Seismology: The hunt for plumes

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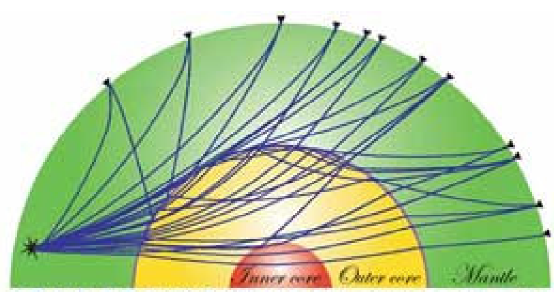
Earth Structure

All high-resolution methods for determining Earth's interior structure are based on analyzing the propagation of *seismic waves* generated by earthquakes and explosions. These are elastic waves, in which the restoring forces come from the resistance of materials to deformation. In an infinite medium they are of two types: *compressional waves*, of which sound waves in air are the most familiar example, and *shear waves*, which propagate only in solids. Compressional and shear waves are called *body waves*, because they propagate through the body of the Earth.

Seismic waves travel at speeds of several kilometers per second in the Earth, with the speed of compressional waves, *Vp*, being about 1.7 times greater than that of shear waves, *Vs*. Seismic wave speeds are different in different kinds of rocks, and in addition increase with pressure (which is very nearly a function of depth alone) and decrease with temperature.Through seismic wave speeds, we know of Earth's major vertical subdivisions and their approximate compositions:

- the *crust*, the outer few tens of kilometers, on which we live.
- the 2900-km thick *mantle*, composed of ultramafic rocks.
- the liquid iron *core* (radius 3475 km), at whose center is the 1250-km radius solid *inner core*.

The boundaries between these major divisions within the Earth produce many kinds of reflected and transmitted *seismic phases*, some of which are shown at right, and cause seismograms to be complicated.



S, P, ScS, PcP, Sdiff, Pdiff, SKS, PKP, SPdKS, SnKS, PnKP

Seismic wave speeds also vary horizontally, but this is a second-order effect. For example, the crust is five to ten times thicker under continents than under oceans. Beneath oceanic trenches the mantle is relatively cool and wave speeds are high, and beneath oceanic spreading ridges the mantle is hotter and wave speeds are lower.

Determining the seismic wave-speed distribution in the mantle is the most powerful way to detect and map plumes. Since plumes were first proposed by Morgan [1971], seismologists have used many methods to look for anomalous deep structures beneath hot spots, including plume heads, which might be easier to detect, but so far they have had little success.

Predicted Effects of Plumes on Seismic Structure

Direct thermal effect – If thermal plumes exist in the mantle, they would have lower seismic wave speeds than their surroundings. In the upper mantle, a 100 K temperature rise lowers *Vp* by about 1%, and *Vs* by about 1.7%. In the deep mantle, this effect is several times weaker. The minimum temperature anomalies proposed for plumes are about 200 K.

Indirect thermal effect – Temperature variations would also cause variation in the depths of *polymorphic phase boundaries* in the *transition zone* between the upper and lower mantle. These are places where pressure causes certain minerals to change their crystal structure, and these changes are accompanied by jumps in density and seismic wave speed. Two such zones in particular, at depths of about 410 and 650 km, are global features and fairly easily detectable. A 100 K temperature rise would depress the “410-km” discontinuity by about 8 km, and raise the “650-km” discontinuity by about 5 km. (Both of these numbers are based on the assumption that olivine is the main mantle mineral, and are subject to significant uncertainty.) Thus a high-temperature anomaly would produce negative and anomalies at 410 km and positive ones at 650 km. The depths to these phase changes can also be measured directly using waves reflected from them (*see* **Receiver Functions**, below).

Chemical effect – If a plume has a different composition from the surrounding mantle, this alone will cause a seismic wave-speed anomaly. The sign and magnitude of the anomaly will depend on what minerals are involved, but as a rule of thumb more buoyant materials have lower wave speeds.

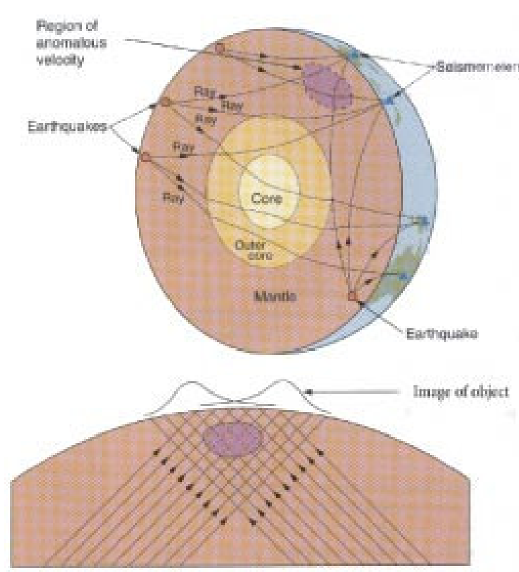
Melting – The presence of even a small amount of melt in a rock has a large effect on its seismic-wave speeds. Partial melting may reflect either thermal (high temperature) or chemical (low melting point) effects. The magnitude of the effect on seismic wave speeds depends strongly on the geometric form of the melt bodies. Thin films on grain boundaries have the largest effect, and approximately spherical melt bodies have the smallest effect [*Goes et al.*, 2000].

Anisotropy – Seismic wave speeds and other properties of rocks vary with direction, and this can be as strong an effect as spatial heterogeneity. Most studies of Earth structure ignore this effect, and their results probably are biased by this oversimplification. Studies dealing explicitly with anisotropy are becoming more common.

Anelasticity – Many physical mechanisms remove energy from seismic waves and convert it to heat, causing the waves to eventually die away. A side effect of this process is to introduce a weak frequency dependence on the wave speeds, which must be accounted for in studies of Earth structure.

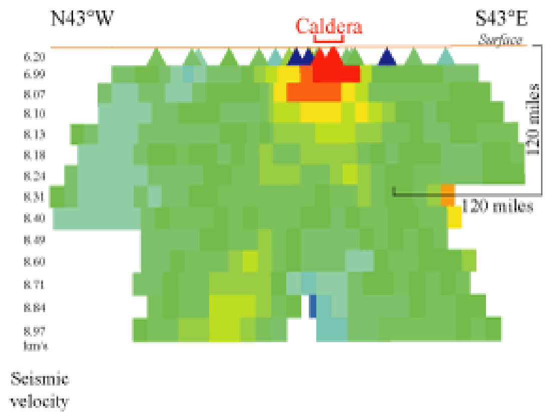
Seismic Tomography

The travel time of a seismic wave through the Earth gives an average of the wave speed along the wave’s *ray path* (but see **Bananas & Doughnuts**, below). If travel times are available for enough ray paths, passing through all parts of a region in many different directions, it is possible to un-scramble the times to determine the three-dimensional wave-speed distribution. The term *tomography*, borrowed from medicine, is given to such seismic techniques. Seismic tomography is much more difficult than X-ray tomography, because the ray paths are curved and initially unknown, and in some cases the locations of the sources are poorly known.



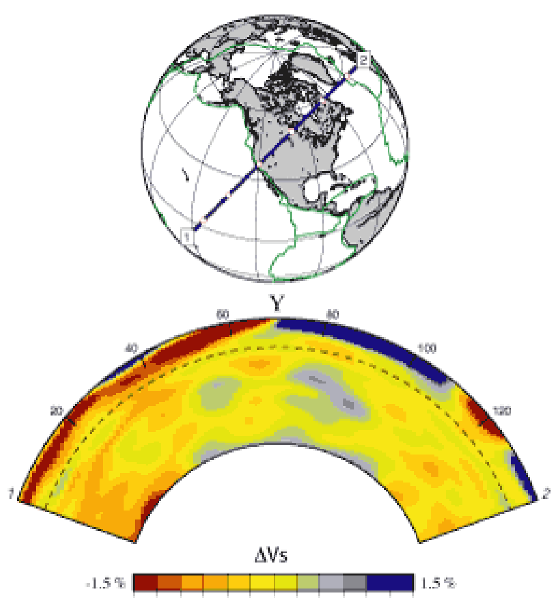
Three seismic tomography techniques are particularly useful in searching for plumes:

Teleseismic Tomography – In order to study the structure immediately under an area, one can deploy an array of seismometers and record waves from distant earthquakes (>~ 2,500 km away). Such waves arrive at angles within about 30° of the vertical, so crossing rays sample the structure down to depths comparable to the array aperture. The ray directions are not isotropically distributed, however; and no ray paths are ever close to horizontal. Consequently, compact structures tend to be smeared vertically in images obtained by this technique [*Keller et al.*, 2000]. This smearing is unfortunate, because it generates artifacts that resemble the structures that are being sought. It is possible to estimate quantitatively the severity of the smearing, however, and if due attention is paid to this error source, teleseismic tomography is the best technique available for studying the upper few hundred kilometers of particular regions. An example of this kind of tomography, applied to Iceland, is described by *Foulger et al.* [2001].



Cross section through a teleseismic tomography model of Yellowstone [from Christiansen et al., 2002].

Whole-Mantle Tomography – There have now been thousands of seismometers deployed globally for decades, and millions of travel-time observations have accumulated and been used to derive three-dimensional models of the whole mantle. Some studies use enormous data sets obtained from seismological bulletins such as that of the International Seismological Centre, but these data are subject to large and systematic observational errors. Others use data measured in more objective and consistent ways, usually using digitally recorded seismograms. Most whole-mantle models agree about the largest-scale anomalies (thousands of kilometers in size), but for a long time this was not so. The model that currently has the best resolution at depths of a few hundred kilometers, most critical for the search for plumes, is described by *Ritsema et al.* [1999].



Cross section through a whole-mantle tomography model through Yellowstone [courtesy of J. Ritsema].

The resolution of these models is limited both by the ray distributions and by the state of computer technology. The smallest anomalies currently resolvable are 500 km or more in size. Furthermore, ray paths fall far short of sampling the Earth uniformly. Both earthquakes and seismometers are distributed irregularly over the Earth, and some places within the Earth are sampled poorly or not at all *e.g.*, the southern hemisphere, and particularly the Indian Ocean. The uneven ray distribution also systematically distorts anomalies in the Earth. As with teleseismic tomography, this distortion can be assessed quantitatively, but not by the general reader unless considerable information on this subject is given in the paper in question.

Surface-wave Tomography – Tomographic methods can also be applied to *surface waves*, low-frequency seismic waves that propagate in the crust and upper mantle and owe their existence to the presence of the free surface. The depths to which surface waves are sensitive depends on frequency, with low-frequency waves "feeling" to greater depths and therefore propagating at higher speeds. (Rule of thumb: Surface waves feel down to about a quarter of their wavelength. They also propagate at about 4 km/s, so this depth, in kilometers, is about 1/frequency (Hz).)

Because of the distribution of earthquakes and seismometers, surface waves can often sample regions of the crust and upper mantle that body waves do not. They are also expected to be highly sensitive to plume heads, which are predicted to flatten out in the upper mantle, producing low wave speed regions that extend for thousands of km [*Anderson et al.*, 1992]. Body-wave and surface-wave data are often combined in whole-mantle tomography studies, such as that of Ritsema shown above.

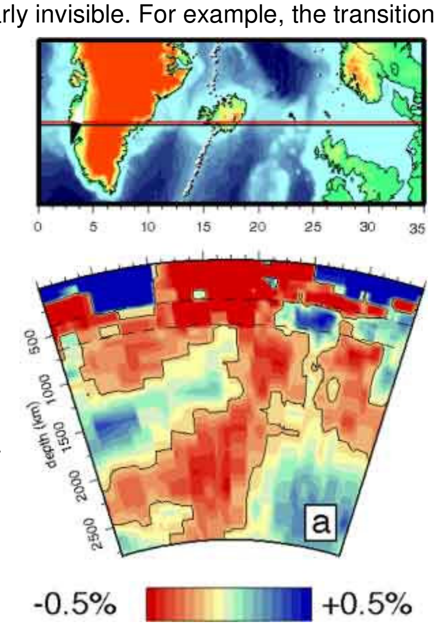
Bananas & Doughnuts – The statement above, that travel times are averages along ray paths, is a simplification. In reality, seismic waves “feel” the structure in a finite volume, and in fact *Dahlen et al.* [2000] have recently shown that travel times are most sensitive near a hollow surface around the ray, whose shape reminds them of certain snack foods. Incorporation of this insight into tomographic practice will significantly improve the quality of three-dimensional Earth models, but only preliminary results are, as yet, available.

Caveat emptor!

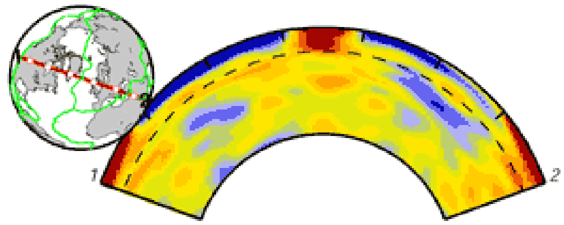
Several aspects of graphical presentation may make it difficult to interpret three-dimensional models in terms of Earth structure and processes:

- A model typically includes a huge amount of information, only a small fraction of which is shown, usually in the form of maps at various depths or vertical cross sections. The visual impression of the results given may be very sensitive to the precise position of the section.
- Wave speeds are usually displayed with colors, blue representing high wave speeds and red representing low ones. It is natural to associate red colors with higher temperatures. However, many factors affect the wave speed, including composition, crystal orientation, mineralogy and phase (especially the presence of melt). Red anomalies may not really be hot, nor blue ones cold.
- The eye’s sensitivity to color varies greatly across the spectrum, so inevitably some features are prominent while other, equally strong ones, are nearly invisible. For example, the transition from blue to yellow is much more noticeable than that from orange to red.
- If the color scale saturates, anomalies may look the same when they actually differ in strength by an order of magnitude. For example, lower-mantle anomalies are much weaker than upper-mantle ones, but this is obscured in figures where the color scale saturates at the maximum lower-mantle anomaly [*Anderson*, 1999].

Because of these factors, the appearance of tomographic images may be highly variable, depending on graphical design choices made by seismologists.



Highly saturated cross section of Iceland through the model of Bijwaard & Spakman [1999].



Less saturated cross section, also of Iceland, through the model of [Ritsema et al. [1999]](#).

The Simple Direct Approach

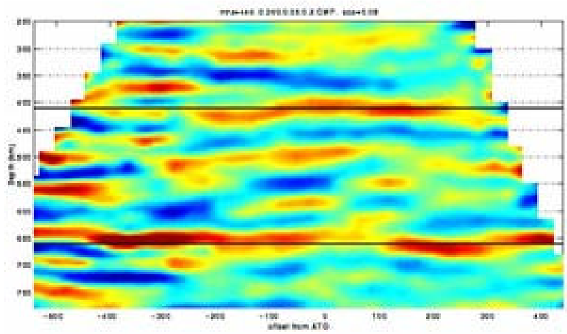
Because they have limited resolution and can distort anomalies in complicated ways, tomographic results often are difficult to interpret. It would be much better if seismic waves sampled precisely a region of interest, and nothing else. Happily, nature occasionally arranges an experiment for us in just this way. For example, the seismic phase *ScS*, a shear wave reflected from the core-mantle boundary (CMB), when observed close to the epicenter of an earthquake, has a nearly vertical ray path through the entire mantle (*Anderson & Kovach*, 1964). Such waves are ideally suited to looking for vertical plumes.

On April 26,1973, a magnitude 6.2 earthquake occurred in Hawaii, and the records from seismometers on Oahu show an usually clear train of multiple-*ScS* phases, reflected repeatedly between the Earth's surface and the CMB [*Best et al.*, 1975]. These waves are sensitive to structure in a vertical cylinder with a diameter of about 500 to 1000 km extending down to the CMB, and they show no indication of a plume. The wave speed V_s in the upper and middle mantle inferred from arrival times is higher than the average for the southwestern Pacific [*Katzman et al.*, 1998 Plate 3(b)], and the propagation efficiency is also high (*i.e.*, the waves are little attenuated) [*Sipkin & Jordan*, 1979]. The location of a possible plume in the lower mantle might be far enough from Hawaii that these *ScS* waves would not sample it, but these observations argue strongly against unusually high temperatures or extensive melting in the upper mantle beneath Hawaii.

Receiver Functions

When a compressional or shear seismic wave strikes a discontinuity in the Earth, it generates reflected and transmitted waves of both types. Because of this, waves from distant earthquakes passing through a layered medium such as the crust or upper mantle generate complicated seismograms containing many echoes. To interpret these records, seismologists process them to generate simplified artificial waveforms, somewhat inscrutably called *receiver functions*. These can be inverted to yield the variation of *Vs* with depth, and they are particularly sensitive to strong wave-speed discontinuities. Receiver functions are particularly powerful for studying the depths to the Moho and the "410-km" and "650-km" discontinuities, which may provide evidence about crustal thickness and temperature at these depths [*Du et al.*, 2002].

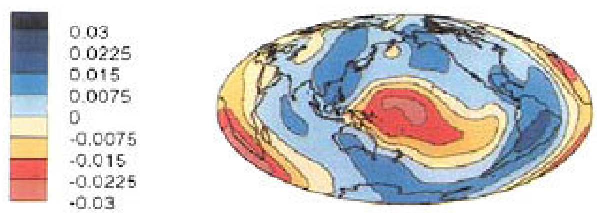
One of the most detailed receiver-function studies done to date took the form of a profile across the eastern Snake River Plain, the suggested track of a mantle plume now beneath Yellowstone, which lies at the northeastern end of the Plain [*Dueker & Sheehan*, 1997]. The results illustrate the complexity of structures revealed by receiver functions, and some of the difficulties of interpreting them. Several "discontinuities" are present, in addition to the major ones near 410 and 650 km. Even these two major features are not continuous, and the 410-km discontinuity appears to split in two near the left end of the profile. The depths to the 410- and 650-km discontinuities are expected to be negatively correlated if their topography results from temperature variations, but actually they are weakly positively correlated. The receiver functions thus provide no evidence of elevated temperatures in this region.



Vertical cross-section showing receiver functions (mapped from the time domain to depth) computed for seismograms recorded on a northwest-southeast profile across the eastern Snake River Plain in southeastern Idaho, near the Yellowstone hot spot. Colors indicate zones of rapid increase (red) and decrease (blue) of with depth. Black horizontal lines: nominal depths of the 410- and 650-km discontinuities. Figure from [the website of Ken Dueker](), University of Wyoming.

The Base of the Mantle

The lowest few hundred kilometers of the Earth's mantle, just above the liquid-iron core, are much more heterogeneous than the 2,000-km thick mantle region above. This basal boundary layer, also known as D'' ("D double primed") was originally detected in studies the travel times of seismic waves from deep earthquakes [*Julian & Sengupta*, 1973] and has subsequently been verified by results from many different kinds of investigations.



Base of the mantle according to the model of Bhattacharyya et al. [1996].

Summary

The main methods for studying Earth structure in a way that is useful in the search for plumes include seismic tomography, studying the transit times and attenuation of individual waves that penetrate the volume of interest, and the use of receiver functions to study topography on the boundaries of the transition zone. Whereas downgoing slabs in subduction zones and their effects on the transition zone have been easy to detect, the same cannot be said about plumes, heads or tails, and promising images often have not proved reproducible by later, more detailed studies. It will be interesting to follow what the next decade brings.

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