Finite frequency tomography reveals a variety of plumes in the mantle.

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Our understanding of the Earth's dynamics relies mainly on the degree of knowledge of the deep Earth structure. Seismic tomography is the only tool available to date able to map the three-dimensional structure of the Earth's interior. It provides a snapshot of the present mantle convection. Even though there is a general agreement on the average, spherically symmetric structure of the Earth, the real fate of sinking plates as well as the origin and geometry of the upwelling regions are still subject of open debate. Hotspots are probably the most intriguing geophysical object. They are approximately fixed with respect to plate motion, providing us with an absolute reference frame. Morgan (1972) proposed that hotspots are due to plume-like upwelling from the lower mantle, but seismic tomography studies have been so far unable to clearly detect such deep plumes.

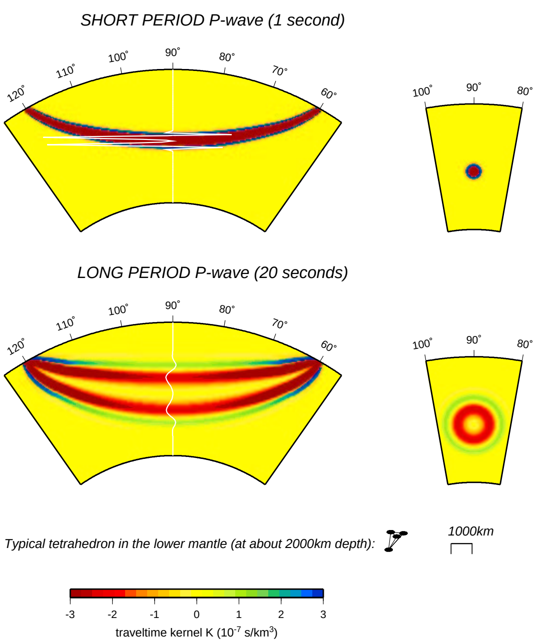

Figure 1: Sensitivity kernels for a direct P wave at an epicentral distance of 60° with two dominant period: 1 s (top), 20 s (bottom). The size of a tetrahedron in the lower mantle is shown for reference below the 20 s kernel.

Our first global finite frequency tomography of compressional waves show distinct conduits rising from the deep mantle (Montelli et al., 2003) What was the problem then with the previous tomographic studies?

Almost all global P-wave tomographic models have been so far obtained by applying the approximation of ray theory. Waves propagate as rays only in the high-frequency limit of the elastodynamics equations of motion. The travel time is only influenced by the Earth's properties along an infinitesimally narrow path that follows Snell's law. This simplifies the mathematics, but it is quite far from the physical reality where rays have a given thickness depending on the frequency content of the propagated wavefield. The traveltime of a finite-frequency wave is sensitive to velocity structure off the geometrical ray within a volume known as the Fresnel zone. Classical ray theory predicts that even a small heterogeneity on the raypath would influence the traveltime. But physics teaches us that small scale objects do not really influence the propagation of waves. They only do when their scale length is comparable to the width of the Fresnel zone. Figure 1 shows the sensitivity region for a P wave at 60° epicentral distance. The top kernel is the sensitivity region of a wave with 1 s dominant period, while the bottom kernel represents the sensitivity of a wave with 20 s dominant period. The sensitivity is significantly different. A broadband P traveltime is sensitive to anomalies in a hollow banana-shaped region surrounding the unperturbed path, with the sensitivity being zero on the ray. Because of the minimax nature, surface reflected PP waves show a much more complicated shape of the sensitivity region, with the *banana-doughnut* shape replaced by a *saddle-shaped* region region upon passage of a caustic. Not surprisingly, the introduction of such complicated sensitivity has consequences for the final tomographic images. A small size heterogeneity would affect the 1 s wave arrival times but would not be seen in the travel time of the broadband P wave (however, it would influence the amplitudes). Mantle plumes are narrow and therefore the most affected by an inappropriate modeling of finite-frequency effects. Because of their size, plume tails could partially be hidden in the region of insensitivity around the unperturbed ray. Wavefront healing, neglected by classical ray theory, but properly accounted for in our finite-frequency modeling enhance the capability to detect such Earth's structures.

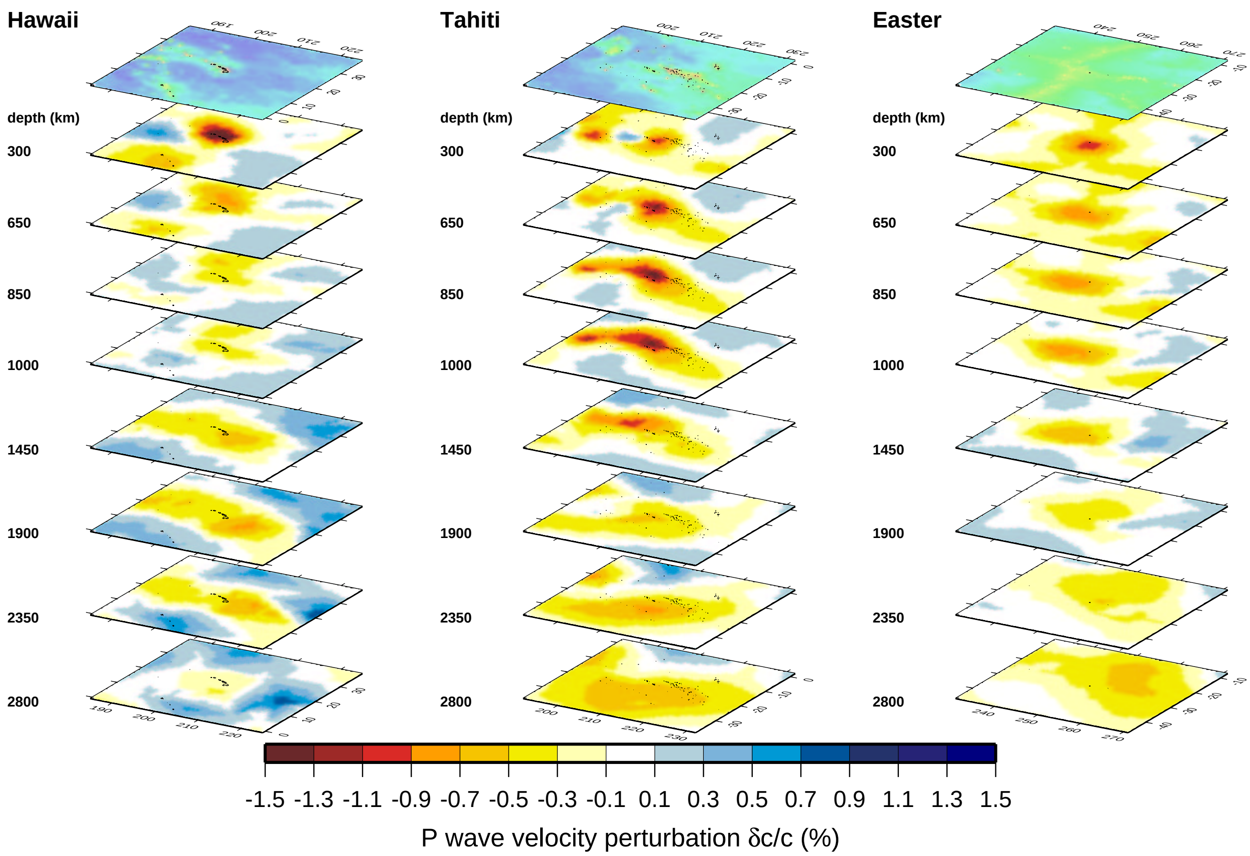

Figure 2. Cross section of the joint inversion (no pP arrivals included here) velocity model as a function of depth at different hotspot locations: from left to right Hawaii, Tahiti, Easter Island.

We present the results of an inversion of finite frequency P, PP and pP waves with a dominant period of 20 s, whose travel time sensitivity kernels are modeled by using the recently developed formalism derived by Dahlen et al. (2000); combined with short period P and pP extracted from the ISC data set (Engdahl et al. 1998) modeled by using standard ray theory. Inverting a combination of low and high frequency waves allows us to properly constrain long wavelength heterogeneity with the kernels, while using the high-frequency data to constrain smaller-scale structure. The velocity structure is sampled using an irregular distribution of points to form a Delaunay mesh (Watson 1981, Watson 1992, Sambridge et al. 1995). Node spacing is adapted to the expected resolving length of our data and ranges from about 200 km in the upper mantle to about 600 km in the lower mantle. This flexibility gives an additional improvement in the tomographic images. As a result our tomographic images provide, for the first time, unambiguous evidence that at least 5 hotspots originate in the deep lower mantle: Hawaii, Easter Island, MacDonald, Samoa, Tahiti (Figure 2) and suggest that few others, such as Kerguelen and Cape Verde might be connected to the core-mantle boundary.

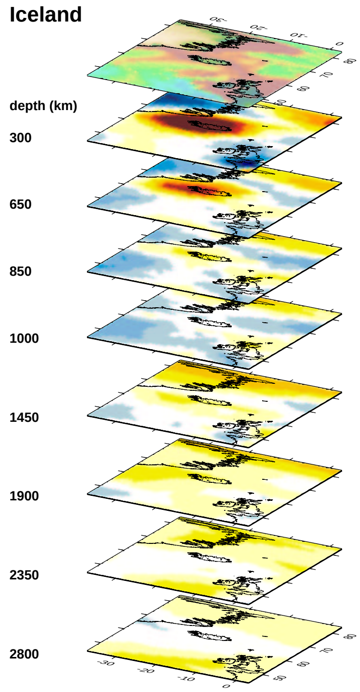

Figure 3: Cross section of the joint inversion velocity model as a function of depth below Iceland.

Major hotspots which do not seems connected to a deep lower mantle plume include Afar, Ascension, Galapagos, Kilimanjaro, Madeira, Reunion, Tristan. These all seem to originate in the mid mantle. Iceland seems of a shallow depth (Figure 3). Indications that Iceland is not a deep-rooted anomaly were already presented by Ritsema et al. (1999) and a shallow origin was argued from indirect evidence by Foulger & Pearson (2001), Foulger et al. (2001) and Foulger (2003). The results of our inversion confirms these observations and clearly contradict the finding of Bijwaard & Spakman (1999), who proposed a plume extending all the way to the core-mantle boundary.

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