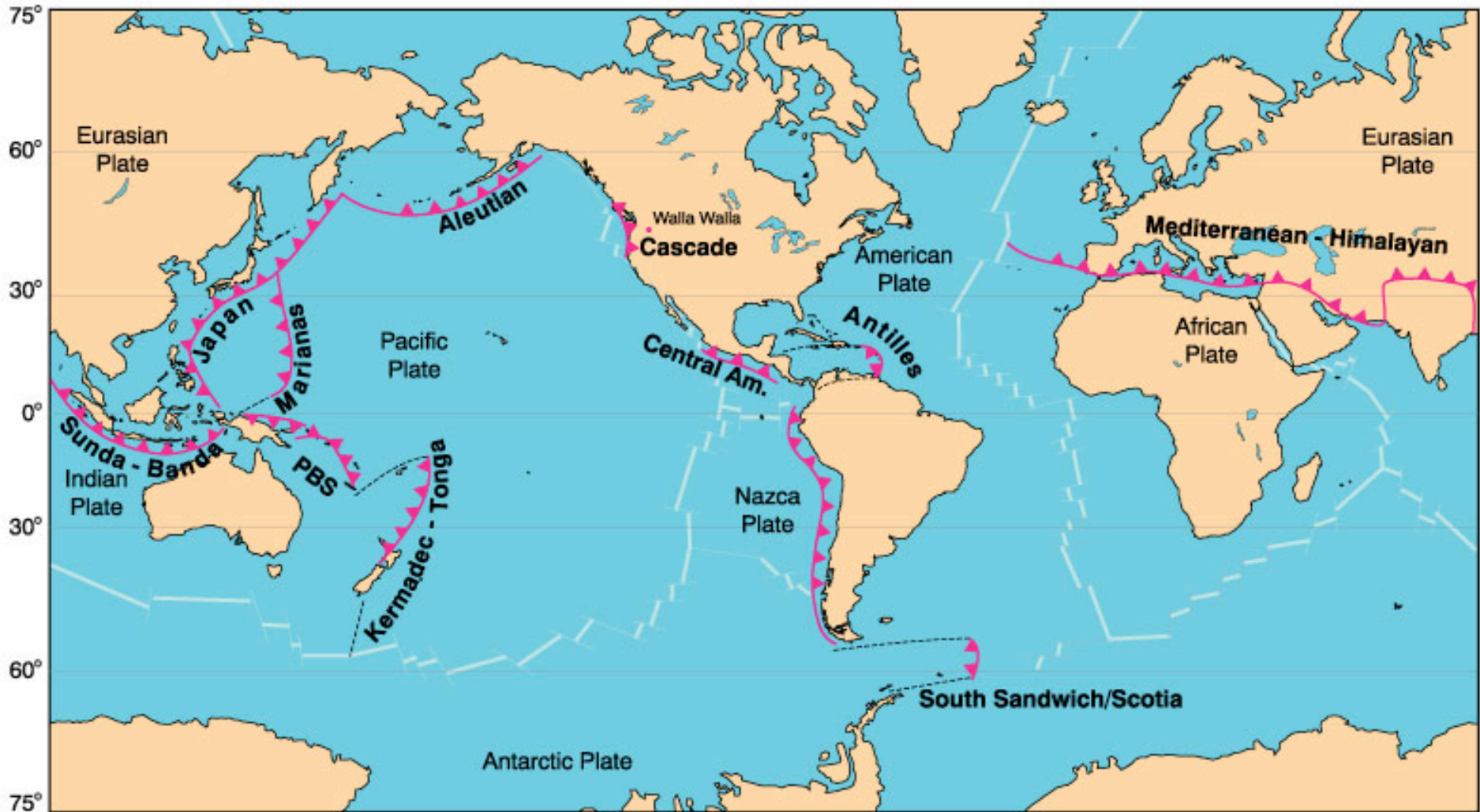


Island Arc Magmatism

- Activity along arcuate volcanic island chains along subduction zones
- Distinctly different from the mainly basaltic provinces thus far
 - ◆ Composition more diverse and silicic
 - ◆ Basalt generally occurs in subordinate quantities
 - ◆ Also more explosive than the quiescent basalts
 - ◆ Strato-volcanoes are the most common volcanic landform

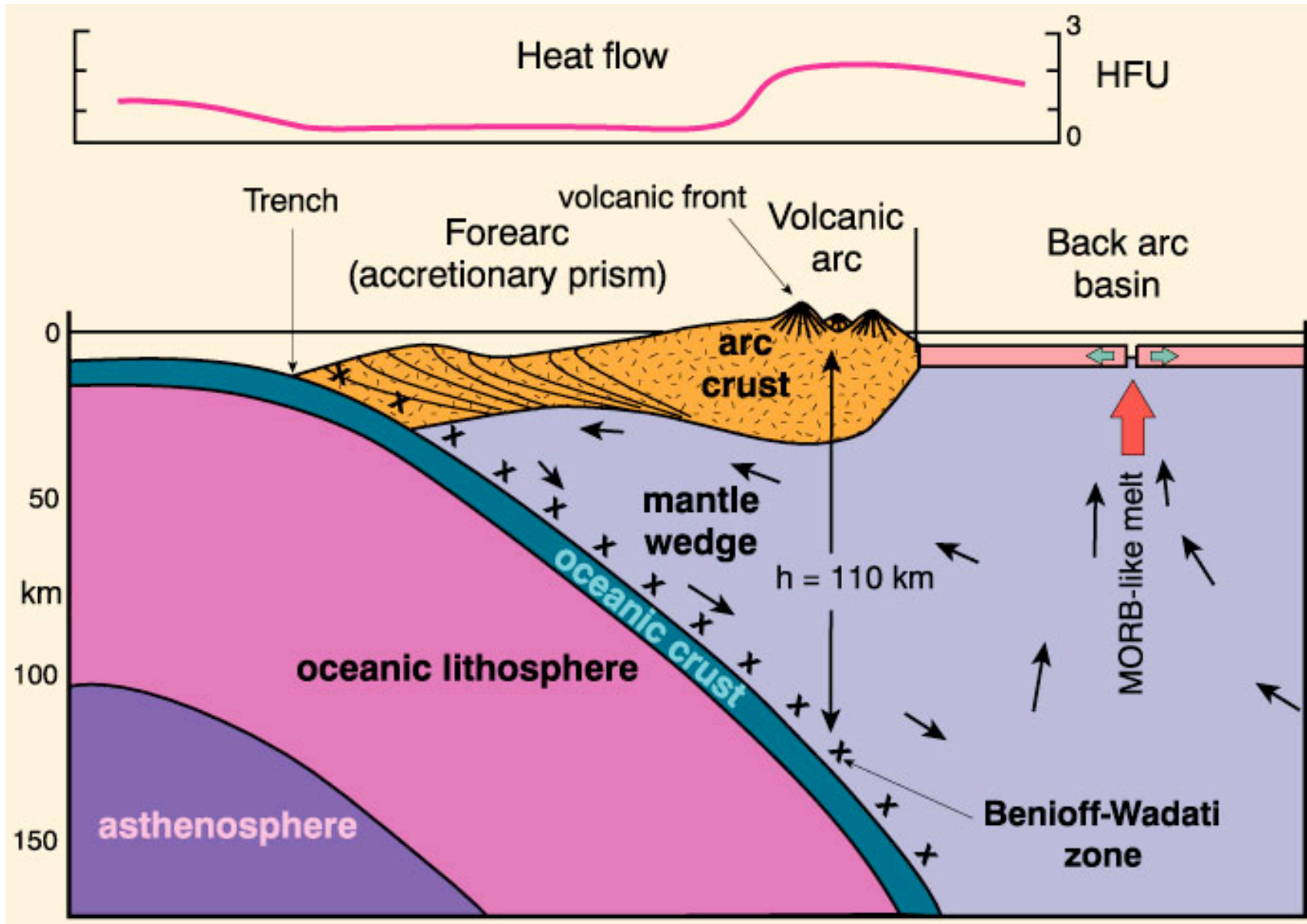
- Igneous activity is related to convergent plate situations that result in the subduction of one plate beneath another
- The initial petrologic model:
 - ◆ Oceanic crust is partially melted
 - ◆ Melts rise through the overriding plate to form volcanoes just behind the leading plate edge
 - ◆ Unlimited supply of oceanic crust to melt

Ocean-ocean → Island Arc (IA)
Ocean-continent → Continental Arc or
Active Continental Margin (ACM)



Principal subduction zones associated with orogenic volcanism and plutonism. Triangles are on the overriding plate. PBS = Papuan-Bismarck-Solomon-New Hebrides arc. After Wilson (1989) *Igneous Petrogenesis*, Allen Unwin/Kluwer.

Structure of an Island Arc



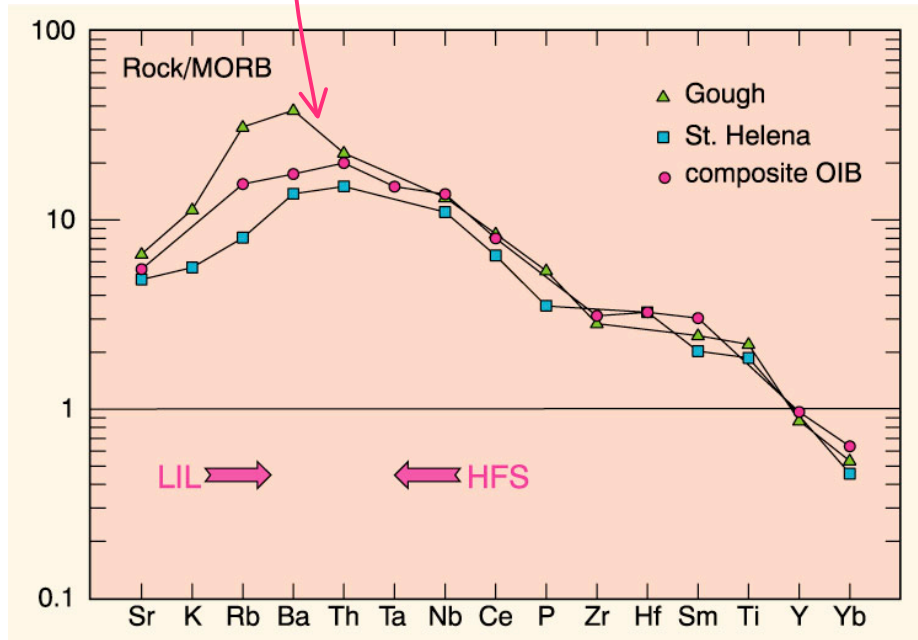
Schematic cross section through a typical island arc after Gill (1981), *Orogenic Andesites and Plate Tectonics*. Springer-Verlag. HFU= heat flow unit (4.2×10^{-6} joules/cm²/sec)

Major Elements and Magma Series

- Tholeiitic (MORB, OIT)
- Alkaline (OIA)
- Calc-Alkaline (~ restricted to SZ)

- MORB-normalized Spider diagrams

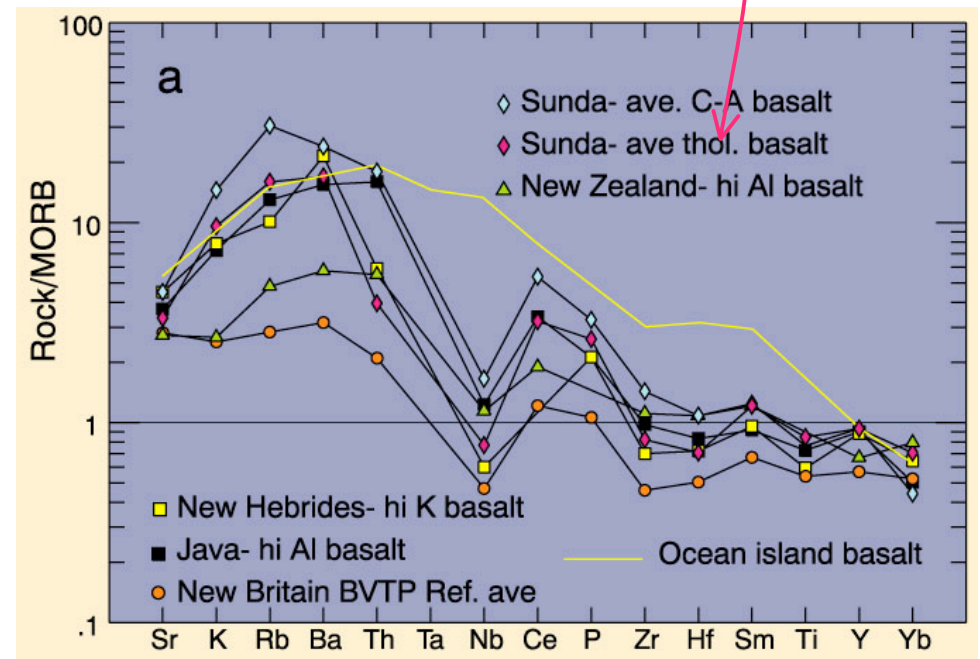
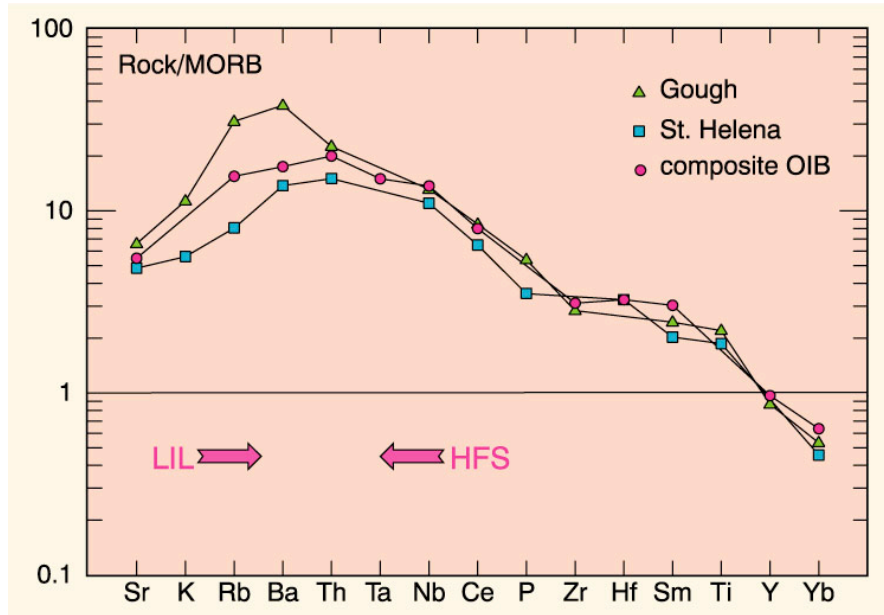
- ◆ Intraplate OIB has typical hump



Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall. Data from Sun and McDonough (1989) In A. D. Saunders and M. J. Norry (eds.), *Magmatism in the Ocean Basins*. Geol. Soc. London Spec. Publ., 42. pp. 313-345.

- MORB-normalized Spider diagrams
 - ◆ IA: decoupled HFS - LIL (LIL are hydrophilic)

What is it about subduction zone setting that causes fluid-assisted enrichment?

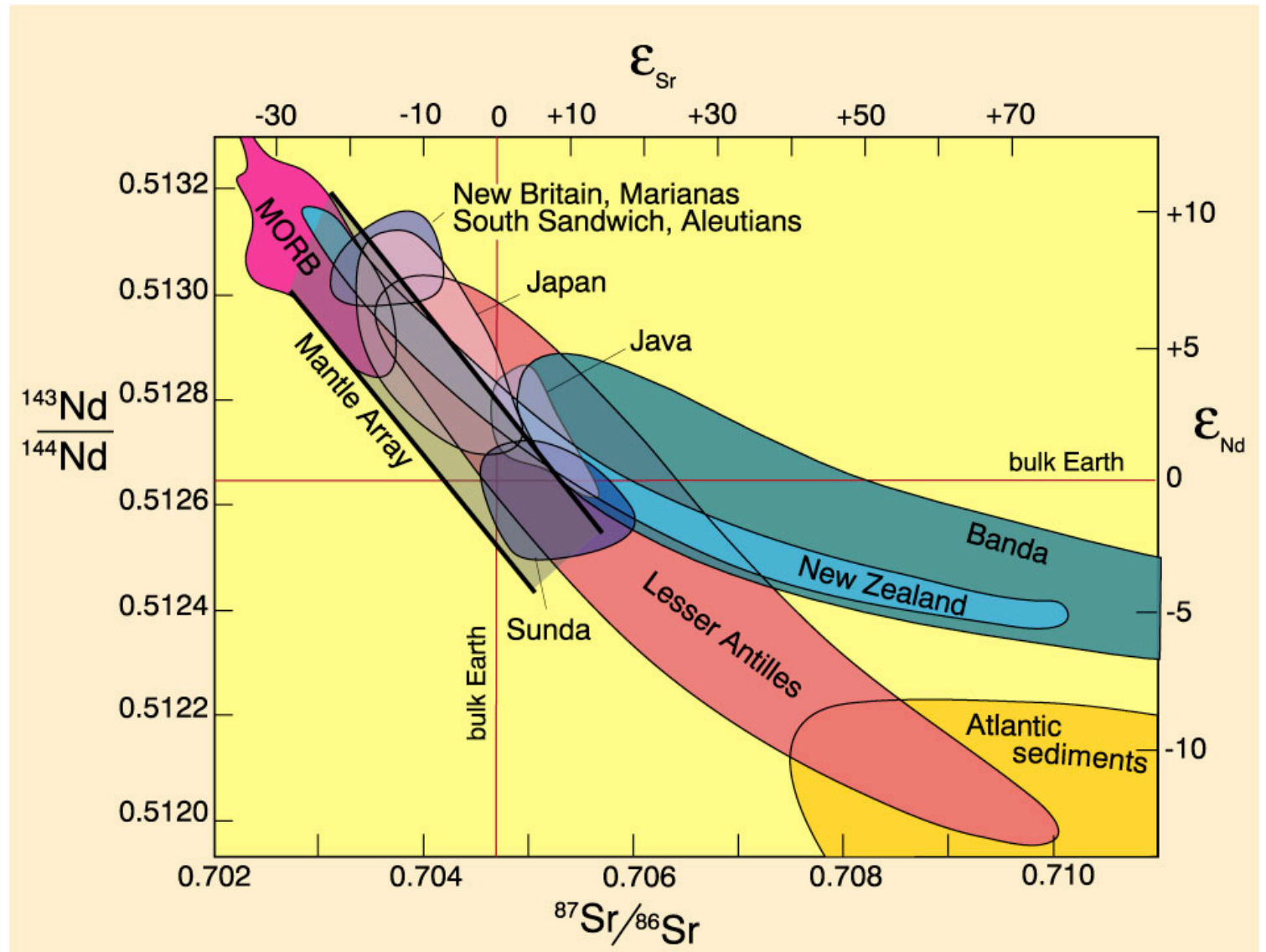


Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall. Data from Sun and McDonough (1989) In A. D. Saunders and M. J. Norry (eds.), *Magmatism in the Ocean Basins*. Geol. Soc. London Spec. Publ., 42. pp. 313-345.

MORB-normalized spider diagrams for selected island arc basalts. Using the normalization and ordering scheme of Pearce (1983) with LIL on the left and HFS on the right and compatibility increasing outward from Ba-Th. Data from BVTP. Composite OIB from Fig 14-3 in yellow.

Isotopes

- New Britain, Marianas, Aleutians, and South Sandwich volcanics plot within a surprisingly limited range of DM

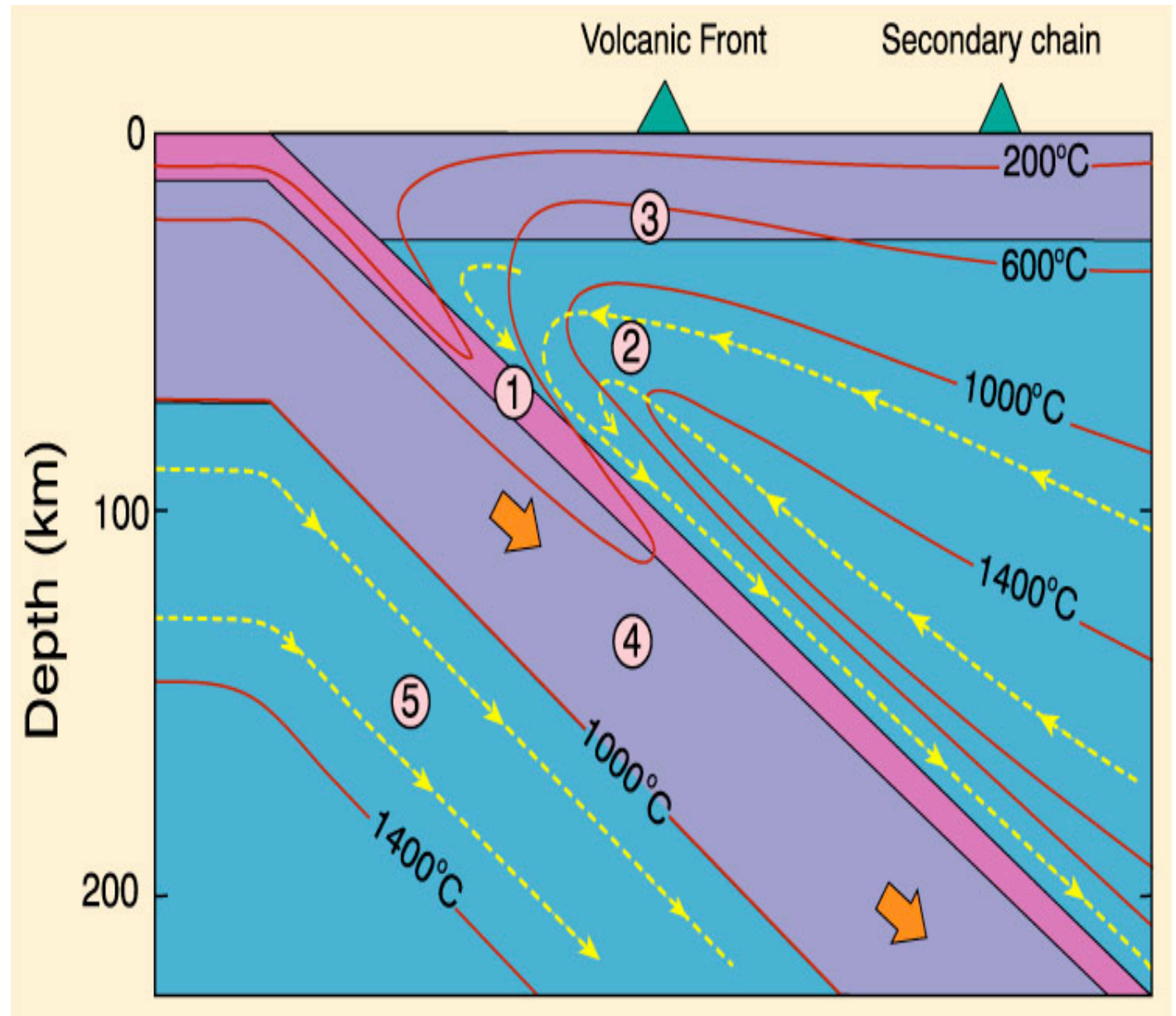


Nd-Sr isotopic variation in some island arc volcanics. MORB and mantle array from Figures 13-11 and 10-15. After Wilson (1989), Arculus and Powell (1986), Gill (1981), and McCulloch *et al.* (1994). Atlantic sediment data from White *et al.* (1985).

Thermal model for a subduction zone

yellow curves
= mantle flow

Cross section of a subduction zone showing isotherms (red-after Furukawa, 1993, *J. Geophys. Res.*, 98, 8309-8319) and mantle flow lines (yellow-after Tatsumi and Eggin, 1995, *Subduction Zone Magmatism*. Blackwell. Oxford).



Of the many variables that can affect the isotherms in subduction zone systems, the main ones are:

- 1) the rate of subduction
- 2) the age of the subduction zone
- 3) the age of the subducting slab
- 4) the extent to which the subducting slab induces flow in the mantle wedge

Other factors, such as:

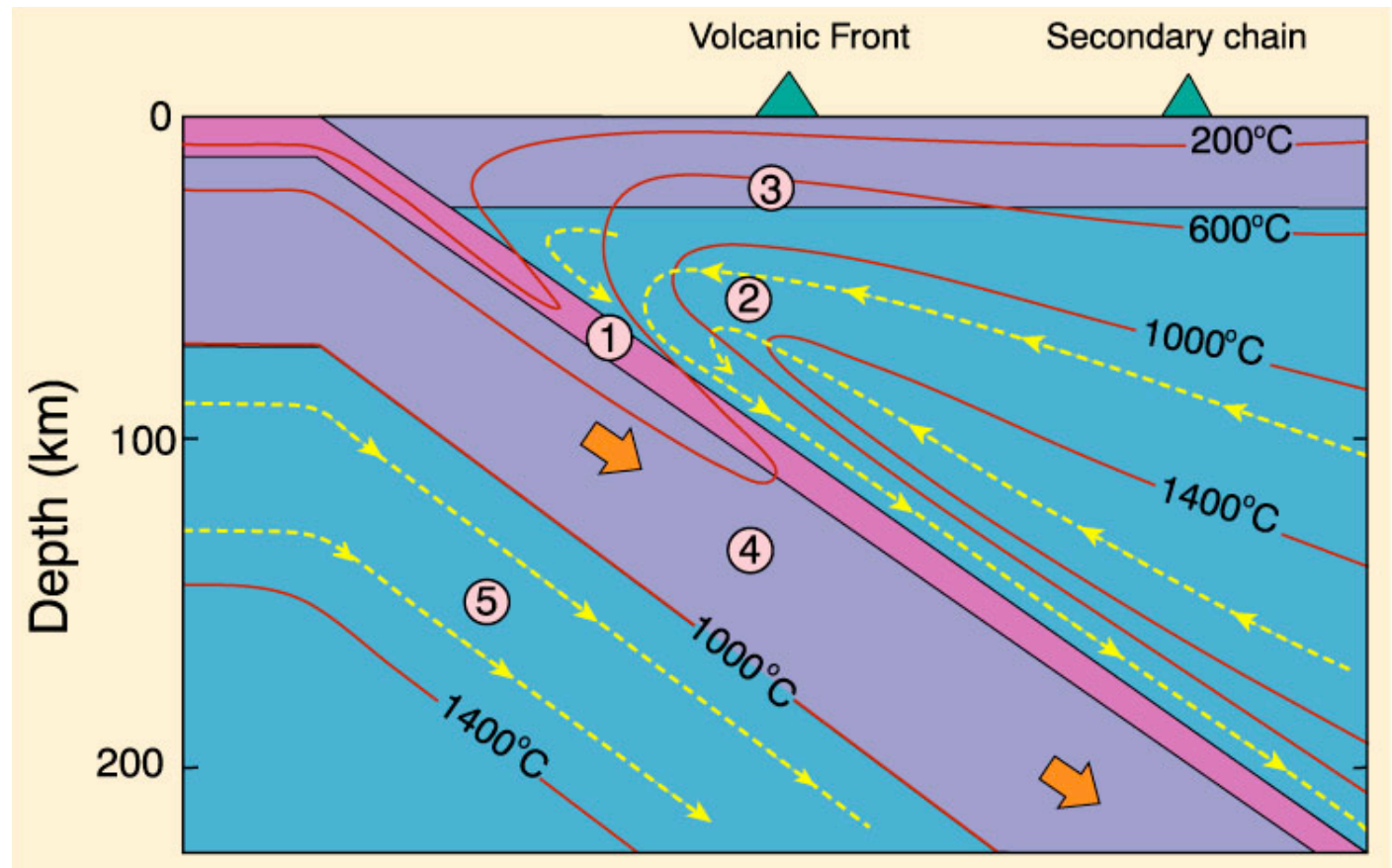
- ◆ dip of the slab
- ◆ frictional heating
- ◆ endothermic metamorphic reactions
- ◆ metamorphic fluid flow

are now thought to play only a minor role

- Typical thermal model for a subduction zone
- Isotherms will be higher (i.e. the system will be hotter) if
 - a) the convergence rate is slower
 - b) the subducted slab is young and near the ridge (warmer)
 - c) the arc is young (<50-100 Ma according to Peacock, 1991)

yellow curves
= mantle flow

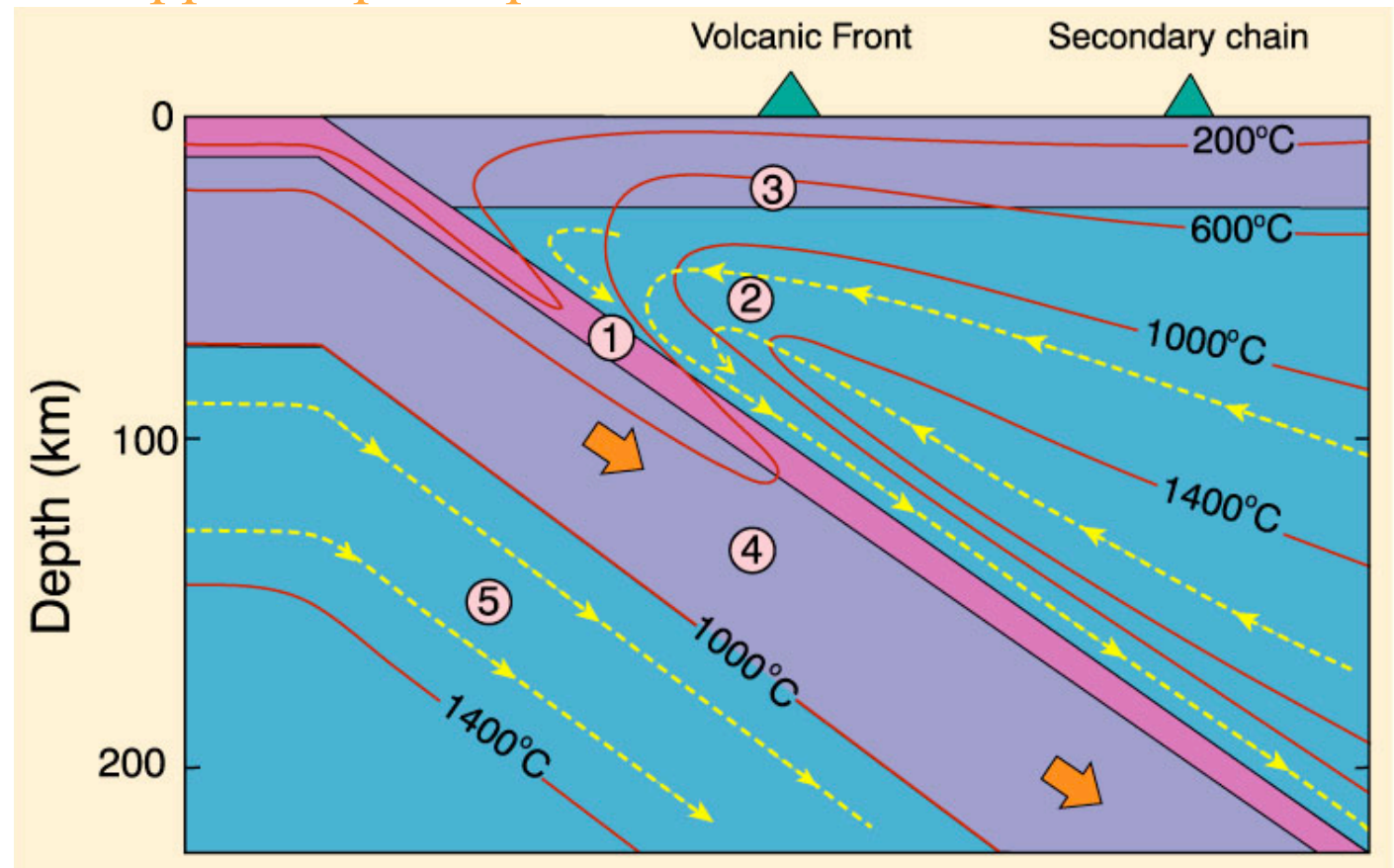
Cross section of a subduction zone showing isotherms (red-after Furukawa, 1993, *J. Geophys. Res.*, 98, 8309-8319) and mantle flow lines (yellow-after Tatsumi and Eggin, 1995, *Subduction Zone Magmatism*. Blackwell. Oxford).



The principal source components → IA magmas

1. The crustal portion of the subducted slab

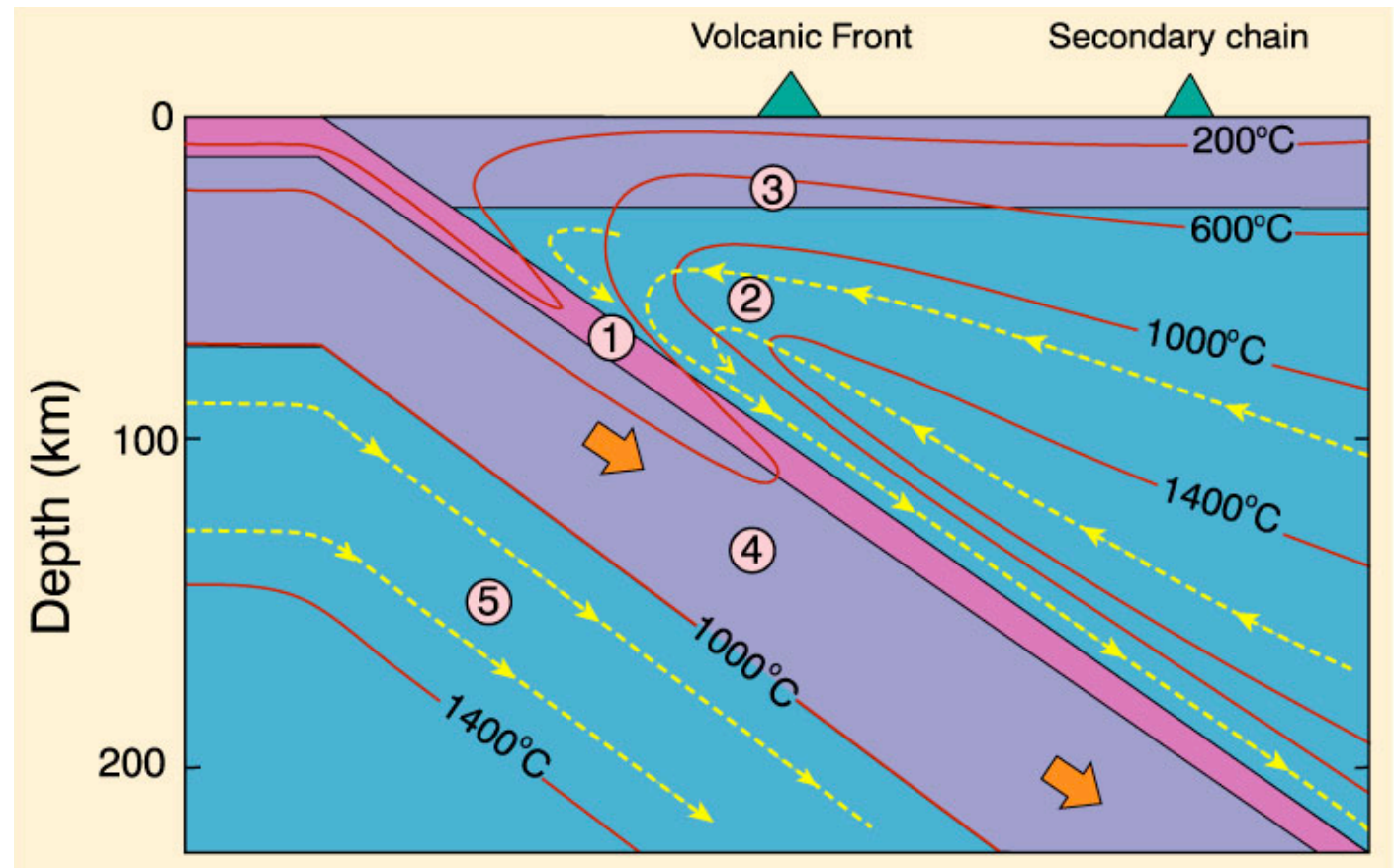
- 1a Altered oceanic crust (hydrated by circulating seawater, and metamorphosed in large part to greenschist facies)
- 1b Subducted oceanic and forearc sediments
- 1c Seawater trapped in pore spaces



Cross section of a subduction zone showing isotherms (red-after Furukawa, 1993, *J. Geophys. Res.*, 98, 8309-8319) and mantle flow lines (yellow-after Tatsumi and Eggins, 1995, *Subduction Zone Magmatism*. Blackwell. Oxford).

The principal source components → IA magmas

2. The mantle wedge between the slab and the arc crust
3. The arc crust
4. The lithospheric mantle of the subducting plate
5. The asthenosphere beneath the slab



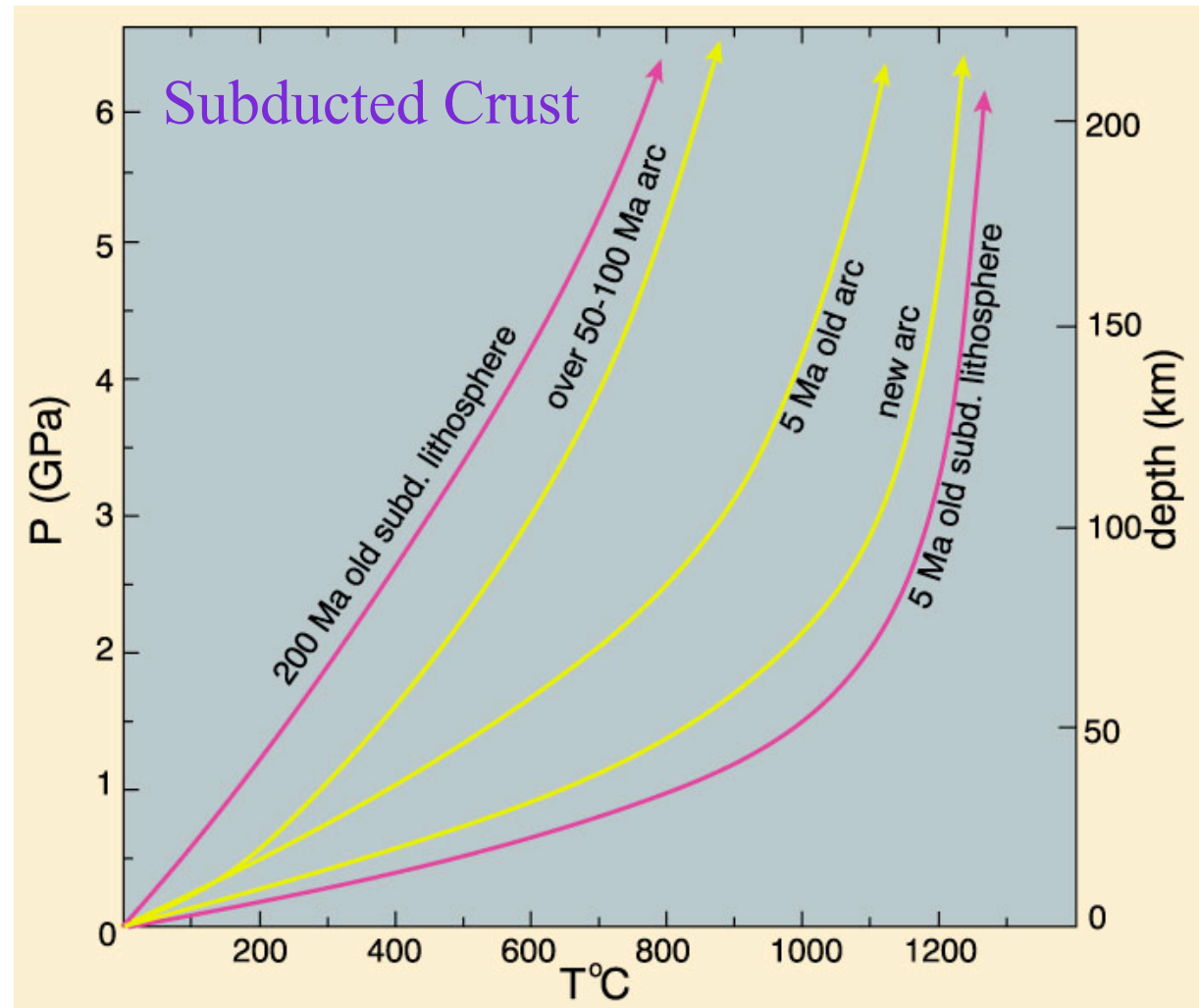
Cross section of a subduction zone showing isotherms (red-after Furukawa, 1993, *J. Geophys. Res.*, 98, 8309-8319) and mantle flow lines (yellow-after Tatsumi and Eggins, 1995, *Subduction Zone Magmatism*. Blackwell. Oxford).

- P-T-t paths for the **subducted crust** in a variety of arc scenarios numerically modeled by Peacock (1990, 1991)
- All curves are based on a subduction rate of 3 cm/yr, so the length of each curve represents about 15 Ma

The **yellow** P-T-t paths represent various **arc ages**

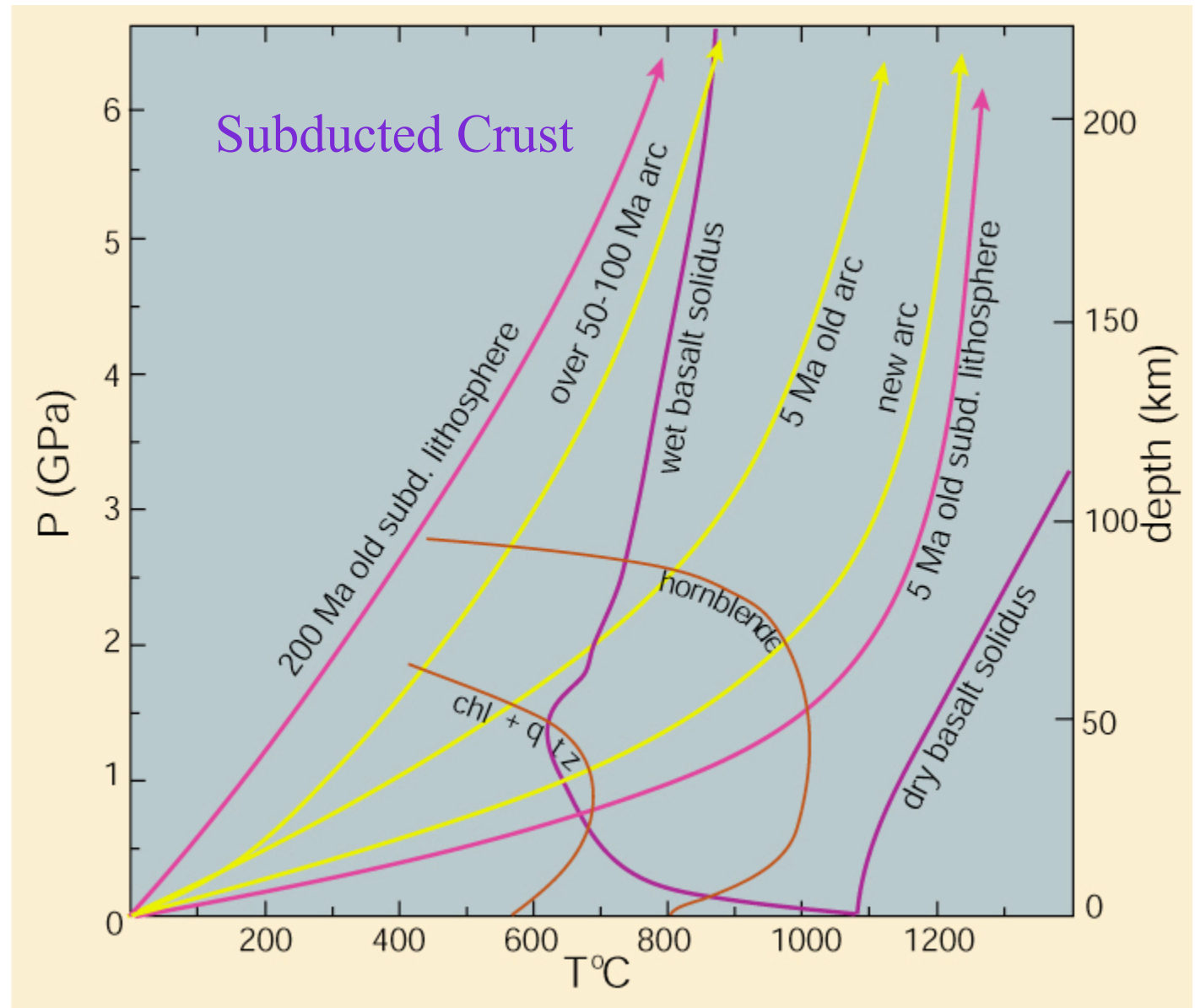
Red curves = age of the subducted slab

Subducted crust pressure-temperature-time (P-T-t) paths for various situations of arc age (yellow curves) and age of subducted lithosphere (red curves, for a mature ca. 50 Ma old arc) assuming a subduction rate of 3 cm/yr (Peacock, 1991, *Phil. Trans. Roy. Soc. London*, 335, 341-353).

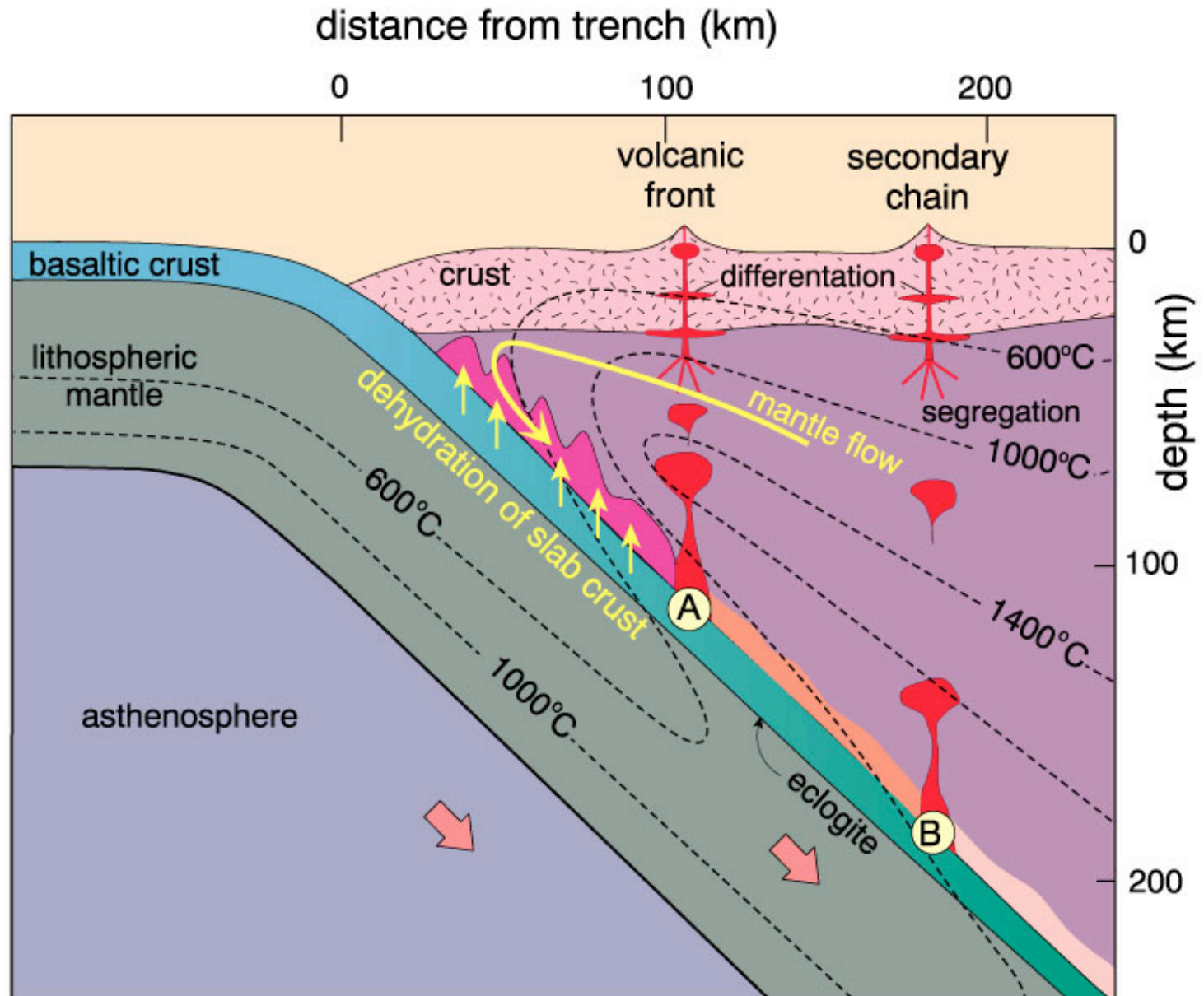


Now add the solidi for dry and water-saturated melting of basalt

Subducted crust pressure-temperature-time (P-T-t) paths for various situations of arc age (yellow curves) and age of subducted lithosphere (red curves, for a mature ca. 50 Ma old arc) assuming a subduction rate of 3 cm/yr (Peacock, 1991). Included are some pertinent reaction curves, including the wet and dry basalt solidi (Figure 7-20), the dehydration of hornblende (Lambert and Wyllie, 1968, 1970, 1972), chlorite + quartz (Delaney and Helgeson, 1978). Winter (2001). *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.



Island Arc Petrogenesis



A proposed model for subduction zone magmatism with particular reference to island arcs. Dehydration of slab crust causes hydration of the mantle (violet), which undergoes partial melting as amphibole (A) and phlogopite (B) dehydrate. From Tatsumi (1989), *J. Geophys. Res.*, 94, 4697-4707 and Tatsumi and Eggins (1995). *Subduction Zone Magmatism*. Blackwell. Oxford.