Hotspots and Absolute Plate Motion

What are mantle plumes and hotspots?

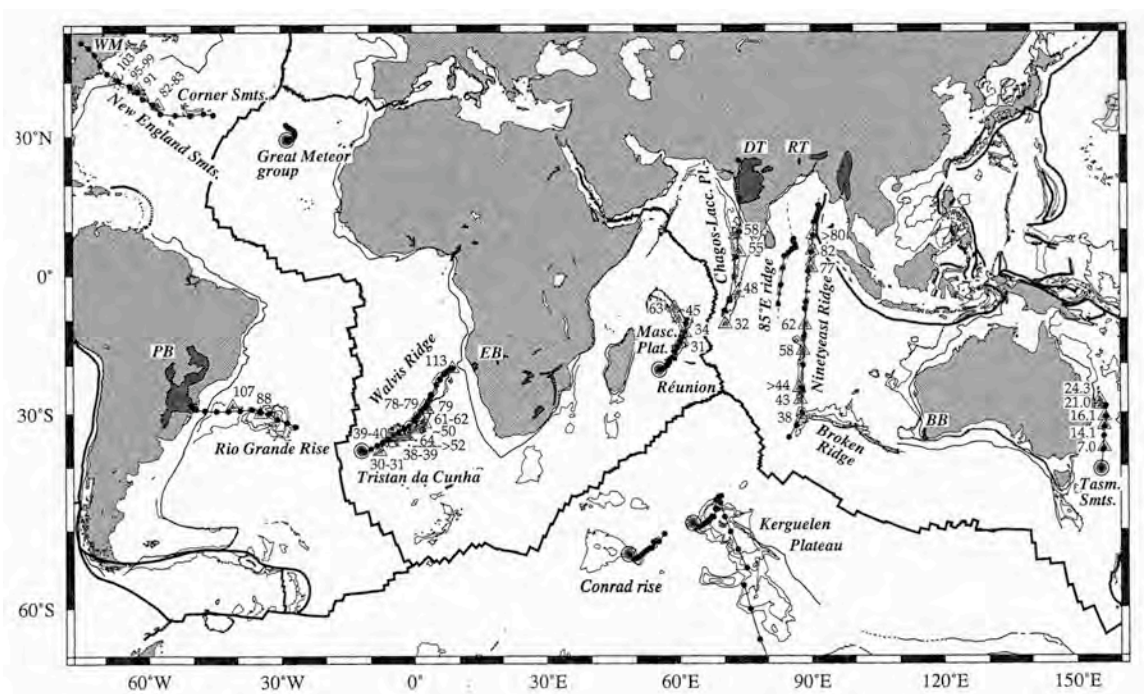
What evidence is there that plumes exist?
- linear volcanic chains, links with large igneous provinces
- topographic signature associated with plumes
- seismic tomography
- geochemistry of plume melting materials
- other geophysical signatures

Origin and evolution of plumes
- why do plumes form, rise?
- stages of plume development

Relative and absolute plate motions

Paleomagnetic tests of hotspot fixity

Controls on plate motion



Hotspots, Mantle Plumes and Absolute Plate Motion **Nov. 27, 2006**

What are mantle plumes and hotspots?

Mantle **plume** = long, slender (~100 km) column of *hot* (100's °C hotter than surrounding mantle) rock ascending from *deep* (we'll discuss later what's meant by deep) in the mantle.

a. upwelling material is hot solid that undergoes decompression melting near surface

b. rise at rates of m/yr (so millions of years to traverse mantle)

c. expression at surface includes volcanism (the locus of active volcanism is a **hotspot**), topographic swell, large igneous provinces, high heat flow

How are plumes related to plate tectonics?

Plate tectonics reflects underlying mantle convection. Plumes represent a distinct type of convection instabilities at hot deep boundary. So plumes are not an intrinsic part of plate tectonics. They are significant in terms of heat and mass transfer from the mantle to earth's surface (particularly early stages of large igneous provinces).

What evidence is there that plumes exist?

1. volcanic chains (age progressive) and large igneous provinces

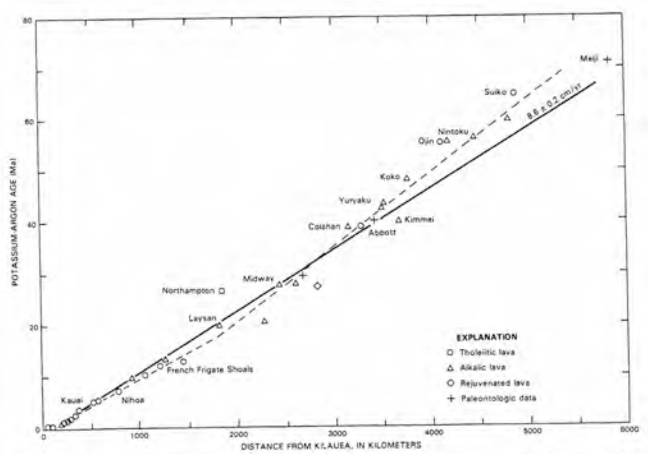


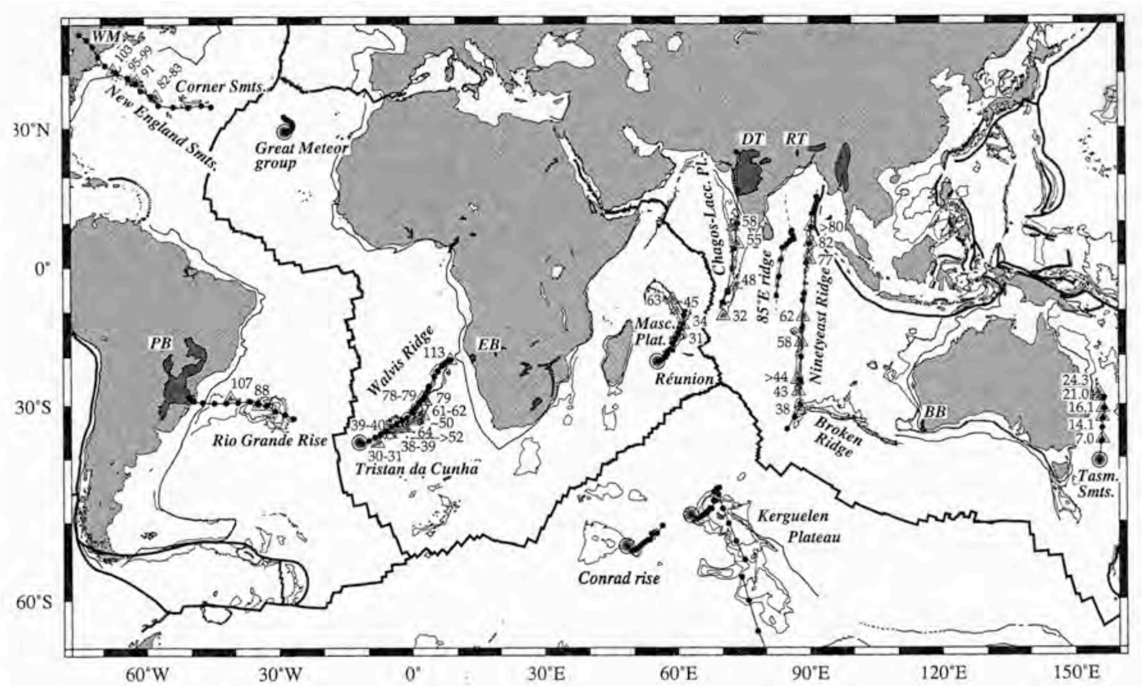
FIGURE 1.5.—Age of volcanoes in Hawaiian-Emperor Chain as a function of distance from Kilauea. Solid line is least-squares cubic fit (York 2) from table 1.5 and represents average rate of propagation of volcanism of 8.6±0.2 cm/yr. Dashed line is two-segment fit using data from Kilauea to Gardner and Laysan to Suiko (table 1.5). Radiometric data from table 1.4, paleontologic data discussed in text.

Hallmark of plume/hotspot volcanism is the formation of age progressive volcanic chains. The Hawaii-Emperor chain is perhaps the most prominent hotspot chain, with the current hotspot at Loihi Seamount (SE of big island).

a. 0-45 my (Hawaiian trend) reflects NW plate motion

b. 45-80 my (Emperor trend) may reflect N plate motion but also may incorporate some hotspot motion (we'll return to this later).

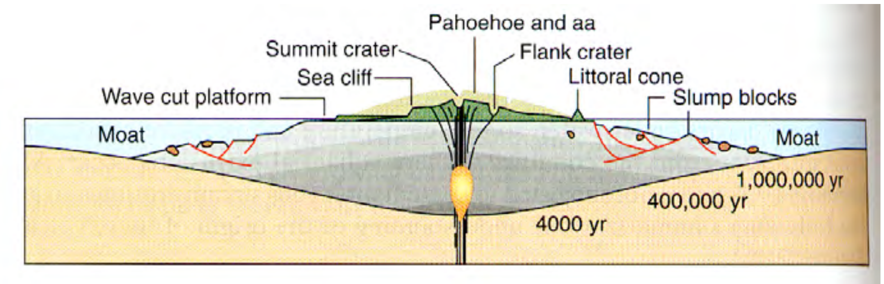
c. parallel chains in Pacific (Louisville). Why is the distance of the 0-45 Ma part of the Louisville chain larger than that of the Hawaiian chain?



A large number of hotspots have documented age progressive chains (see above), although the age progression in slower spreading oceans is sometimes not as clear as for the Hawaii-Emperor. Note in the above figure that the old end of several hotspot chains is associated with **large igneous provinces** or **flood basalts**. These large outpourings of lava are thought to be associated with the arrival of the plume head, with the volcanic chain representing the track of the plume conduit.

a. formation of instability at CMB or shallower level
    laboratory experiments indicate such instabilities are norm
    theoretical considerations (flow cusps from convection)
    why does the plume rise?
b. rise of plume with entrainment of mantle material
c. plume head >> large igneous province
    can be extraordinarily rapid (e.g. Deccan traps, Ontong Java?)
    OTJ plateau is 2/3 the size of Australia and 25-45km thick.
    thought to have erupted in few million years, so 15-20 km3/yr which is comparable to all mid-ocean ridges (cf Mt St Helens eruption 1 km3)
    topographic uplift
d. plume tail >> volcanic chain

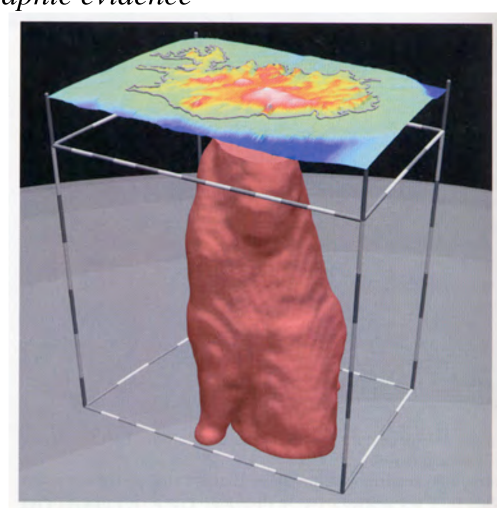
2. topographic swells



Hotspots generate several topographic expressions in addition to the initial upwarp associated with arrival of the plume head. The diagram above illustrates the present situation at Hawaii.

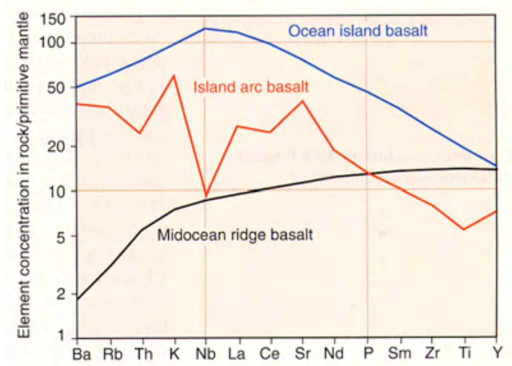
a. initial submarine growth of the seamount
b. subareal volcanism and continued subsidence
   isostatic response to this loading (**plate flexure**)
   strength of the plate (increases with age) determines deflection
   development of **moat**
c. post-volcanism subsidence as plate continues to age/subside
   atoll development

3. seismic tomographic evidence



Seismic tomography (like a CAT scan) provides a method for imaging hot upwelling material of a plume. The above diagram illustrates the extent of hot (seismically slow) mantle material beneath Iceland.

4. geochemically distinct



Hotspot volcanism generally produces basaltic volcanism by adiabatic decompression melting. However, the details of the chemistry of the lavas are distinct from the basalts produced at mid-ocean ridges (or island arcs). Recall that when the mantle partially melts, **incompatible elements** (those that are not incorporated into the minerals of the unmelted residual) are preferentially incorporated into the melt. Mid-ocean ridge lavas result from melting of an already depleted mantle reservoir (hence low in these incompatible trace elements). In contrast, melting at hotspots can tap more fertile mantle (perhaps coming from the deep mantle plume) and results in lavas that are enriched in incompatible elements.

Melting may also commence at higher pressures (greater depth) than for mid-ocean ridge basalts. The result of this higher pressure melting is to drive the initial melt composition towards the olivine endmember of the Fo-Di-Pyrope ternary. The resulting liquids are less SiO_2 rich and may be **nepheline** (a SiO_2 poor version of feldspar) normative.

$$NaAlSiO_4 \text{ (nepheline)} + 2SiO_2 >> NaAlSi_3O_8 \text{ (albite)}$$

These deep melts may also bring **xenoliths** (an exotic rock fragment, in this case fragments of the surrounding mantle) to the surface. Plume lavas also are rich in **Helium 3**, thought to be indicator of undegassed mantle.

5. high heat flow and gravity signature

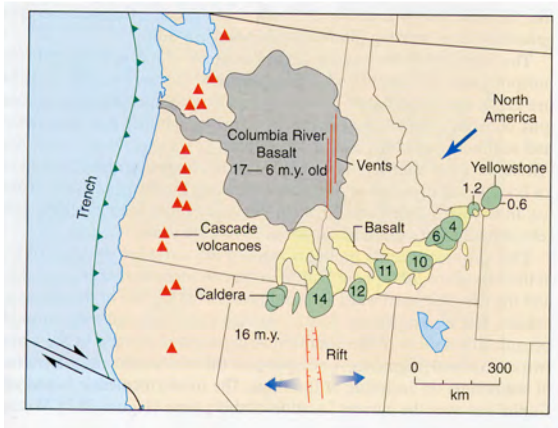
The higher temperature of mantle plumes is also associated with elevated heat flow. The hotter mantle is also less dense, resulting in gravity low.

Plumes under continental areas

There is no reason why plumes need be exclusively under oceanic lithosphere and indeed several plumes are found in continental areas. The Yellowstone hotspot is one such example.

a. note the presence of Columbia River basalts
    initial plume activity leads to higher % melts (more basaltic)
b. plume tail is associated with less heat, melting of granitic crust

product is silicic magmatism typical of Yellowstone today



Relative and absolute plate motions

Most plate motion studies (utilizing magnetic anomaly lineations and fracture zone orientations) provide information on the **relative** motion between plates. For example, the lineated anomalies in the Atlantic ocean record the relative separation of North America and Europe, but these anomalies do not provide any information on the **absolute** motions of the plates. To examine absolute motions we need a reference frame that is not moving (or is very slowly moving relative to typical plate speeds).

Plumes as absolute motion reference frame

Mantle plumes are perhaps the best candidate to provide such a stationary reference frame. This is because many plumes are thought to originate in the deep mantle.

How can we test whether plumes do originate in the deep mantle?

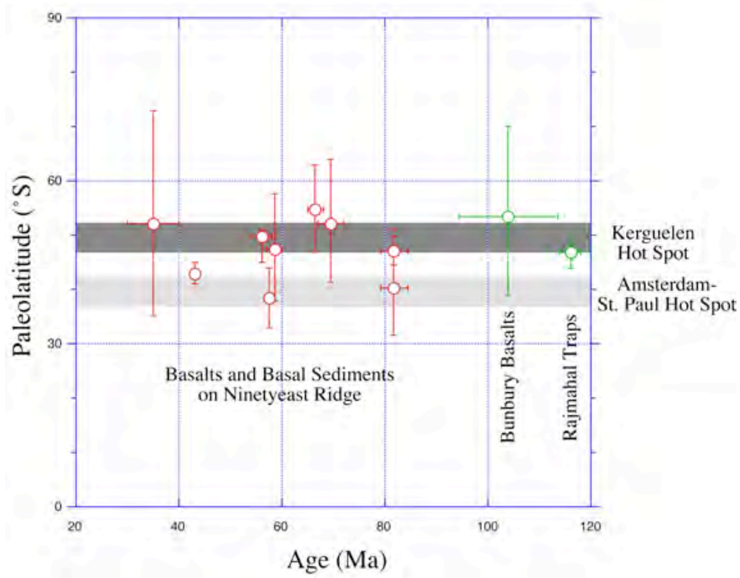
a. geochemistry (isotopic signature of distinct mantle reservoir, PGEs)
b. seismic tomography studies
c. paleomagnetism
recall the dipole formula (tan(inclination) = 2*tan(latitude))
so if plumes are stationary (or nearly so) then paleolatitude constant

Paleomagnetic tests of hotspot fixity

Kerguelen-Ninetyeast Ridge

paleolatitude of flood basalts ~50°S
present hotspot location also ~50°S
complications (second hotspot, large errors)

Paleolatitude Record of Volcanic Rocks Produced at the Kerguelen Hotspot



Hawaii-Emperor Chain

a. Emperor portion of chain interpreted as hotspot drift