Project Description

1. Proposal Overview

This two-year proposal seeks funding for seismological imaging of lower mantle heterogeneity beneath the Pacific Ocean, and numerical convection calculations to put the seismic imaging into a dynamically consistent framework; thus the proposed multidisciplinary work combines seismological (PI Garnero) and geodynamics (PI McNamara) analyses. The funding is for a geodynamics graduate student (3 months/year), a postdoctoral researcher (6 months/year) principally focused on seismic imaging, and nominal summer salary for PIs Garnero and McNamara.

Recent seismological work has added great detail to deep mantle structure beneath the Pacific, including large low shear velocity provinces (LLSVPs), ultra-low velocity zones (ULVZs), plume source regions, and sharp margins to the LLSVPs, suggesting that they are compositionally distinct from the surrounding lower mantle. This research is directed at seismic imaging of these topics, and relating them to important dynamical (e.g., plumes, slabs, core-mantle boundary topography) and chemical (LLSVP reservoirs, partial melt) hypotheses. We seek to advance our understanding of the structure and dynamics of LLSVPs in a whole mantle framework.

2. Results From Prior NSF Funding

PIs Garnero and McNamara have carried out several lower mantle research projects under NSF funding, which lay the groundwork for research proposed here. We summarize the most recent past work below.

2.1 PI Garnero: Prior NSF Funding

EAR-0711401: *High Resolution Seismic Experiments Aimed at Mapping Dynamical Processes within Earth's Interior*, 06/01/2007-05/31/2011 ($270,365). This grant covered a wide range of research activities as a "research program" proposal of PI Garnero, with several research foci: (a) upper mantle discontinuities and transition zone structure, and their connection to temperature and chemistry; (b) seismic wave scattering beneath subduction zones; (c) lower mantle discontinuity, heterogeneity, and anisotropy structure, (d) ultra-low velocity zones, and (e) outer core and CMB structure. Two ongoing grants (which will finish or nearly be finished by the time the proposed work initiates) are EAR-0948591: *Collaborative Research: High Resolution Imaging of Deep Mantle Structure and Dynamics Using USArray Data*, 06/01/2010-05/31/2012 ($140,750), and EAR-0944283: *Probing the Earth's Outer Core for a Stratified Layer*, 12/01/2009-11/30/2011 ($184,271). Data and preliminary findings in these have in part made possible work we propose here. Published manuscripts acknowledging grant EAR-07411401 are: Schmerr and Garnero (2007); Kito et al. (2007); Garnero et al. (2007); Lay and Garnero (2007); Semken et al. (2007); Garnero and Thorne (2007); Garnero et al. (2007a, 2007b); Thorne et al. (2007); Hutko et al (2008); Garnero and McNamara (2008); Rost et al. (2008); Kito et al (2008); Mercier et al. (2008); McNamara et al. (2010); Lassak et al. (2010); Mercier et al. (2009); Marquardt et al. (2009); Schmerr et al. (2009); Rost et al. (2010a, 2010b); Courtier et al. (2010); Weber et al. (2011); Garnero et al. (2011); Lay and Garnero (2011).

2.2 PI McNamara: Prior NSF Funding

EAR-0510383: "An Investigation into Thermochemical Piles beneath Africa and the Pacific"; $199,942, 07/15/05-07/15/09. This grant supported former PhD student Abigail Bull's multi-disciplinary collaboration on tomographic filtering of geodynamical models of large-scale thermochemical convection. She performed research investigating the cause of the large, low shear velocity provinces beneath Africa and the Pacific, investigating the hypothetical models of thermochemical piles and isochemical plume clusters (Ritsema et al. 2007; Bull et al. 2009). This grant also partially supported Teresa Lassak's PhD research in which she investigated how isochemical and thermochemical models affect CMB topography in both 2D Cartesian and 3D spherical geometries (Lassak et al. 2007, 2010). This grant supported work by PI McNamara that investigated how subduction history is expected to affect the positions of thermochemical piles (McNamara and Zhong, 2005) and isochemical plume clusters (Garnero and McNamara, 2008). Furthermore, these models have been used in conjunction with seismology efforts to investigate whether predicted thermochemical piles are consistent with seismic observations of "sharp edges" of the large, low-velocity anomaly beneath the Pacific (Ford et al. 2006) and the formation of mantle plumes along the periphery of that anomaly (Garnero et al. 2007ab).

3. Introduction: Deep mantle LLSVP structure and dynamics

It has been long recognized that Earth's deep mantle is heterogeneous at long wavelength [Dziewonski and Woodhouse, 1987; Tanimoto, 1990], with reduced seismic wave speeds beneath hotspots, and elevated wave speeds beneath subduction [Hager et al., 1985; Grand et al., 1997]. This is consistent with the hypothesis of whole mantle convection [Morgan, 1971; Grand et al., 1997; Bunge et al., 1998]. While details differ between P-wave (δV_P) and S-wave (δV_S) velocity perturbations, sometimes significantly [e.g., see Masters et al., 2000], there is consensus that two, nearly antipodal, large low shear velocity provinces (LLSVPs) exist at the base of the mantle – one beneath Africa and the southern Atlantic, and one beneath the Pacific (Fig. 1).

The implied thickness of LLSVPs differs between tomographic models as well as details of their geographic location and strength, but in places, LLSVPs appear to extend above the core-mantle boundary (CMB) some 1000 km or more. For example, for the Pacific LLSVP, see He and Wen [2009]; for the African LLSVP, see Ni et al. [2002]. LLSVP height has been derived by combining travel time analyses with global tomography heterogeneity maps. However, a notable tradeoff exists if ray path coverage is not dense; imaged LLSVP height trades off with LLSVP velocity reduction (the latter is typically assumed). Nonetheless, clear evidence is present for strong LLSVP heterogeneity, and particularly an abrupt transition from the surrounding mantle to LLSVP, from waveform broadening, waveform multi-pathing, and travel time studies, which coincides with the strongest lateral gradients in tomography, and qualitatively with edges of chemically distinct material in convection calculations (Fig. 1).

LLSVPs may be denser than surrounding mantle material (Ishii and Tromp, 2004; Trampert et al, 2004], and hence chemically distinct [Tackley 2000, Garnero and McNamara, 2008]. Surface locations of hot spots and reconstructed locations of origin of large igneous provinces appear to overly the margins of the tomographically- derived LLSVPs [Thorne et al., 2004; Torsvik et al., 2008], further support for chemically-distinct LLSVPs.

Evidence for structural variations within the LLSVP come from both seismology (e.g., mapped heterogeneity, including possible post-perovskite "lenses", Lay et al., 2006). and geodynamics calculations. The latter establishes strong internal thermal heterogeneity [e.g., Garnero et al., 2007a; Tan et al., 2007] as well as the possibility of smaller-scale compositional heterogeneity [e.g., Hernlund and Tackley, 2007; McNamara et al., 2010]. We thus desire to understand internal LLSVP structure in greater detail, as it relates to LLSVP dynamics, and hence deep mantle dynamics and properties as a whole. Furthermore, the distribution and structure of internal LLSVP heterogeneity may relate to the origin of LLSVPs. Two possibilities include (a) accumulation of dense former-MORB material, and (b) accumulated reaction products from the silicate mantle chemically reacting with the fluid, predominantly iron, outer core.

If LLSVPs are compositionally distinct, their morphology depends strongly on density and viscosity relative to the surrounding mantle, combined with the strength of subduction-related downwelling currents [e.g., Deschamps and Tackley, 2008; Garnero and McNamara, 2008]. Fundamentally different dynamical behaviors are possible for the material seismically imaged as LLSVPs, which includes: (a) dense, relatively stable, and long-lived LLSVP compositional reservoirs, with sloped sides leading to peaks or ridges, with plumes forming at topographical high points; versus (b) buoyant, (and hence unstable) LLSVP material that ascends in upward convective flow. Depending on LLSVP properties, entrainment can be tendril-like or a wholesale unstable "blob"-like ascent of the material, the latter commonly referred to as a "superplume" [e.g., Davaille et al., 1999]. These contrasting LLSVP scenarios have far-reaching and profoundly different affects and implications on mantle phenomena (chemistry, dynamics, and seismic structures), as well as the origin of the LLSVP (formed from above, the CMB, or is it primordial?).

CMB topography is one such structure that depends directly on the nature of lowermost mantle thermochemical reservoirs – CMB topography is essentially defined by mantle flow and the heterogeneities entrained and swept around in convection [e.g., Lassak et al, 2007, 2010]. Recent calculations show that a dense, stable LLSVP has a topographically upwarped CMB "ridge" along the LLSVP margin, from the upward mantle flow against the LLSVP sides. (i.e., the subduction related flow that shapes the LLSVP material turns upward at LLSVP boundaries, as upward convective return flow). Fig. 2 shows one such model. This is very different from CMB topography expected from a mantle lacking lowermost mantle dense and stable reservoirs, or from that expected for unstable reservoirs (superplumes), which should have CMB upwarping in the center of the return-flow regime.

A number of critical questions should be targeted by a joint seismic-geodynamic study, i.e., questions where seismic analyses may provide models that bear upon convective styles of compositionally distinct material:

I. What is the morphology of LLSVP sides and top and how does it relate to mantle upwelling that includes plumes?
II. What is the internal structure of LLSVPs, especially for different LLSVP origins (e.g., former MORB versus CMB reaction products)?
III. Where are ULVZs in relationship to LLSVP margins, and what is their structure?

IV. What is the nature of CMB topography in and around LLSVPs, and how does it relate to ULVZs?

In the next section we propose a number of seismic analyses that will help to resolve structure that depends on these phenomena, especially if done in conjunction with geodynamical calculations that define viable dynamical motions to explain observations. We are first and foremost focused on pursuing questions relating to LLSVP material stability and longevity.

4. High resolution seismic analyses

The combination of freely and abundantly available high-quality broadband data (e.g., EarthScope USArray's Transportable Array, regional networks in California, Canada, and portable deployments throughout North America) with numerous deep focus earthquakes in the southwest Pacific (e.g., Fiji-Tonga, Vanuatu, etc.) makes the lower mantle beneath the central Pacific unique: nowhere on Earth is the deep mantle so densely sampled by modern high quality data. Here we describe the significant data set collected thus far, our initial analyses with it, data to be added, and proposed seismic analyses to be conducted.

As part of research conducted under our recent past NSF awards, we have collected large high quality data sets of the waves SKS, SKKS, S, S_{diff}, and ScS (see Fig. 3). We have developed a number of algorithms to collect and process the data, which will be used in the proposed work. These include:

Initial collection and processing. Collect any and all globally available broadband seismic data for any deep focus earthquake (deep events are preferred, to minimize contamination from surface reflected depth phases). Data are instrument-deconvolved and rotated to the great circle reference frame of radial, tangential, and vertical components of ground motion.

Empirical source construction for seismic phases of interest. A phase of interest is auto-aligned in time according to a reference model prediction, and summed. The sum ("stack") is then cross-correlated with every individual SKS to re-align, and re-stack. Cross-correlation coefficients are used as weighting factors in an iteratively updated stack, and the stack is referred to as the 'empirical source' for that phase.

Documenting travel times and waveform abnormalities. The above step produces travel time perturbations of all data. A further characteristic is defined from (a) cross-correlating and differencing individual waveforms from the stack to produce "residual" traces, then (b) computing a ratio of the envelope of each residual trace to the envelope of the empirical stack trace. This ratio is defined as the waveform "misfit", thus identifying anomalously broadened waves automatically.

Construction of graphical catalogs for human double-checking. All data are plotted with computed time delays, cross-correlation coefficients, misfit estimation, with the empirical source overlaid at the best-fit time, along with estimates of signal to noise ratios. These catalogs are visually inspected to identify any possible problems (which arises for some records with excessively high noise), and such data are discarded.

Figure 1. (a) Tomography map of the lowest 200 km of the mantle (Grand, 2002) showing high (blue) and low (red) velocities, and hotspots (yellow circles) sized for plume flux (Sleep, 1990). The two large red regions are LLSVPs. Black line indicates cross-section region of Figure 4b. (b) Lateral shear velocity gradients of the tomography model in (a), with strongest gradients in red, which are located at the LLSVP margins. The strong gradient locations coincide with locations where high resolution studies image sharp boundaries to the LLSVP, indicated by solid thick black lines [from studies: Breger & Romanowicz, 1998; Luo et al., 2001; Ni et al., 2002; Ni and Helmberger, 2003abc; Wang and Wen, 2004; Ni et al., 2005; To et al., 2005; Ford et al., 2006; He et al., 2006; Sun et al., 2007; Sun X, et al., 2007; He and Wen, 2009; Sun et al., 2009]. Hotspot locations from (a) are also shown as small black crosses. (c) Temperature field from the thermochemical convection calculation of Garnero and McNamara [2008], which shows the hottest mantle temperatures are at the margins of the dense, chemically distinct reservoirs, and resemble strong gradient locations in (b) Seismic LLSVP "edge" study lines from (b) are duplicated here.

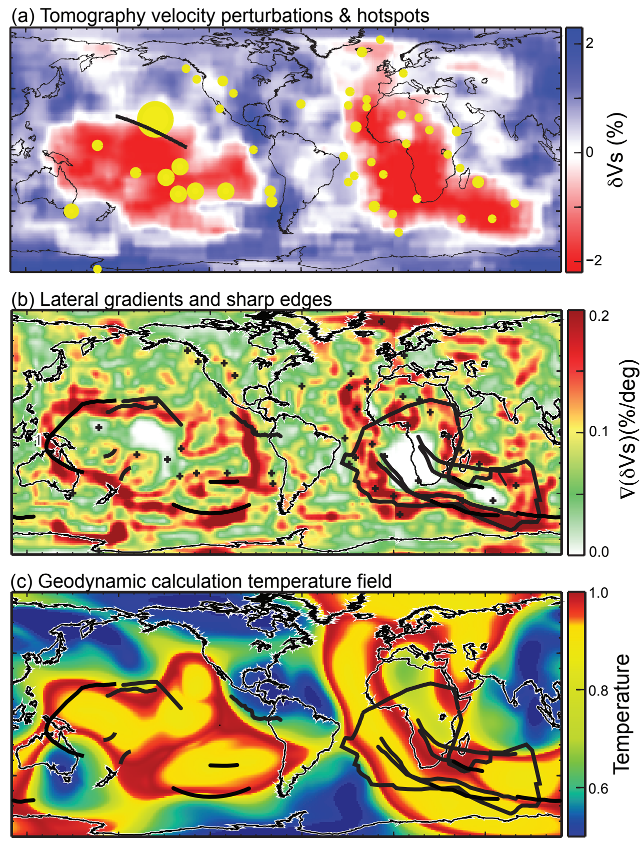
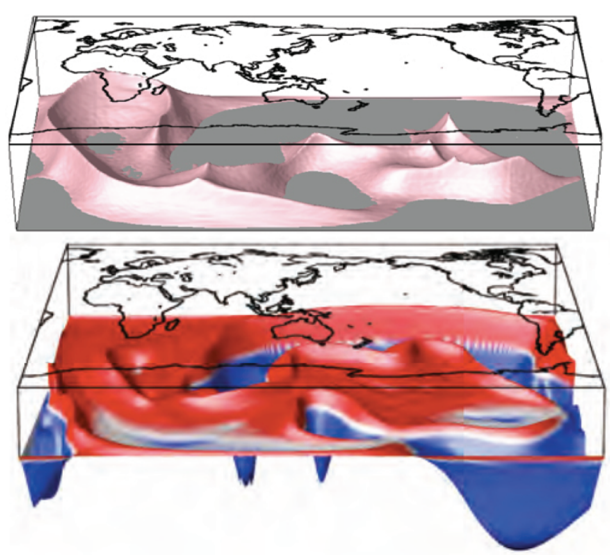


Figure 2. Results of a 3D, spherical thermochemical convection calculation that employs Earth's subduction history to guide downwelling locations [Lassak et al., 2010]. (a) Compositional field showing the presence of compositional reservoirs (i.e., thermochemical piles) (pink). The reservoirs are ridges of intrinsically more-dense material that are swept toward mantle upwelling regions beneath Africa and the Pacific. Each of the two resultant structures is a superposition of ridges. Plumes originate at cusps that form along the top of the reservoirs. (b) Predicted CMB topography caused by convection associated with the reservoirs of part (a). Beneath reservoirs, CMB topography is generally upward (red), with a narrow ridge of accentuated topography along the reservoir margins. CMB topography is downward (blue) in downwelling regions.



Sections 4.1 to 4.4 introduce seismic targets that we propose to pursue with the above methodologies as the initial step. Section 4.5 describes important next steps beyond the work we introduce here, in a synthesis framework.

4.1 Sharp LLSVP margins

Using 1000's of lower mantle bottoming S-waves, we find strong variability in waveform broadening for any given earthquake, for Fiji-Tonga earthquakes recorded in North America, as indicated by our misfit measurement (described above). When inspected geographically, broadened waveforms correspond to locations that are near the LLSVP edge (as defined by tomography), and extend up into the lower mantle, in a near triangular shape (Fig. 4). This is consistent with geodynamic predictions for a dense, stable compositional reservoir (i.e., thermochemical pile) (Fig. 4b), and combined with results from other studies suggests this may be the location of the root of the Hawaiian plume (Fig. 5). We also note the anomalous waveform broadening within the LLSVP, closer to the CMB.

4.2 LLSVP isotropic heterogeneity

A number of seismic waves traverse the general region depicted in Fig. 5, most notably, SKS, S, and ScS. Using our algorithm that documents travel time perturbations, we employ a forward iterative approach to assign velocity perturbations along ray paths, with a scheme that averages δV_S variations in volumetric cells. This approach was chosen, rather than a formal inversion, owing to the expected uncertainties and smearing, since our current data set has little crossing path coverage. Even with some along path smearing, the different wave types identify strong heterogeneity (Fig. 6), implying significant internal LLSVP variations.

4.3 ULVZ structure

We have developed an ScS wave stripping algorithm, whereby the core-reflected ScS is removed from seismograms to identify neighboring, faint, more subtle reflections and reverberations associated with ULVZs. This method exploits the fact that a flat ULVZ produces two primary arrivals around the core-reflected ScS: a precursor (that reflects off the top of the ULVZ), and a post-cursor (that is a multiple reflection/reverberation inside the ULVZ). These arrivals are opposite polarity and nearly identical in their time interval in front of or behind ScS – thus the trace can be (a) split into two separate traces at the ScS peak, (b) the half leading up to ScS flipped in polarity, (c) the flipped half is reversed in time, and finally, (d) summed to make a residual trace that constructively sums the precursor and post-cursor, while eliminating ScS (see Fig. 7). We have demonstrated the method with synthetic seismograms, and results from our initial data set show the presence of a ULVZ within the margin of the Pacific LLSVP (Fig 7). Data are first source-deconvolved, to remove any possible source effects.

4.4 Effects of CMB topography

A large data set of SKKS waves was constructed as part of a funded effort to study outermost core fine layering. Analyses of SKKS waveforms at epicentral distances where SKKS is first initiating (roughly 88 to 95 deg) show geographic systematics to SKKS waveform abnormalities. SKS at this distance is unaffected by other phases (such as SP_dKS), and hence can be used as a reference if SKKS is transformed (by

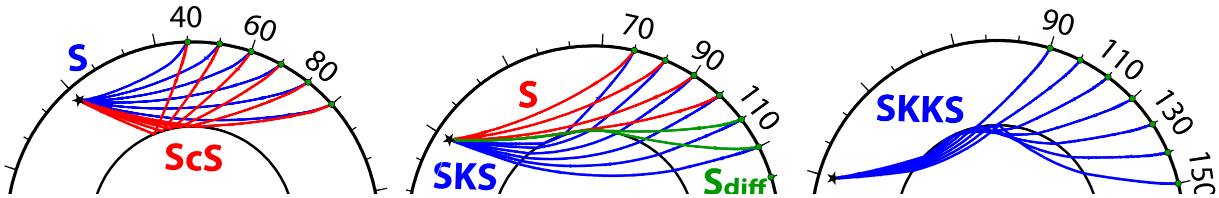


Figure 3. Cross-sections showing geometric systematics of seismic ray paths in the Earth: (left) S and ScS; (middle) SKS, S, and Sdiff; and (right) SKKS. Numbers are epicentral distance ranges. Many southwest Pacific earthquakes recorded in North America span a distance range that includes all of the above seismic phases (e.g., from 75-115 deg), which samples the Pacific LLSVP with unprecedented ray density. SKS and SKKS are on studied on the SV component of motion, ScS, S, and Sdiff are studied on the SH component.

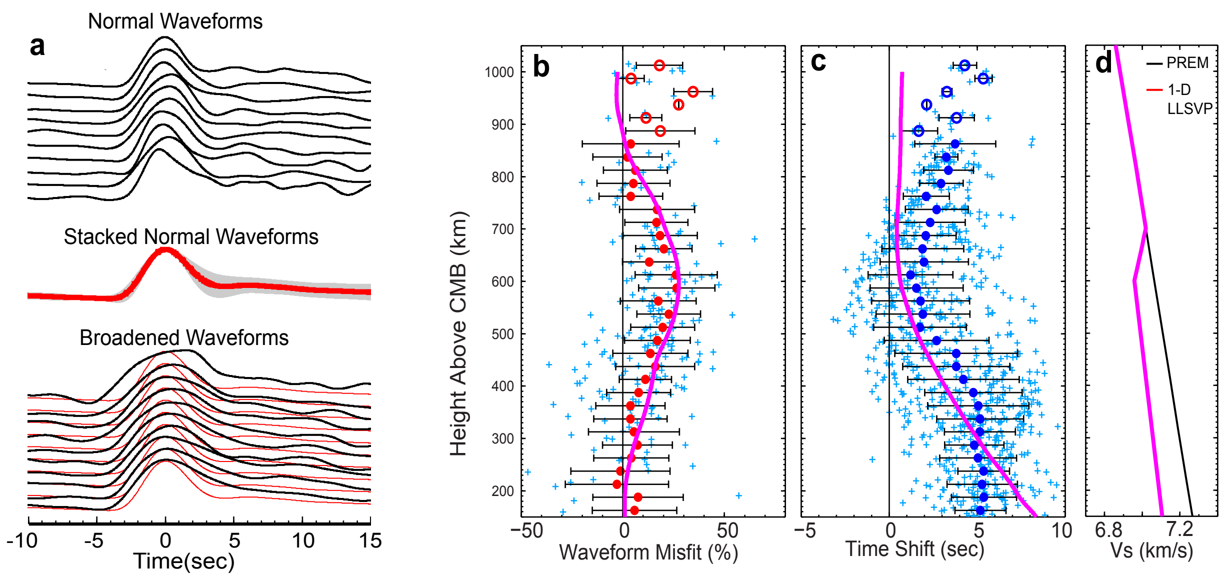
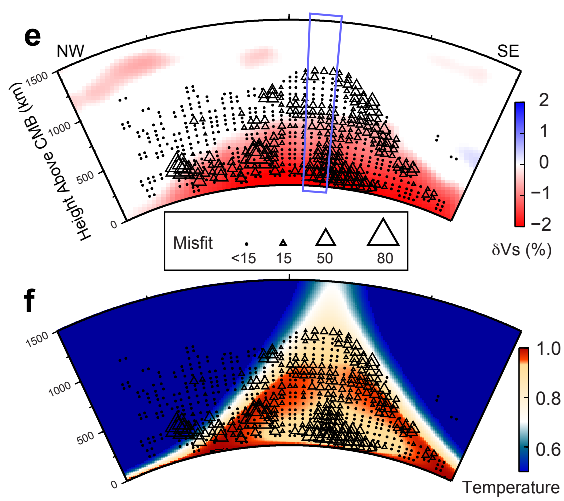


Figure 4. Waveform misfits. (a) A sample of "normal" S waves are shown for a Fiji earthquake, along with a stack of all normal data for that event (red trace), and compared to broadened records (below) for the same event. Clear evidence for broadened waveforms is present. (b) Misfit (measure of broadening) shown (blue crosses) at S wave bottoming depths, along with averages (red circles) in 25 km depth bins. (c) Travel times of same S waves, plotted the same way. Open circles in b and c have fewer than 5 data in that depth bin. (d) a 1-D LLSVP model that well predicts the depth behavior of the misfits and times (magenta curves in b and c. (e) Cross-section (corresponding to black line in Fig 1a) with misfits plotted where S-waves bottom and pierce the cross-section, displayed with dVs tomography of Grand [2002]. Blue rectangle indicates region for data shown in panels b and c. (f) Same as (e), but misfits are plotted on the temperature field from a thermochemical dense reservoir. Waveform broadening locations appear consistent with the dense stable pile hypothesis.



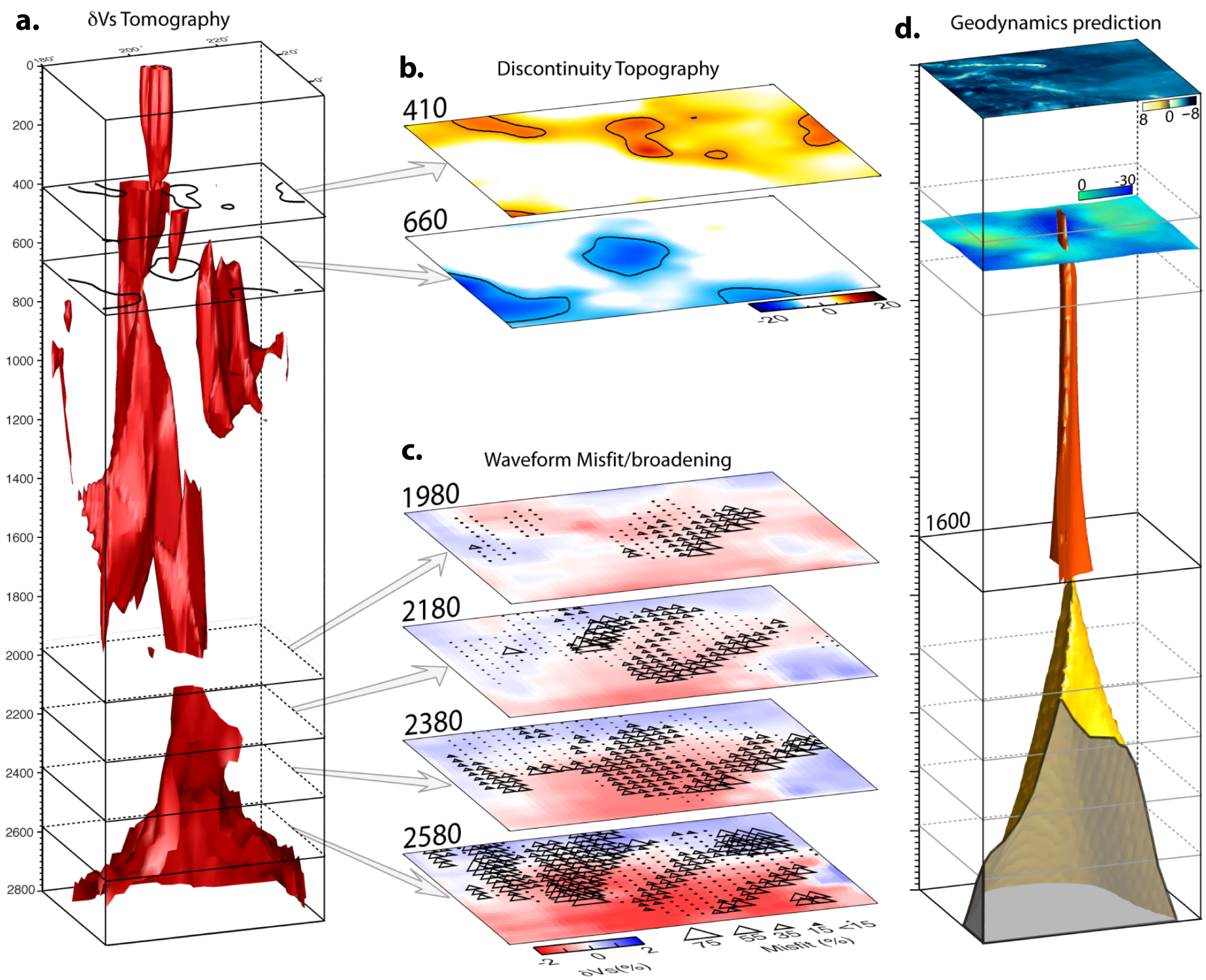
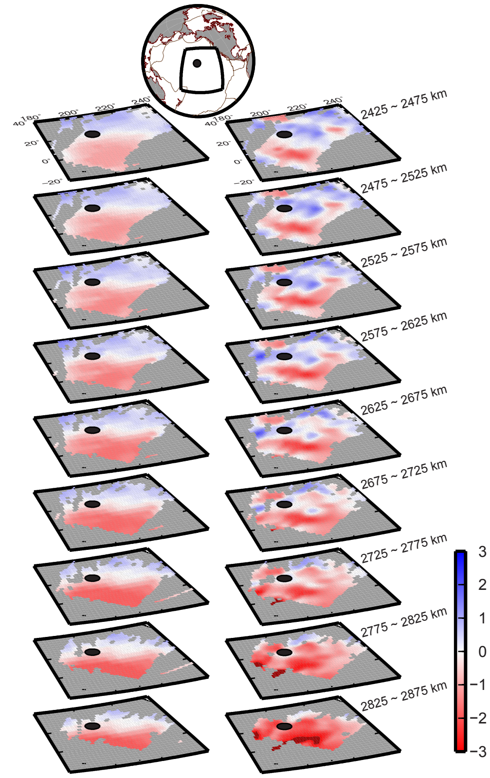


Figure 5. Seismic and geodyanmic results for the region beneath Hawaii. (a) a volume rendering of the mantle from the surface down to 2800 km depth, centered on Hawaii, featuring results of 3 different Vs tomography studies: between 0-400 km depth, the result is of Wolfe et al. [2009]; between 400 and 2000 km depth, the model is from Montelli et al., [2004]; below 2000 km depth, the model is from Grand [2002]. Shear velocity reductions are isocontoured, and highlights the evidence for CMB to surface velocity reductions, with appearance of a plume-like nature. (b) The topography on the 410 and 660 km discontinuities is shown [Schmerr et al., 2010], indicating a depressed 410 and elevated 660 in the vicinity of the proposed plume, consistent with a vertically continuous conduit of elevated temperature. The outlines of the strongest topography is shown as black lines, which are also included in panel a. (c) Waveform broadening measurements of Figure 2 (triangles) are plotted on top of tomographically derived shear velocity reductions [Grand, 2002] in 4 horizontal depth slices. The strongest misfit appears consistent with waveform broadening, and hence multipathing, on the sides of an elevated portion of a chemically distinct LLSVP. (d) At the base of the mantle, a portion of a compositionally-distinct, intrinsically more-dense reservoir is shown (yellow, outlining the dense material) from one of our geodynamical calculations. Above this, a hot thermal plume rises vertically from a cusp (red vertical condiut, an isocontour of the temperature field). The thinned mantle transition zone (defined by taking the difference of the maps in panel b) is also displayed, with the bluest colors corresponding to the most thinned region, consistent with a hot plume. These finding taken in concert suggest Hawaii is a vertical plume forming off a cusp of a compositional reservoir, in this case located near the northeast margin of the Pacific LLSVP.

Figure 6. Using 1000's of high quality S-SKS and ScS-S differential traveltimes, an iterative forward mapping algorithm was developed an employed, whereby travel time residuals were mapped to the ray paths of the waves in the lowermost 600 km of the mantle (after first adjusting the observed residuals by predictions from tomography outside our volume of interest). The small globe presents our study region of focus, which is shown below in map-view depth sections for two different models. The left column is that of Grand [2002], the right column is the result of our analysis. Cross-correlation coefficients between individual wave-forms and empirical source wave-shapes were used as weights in a process that averages velocity perturbations derived from travel time residuals in each cell in our volume. The black circle denotes Hawaii's surface location. We note several key points: (1) we find evidence for much stronger velocity reductions within the LLVZP, as well as velocity elevations outside the LLSVP; (2) LLSVPs appear to have significant internal variations; and (3) the transition from the lowered velocities within the LLSVP to the surrounding mantle appear relatively sharp. The core-reflected ScS data help to resolve the smaller-scale dVs perturbations. Gray regions denote areas lacking ample ray path coverage. Darkest reds correspond to dVs<-3%.



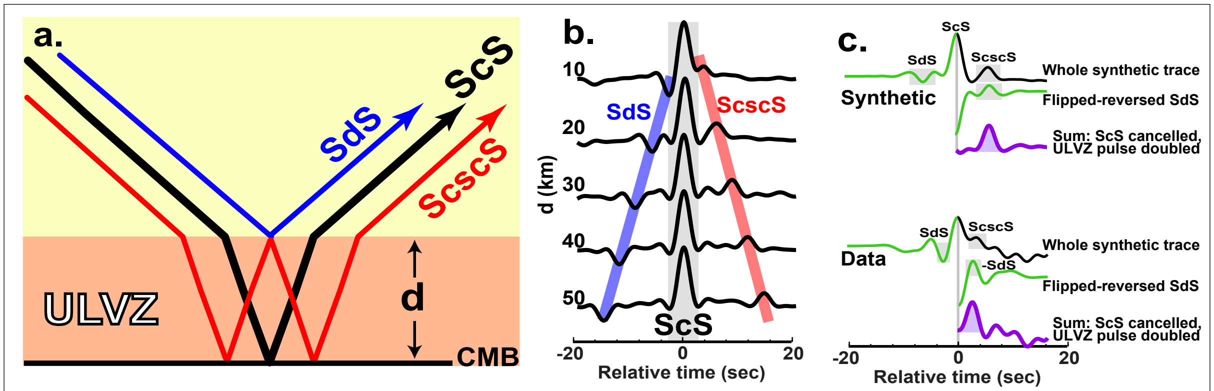
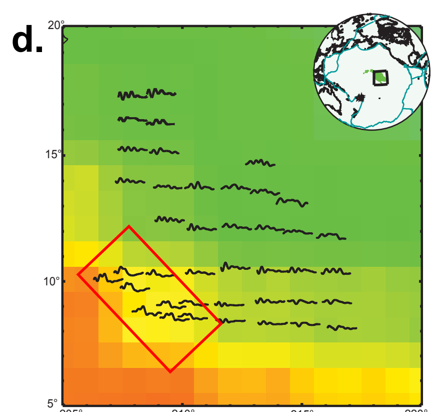


Figure 7. (a) Schematic showing the pre- (blue) and post-cursor (red) to ScS (black), due to a locally flat ULVZ. (b) These additional arrivals, SdS and ScscS are opposite polarity, and equal in time away from ScS. They are shown for different ULVZ thicknesses: thicker ULVZs result in larger time separations relative to ScS. (c) Synthetics, and data show that the ScS can effectively be stripped from traces, while the ULVZ arrivals can be enhanced, by taking the part of the trace in front of ScS (green trace), flipping its polarity, reversing its time, then summing with the part of trace following ScS (black trace), to yield a trace with the ULVZ signal boosted (purple trace). (d) in local bins with stacks of 20 or more such flip-reversed-summed traces, evidence for ULVZ presence is highlighted in beneath the Pacific near the edge of the LLSVP beneath Hawaii, as seen by traces with positive amplitude in the front part of stacks in the southwestern region of our study area (see traces in the rectangle).



$3\pi/2$) to SKS's phase. SKKS wave-shape irregularities include: complete absence of SKKS (not predicted to be due to low SV radiation pattern), SKKS appearing out of phase from its expected $\pi/2$ phase shift from SKS, and SKKS looking complex, with additional waveform structure. Fig. 8 displays examples, and maps the region of the complexities. A remarkable geographic correlation is present between the region of SKKS underside CMB bounce locations for complex SKKS data and imaged ULVZ location from our ScS topside CMB modeling, suggesting a relationship between the two. Indeed, viscous coupling from upward flow is predicted to upwarp the CMB and focus a ULVZ there [e.g., Lassak et al., 2010; McNamara et al., 2010]. Our initial modeling experiments included a cross-section through the CMB topography model of Lassak et al. [2010] (using a 2.5D axis-symmetric P-SV code of M. Thorne, as with the SH code in Thorne et al., 2007).

4.5 Next steps and structural synthesis

The above subsections present several important structural features of the deep mantle. For each, we will add data to the current data sets to (a) push our resolution to shorter scales from increased data density, and (b) expand our modeling results to a broader region of the Pacific using other event-receiver geometries utilizing the abundant and available circum-Pacific data. Where possible, data will be compared to predictions of synthetic seismograms to guide our interpretations. We have 1-D waveform synthesis methods, as well as 2.5-D axi-symmetric codes from active collaborator Michael Thorne. We propose to pursue each analysis using the information and results of the other analyses. It is a primary structural target to better understand the relationship between ULVZ location, CMB topography, LLSVP internal heterogeneity, and LLSVP margin (or "edge") slope and structure. As we emphasize in the next section, these relationships hinge critically upon the nature (chemically distinct and/or dense?), origin (primordial vs. created from above or below?), and convective style (stable or transient?) of LLSVPs.

5. Integration with Geodynamical Modeling

We will perform numerical, geodynamical calculations to (a) construct dynamically-consistent hypothesis tests for conceptual mantle models that can be tested by seismological observations, and (b) provide guidance to the seismic modeling (i.e., what should seismology look for and where). The dynamical modeling will allow us to develop a stronger understanding of lower mantle dynamical processes.

Currently, several conceptual, dynamical models exist for the cause of the LLSVPs [e.g., Christensen and Hofmann, 1994; Tackley, 2002; Davaille, 1999; Kellogg et al., 1999; Jellinek and Manga, 2004; McNamara and Zhong, 2005; Tan and Gurnis, 2007; Garnero and McNamara, 2008]. Although isochemical models cannot be excluded [e.g., Schubert et al., 2004; Bull et al., 2009; Schuberth et al., 2009], most models include a combination of thermal and compositional heterogeneity (i.e., thermochemical), with end-members ranging from long-lived, stable compositional reservoirs (i.e., thermochemical piles) to geologically shorter-lived, unstable thermochemical superplume structures. It is important to distinguish between these conceptual models because they form the foundation for our understanding of heat transport, chemical evolution, and mantle driving forces. For example, unstable superplumes provide driving forces for large-scale mantle convection while stable reservoirs are more-passively swept toward upwelling centers by downwelling slabs.

Past and current geodynamics work has shown that long-lived, stable compositional reservoirs are expected to have the following characteristics, which we propose to examine both geodynamically and seismically, as hypothesis tests for their existence and possible cause of LLSVPs:

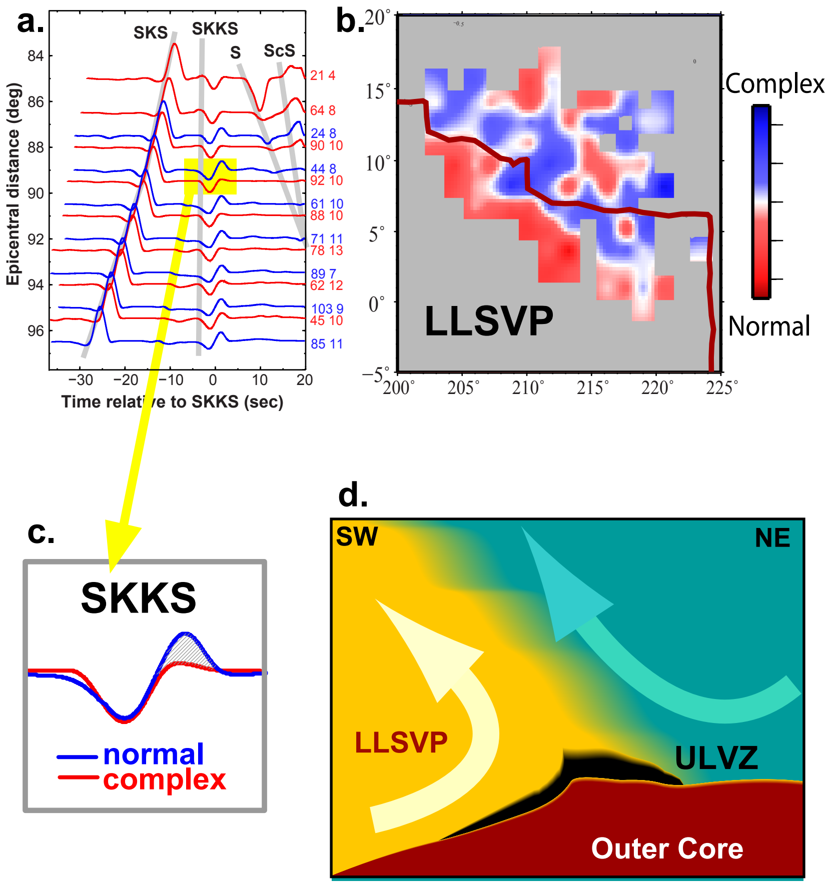
- *sharp compositional edges*
- *an overall morphology consisting of interconnected ridges that overlap within mantle upwelling regions*
- *thermal plumes originating from elevated cusps on the top of ridge-shaped reservoirs*
- *a narrow ridge of upwarped CMB topography along reservoir margins*
- *accumulation of ULVZ material along reservoir margins*
- *entrainment of subducted, oceanic crust into reservoirs through their top surface*
- *plating of subducted, oceanic crust along subduction-facing sides of a reservoir*

The latter two were discovered in preliminary work for this proposal (Fig. 9)._We propose work along the following topics that examines the hypothesis that long-lived, stable compositional reservoirs are the cause of the LLSVPs beneath Africa and the Pacific.

5.1 Reservoir Morphology

Previous work has shown that compositional reservoirs are expected to form a morphology that consists of a network of interconnected ridges. Where compositional ridges intersect, cusps form along their top where thermal plumes originate [e.g., Jellinek and Manga, 2002, 2004; Tackley, 2002; McNamara and Zhong, 2004; Deschamps and Tackley, 2008]. In a generic fluid dynamical system, these ridges are ubiquitous along the base of the system and are relatively evenly spaced apart. However, in the Earth, where downwellings are heterogeneously-spaced, the ridges are swept toward large-scale upwelling regions formed beneath Africa and the Pacific, resulting in overall structures that consist of a superposition of compositional ridges (Fig. 2a) [e.g., McNamara and Zhong, 2005; Bull et al., 2010; Lassak et al., 2010, Tan et al., 2011]. The reservoirs are predicted to have sharply-defined compositional boundaries, and seismic detection of the elastic contrasts associated with the proposed edges of these structures is a powerful method to map compositional heterogeneity in Earth's lowermost mantle [e.g., Ni et al., 2002; To et al., 2005; Ford et al., 2006; Wang and Wen, 2007; He and Wen, 2009; Zhao et al., in prep]. We will perform a geodynamical study in 3D spherical geometry to investigate the relationship between ridge spacing, slope of edges, and height of reservoirs as a function of reservoir volume, reservoir density, and lower mantle viscosity, within the range of material parameter uncertainty associated with the Earth. In particular, we are interested in investigating the spatial and temporal variability in the slope of reservoir edges and height of plume-forming cusps. An understanding of the variability associated with reservoir edge slopes will guide our seismic investigation of mapping out the shape of the Pacific LLSVP. *For example, if a superposition of compositional ridges are forming the Pacific LLSVP, do*

Figure 8. The phase SKKS is sensitive to outermost core structure. However, complexities in the SKKS shape near its inception distance (85-90 deg, panel a & c) are clustered geographically near the SKKS underside CMB bounce location (panel b): the blue regions are bounce points of complex waveforms, which roughly coincide with the LLSVP boundary (of Grand, 2002, as in Fig 1, thick line). The complex waveforms (red traces in panels a and c) lack the characteristic 2nd upswing of the Hilbert transformed SKKS seen in the normal traces (blue lines). The numbers on the right in panel a represent the number of records and events used to make the stacks shown in the panel (data were source-deconvolved first). Normal SKKS waveshapes are towards the SW. The complex zones coincide with the ScS-derived ULVZ region of Fig 7. Panel d presents the possibility of a ULVZ and upwarped CMB coinciding with the edge of a chemically distinct LLSVP.



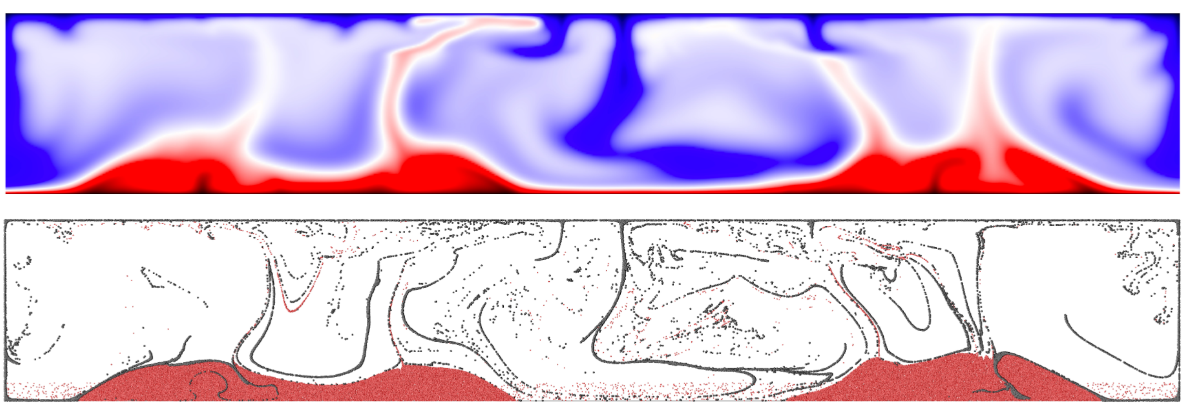


Figure 9. Hypothetical whole-mantle model containing a 3-component system (background mantle, long-lived compositional reservoirs, and subducted oceanic crust). LLSVPs are hypothesized to be caused by the compositional reservoirs. Top panel shows the temperature field, with redder and bluer colors representing hotter and colder material, respectively. Bottom panel shows tracers representing the compositional field. Subducted oceanic crust is gray, compositional reservoirs are red, and background mantle is white. Notice that plumes form at the cusps of the reservoirs, in regions where 2-way entrainment occurs; subducted crust is entrained into both the reservoir and thermal plumes, and reservoir material is entrained into the plumes.

we expect the different margins of this overall structure to have similar slopes? If not, what is the range of variability expected? Furthermore, we will examine whether the following hypothesis is dynamically feasible*: is the height of a cusp (where plumes form at the intersection of ridges) related to the buoyancy flux of the plume associated with it?* If we find that this hypothesis test is dynamically feasible, we can use our Hawaiian results [Zhao et al., in prep] as a benchmark to examine the top boundaries of other regions of the Pacific LLSVP that underlie hotspots. We can then propose and seismically examine the following hypothesis-test: *If the Pacific LLSVP is formed by a long-lived, stable compositional reservoir, then its highest extent should exist beneath Hawaii (because its plume has the highest buoyancy flux)*.

5.2 Core-Mantle Boundary Region along Reservoir Margins

Our previous work has shown that viscous coupling is expected to produce a narrow rim of positive CMB topography (toward the surface) along the margin of a stable, compositional reservoir [e.g., Lassak et al., 2007, 2010] (Fig. 2b). However, the lateral length-scale of the expected topography is much smaller than previous seismic studies have examined. Furthermore, we have found that dense ULVZ material is expected to accumulate along the margin of stable reservoirs [e.g., Hernlund and Tackley, 2007; McNamara et al., 2010]. Combining these results, we expect a scenario similar that shown in Fig. 8d in which the margins of stable reservoirs experience a combination of upwarped CMB topography and accumulations of ULVZ. However, it is unclear how the interaction of these processes will affect the shape of ULVZ and the wavelength and magnitude of the CMB topography. PI McNamara is currently funded by another proposal to examine this particular dynamical interaction, and we will utilize the results from that study to provide guidance to the seismological work of mapping CMB topography along LLSVP margins, proposed in section 4.4. Important questions that we will address include: *What controls the lateral length-scale of expected CMB topography? How does the presence of ULVZ modify this? Can we detect small-scale CMB topography along LLSVP margins?* Detection of elevated topography along the LLSVP margin would provide powerful evidence supporting the existence of a stable, compositional reservoir.

5.3 Entrainment of Subducted Oceanic Crust in LLSVP Region

Preliminary work for this proposal [Li et al., in prep] investigates the interaction of subducted oceanic crust with a stable, long-lived compositional reservoir (Fig. 9). We find that subducted oceanic crust is expected to descend to the CMB region before getting swept into lateral flow toward the reservoir. Some of the crust slides up along the reservoir edge and ultimately gets entrained into the reservoir through the top cusp. This entrainment could be a source of inter-LLSVP heterogeneity, inferred in seismic studies [Lay et al., 2006]. We will perform high-resolution 2D, multi-component geodynamical calculations to investigate the following questions: *What is the ultimate fate of entrained crust within the reservoir; does it completely mix or does it segregate within the reservoir, forming a multi-layered reservoir? What material parameters control this behavior? How does the entrainment affect the longevity and/or the time-dependent properties of the reservoir?* Because the Pacific is surrounded by subduction, it is critical to understand all of the possible dynamical implications of this entrainment. We will then apply our understanding to seismic interpretation of inter-LLSVP heterogeneity. We will perform forward seismic modeling for the different modeling cases to understand how entrained crust is expected to appear seismically, within the LLSVP. Furthermore, we will investigate how the plating of crust along some reservoir margins is expected to produce a unique signature of waveform broadening (as opposed to margins not plated by crust). We will examine whether it is seismically feasible to trace inter-LLSVP heterogeneity to the top of the reservoir in order to locate the top cusp, where entrainment occurs (and where a plume is expected to be rooted).

6. Work Plan

This joint seismological and geodynamical research project focuses on LLSVPs and associated structures. The ASU PI team (Garnero, McNamara) and their students regularly interact via classes, weekly group meetings, and seminar series, which includes regular interaction with scientists from broad spectrum of disciplines (petrology, geochemistry, mineral physics, planetary science). Thus work proposed here will benefit from this tight knit (and growing) program of interested and engaged researchers (students, postdocs, faculty). Here we delineate the team to carry out research, break down specific activities in a time line, and our proposed management/mentoring structure

6.1 Research team and management structure

The proposal seeks funding for a ½-time seismology postdoctoral researcher, partial support for a geodynamics graduate student (3 months/year), and nominal summer salary for PI Garnero. The research team is entirely at ASU, and listed below with expected activities. We note that the PI team has several years of experience of cross-disciplinary co-mentoring of PhD students at ASU.

Name	*Status*	*Supervisor*	*Discipline/Activities*
Chunpeng Zhao	Postdoc	PI Garnero, w/ interaction w/ geodynamics team	Seismology. Collect and process data, construct synthetic seismograms to compare to data. Build models informed by geodynamics simulations.
Mingming Li	Phd Student	PI McNamara, w/ interaction w/ seismology team.	Geodynamics. Perform high resolution, multi-component calculations to examine crustal entrainment into compositional reservoirs. Summarize findings of past and ongoing simulations of the ASU group, and work closely with the seismologists to build dynamical framework models that are consistent with seismic models
Ed Garnero	PI, faculty	-	Seismology. Directly mentor postdoc, and co-mentor PhD student.
Allen McNamara	Co-PI, faculty	-	Geodynamics. Directly mentor PhD student, and co- mentor postdoc.

As the above table indicates, PI Garnero will principally supervise seismological activities, and PI McNamara will principally supervise geodynamic activities. But each PI will be actively involved co-mentoring, as this has been emphasized in their involvement with past students. It is noteworthy to mention that ASU's School of Earth and Space Exploration will have faculty moving into a brand new building on campus, and geophysics faculty (Garnero, McNamara, Dan Shim, and a to-be-hired seismologist) will be housed next door to each other. Thus multi-disciplinary student and postdoc mentoring will be further facilitated.

6.2 Work plan calendar

The first 6 months of the proposed work will heavily focus on continued seismic data collection and processing. This stage of the work will involve identifying new source-receiver geometries that permit expansion of the focused study regions presented in this proposal. Synthetic seismogram modeling and geodynamic predictions will be an area of central focus following this initial time period, and continue throughout the remaining proposed time period. Data collection will continue as relevant earthquakes occur. We anticipate a minimum of two publications first-authored by the post-doctoral researcher, and one by the graduate student.

7. Broader Impacts

The proposed research will provide advanced seismological training for post-doctoral researcher, Chunpeng Zhao, and will be a component of Mingming Li's PhD dissertation research. There will be a significant amount of cross-training between the post doc and PhD student as they work together to integrate the seismological and geodynamical components of this research. The student will learn the fundamentals of 2D and 3D geodynamical modeling, parallel processing, and 3D visualization. Results from this research are aimed toward providing the geophysical community with valuable information on linking seismological observations to large, mantle-scale dynamics. PIs Garnero and McNamara typically share research images, movies, data, etc., online for use by the wider geophysical research and teaching community.