Imaging the earth's deep interior using seismic waves in the age of high-performance computing

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Global seismic tomography was first developed in the late 1970's and early 1980's. P wave travel time tomography based on data from ISC bulletins revealed for the first time the unique long wavelength structure in the lowermost mantle (Dziewonski et al., 1977; Clayton and Comer, 1983; Dziewonski, 1984). This structure, correlated with the earth's geoid, consists of two large low velocity regions, located antipodally in equatorial regions under the Pacific Ocean and under Africa, andnow commonly referred to as "large low shear velocity provinces" (LLSVPs). They are surrounded by a ring of fast velocities, which is generally interpreted as the graveyard of tectonic slabs. Concurrently, the first images of upper mantle structure obtained using surface wave data confirmed the main features expected from plate tectonics theory (Woodhouse and Dziewonski, 1984), with lower than average (hotter) shear velocities along the mid-ocean ridge system, increasing with age of the plate, and thick, faster than average (colder) continental roots, as well as evidence for large scale convection below the plates from the first images azimuthal anisotropy (Tanimoto and Anderson, 1984).

Since then, various datasets utilizing teleseismic body wave travel times, normal mode splitting data, surface wave dispersion and/or long period waveforms have led to sharper images, particularly in subduction zones, where different behaviors of slabs have been shown, some ponding in the transition zone, and some penetrating deeper, and ponding around 1000 km depth, as was recently clearly shown (Fukao and Obayashi, 2013). In the lowermost mantle, anticorrelation of tomographically inferred shear wave speed and bulk sound velocity suggests that the LLSVPs are not only hotter but also chemically distinct from the surrounding mantle, which is confirmed by observations of body waveform distorsions indicating sharpness of their borders.

Detecting the narrow plumes expected to arise at boundary layers from simple thermally driven mantle convection, and suggested to be the origin of mid-plate, hotspot volcanism (Tuzo-Wilson, 1963; Morgan, 1971) has been more challenging. While their presence in body wave travel time images has been suggested (Zhao, 2004; Montelli et al., 2005), the existence of these plumes has remained controversial, because of the poor illumination afforded for travel time tomography by the available distribution of earthquake sources and receivers, generally combined with modelling of first arrivals based on ray theory, which "hides" low velocity structures, due to wavefront healing.

With the advent of numerical methods that enable accurate seismic wavefield computations in arbitrary three-dimensional structures at the global scale, it is now possible to apply the tools of waveform tomography to better detect the presence of slow velocity anomalies of limited extent in the earth's mantle. Such methods have first been applied at the continental scale (e.g. Zhu et al., 2012, Rickers et al., 2013), and more recently at the global scale (e.g Lekic and Romanowicz, 2011; French et al., 2013; French and Romanowicz, 2014,2015 ; Bozdag et al., 2017).

Global mantle imaging now reveals better focused, finer scale low shear velocity structure both in the upper and in the lower mantle. In the deep mantle, broad columns of lower than average velocity extend from the core-mantle boundary to ~1000 km depth in the vicinity of those active hotspots that lie above the LLSVPs, while no such structures are present under other hotspots. These columns of diameter larger than 500 km, are wider than expected for classical thermally driven plumes, and likely involve thermo-chemical processes. Their quasi-vertical orientation indicates absence of significant mantle wind in the lower mantle, implying very sluggish motions away from these localized upwellings. In contrast, many of these columns are deflected horizontally when they reach 1000 km depth, where they become thinner and are not as well resolved at present. There is evidence, on the basis of observations beneath Iceland, Hawaii and Samoa, that the roots of these broad plumes contain large (800 - 900 km wide), thin (less than 30 km) ultra low velocity zones (ULVZs), with reductions in shear velocity in excess of 25%. In particular, under Iceland, the mega-ULVZ's shape is axisymmetric, implying a close dynamic relationship with the plume, and likely the presence of partial melt.

In the upper mantle, we observe quasi-periodic, low velocity structures with a wavelength of ~2000 km, elongated horizontally for thousands of kilometers in the direction of absolute plate motion (APM), most prominent in the depth range 200-300 km, but extending from the base of the lithosphere into the transition zone, suggesting the presence of secondary scale convection similar to "Richter rolls" (Richter and Parsons, 1975), possibly interacting with fingering due to injection of low viscosity fluid from mantle plumes.
With further improvements in our ability to more completely exploit information in seismograms, the new type of tomography illustrated here opens the way to exciting new discoveries and better understanding of mantle dynamics.