Improving constraints on multi-scale heterogeneity in the upper mantle

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Globally-averaged amplitudes of scattered coda waves suggest strong and pervasive heterogeneity throughout the uppermost mantle at lateral scale-lengths ranging from a few to thousands of km. The precise depth extent and root-mean-square velocity perturbation of this heterogeneous zone is poorly constrained owing to the linear tradeoff between these two quantities. Nonetheless, evidence from PKP precursors implies that small- and intermediate-scale heterogeneity throughout the lowermost mantle is, on average, at least a factor-of-ten weaker than that in the uppermost mantle.

Here we explore the possibility that the mantle is a self-similar mixture of basalt and harzburgite, in which case the dichotomy in heterogeneity strength between the uppermost and lowermost mantle may be due to the post-garnet phase transition at the base of the mantle transition zone, as the velocity contrast between basalt and harzburgite is thought to drop from about 10% to less than 1% across this boundary. To improve our understanding of the strength and scale of mid-mantle heterogeneity, we undertake a series of analyses including (1) characterization and modeling of coda-wave amplitude variation with event depth; (2) comparison with surface-wave phase-velocity maps to tighten constraints on uppermost mantle heterogeneity; and (3) determination of what fraction of root-mean-square heterogeneity comes from well-understood long-wavelength structure such as the continent--ocean function and the thermally controlled mid-ocean ridge system.

Keywords: mantle heterogeneity, scattering

Toward a comprehensive understanding of transition zone discontinuities: Inferences on the thermochemical state of the transition zone near a stagnant slab region beneath China

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Plate tectonics and subduction operating over much of the Earth’s history can induce mantle mixing, chemical heterogeneities and recycle volatiles into the mantle. Some slabs are penetrating into the deep lower mantle, but others are stagnated near the transition zone (TZ). Presumably, the thermochemical state of the TZ is a consequence of delicate balance and feedback between the short-term and long-term mixing.

TZ seismic discontinuities hold the key resolving the mystery of mass and heat transport in the Earth’s mantle as well as the composition of the Earth’s interior. But deciphering discontinuity properties are not trivial. Data were typically limited to either mantle triplications, converted waves (P-to-S or S-to-P) or mantle reflections (e.g. SS precursors, ScS reverberations). These observations place constraints on the velocity gradient near the discontinuity as well as discontinuity reflectivity, but hardly offer independent information on the density jump or/and density gradient. In few cases where multiple datasets are jointly analyzed to resolve the density jump, the region of sensitivity (or the fresnel zone) of different dataset does not necessarily coincide. Finally, the use of short period (˜1 Hz) data (e.g., P’P’ precursors) or long period (˜> 0.1 Hz) data (e.g., SS precursors) does not allow us to simultaneously address the transition width and the gradient near the discontinuity.

We advocate a simple and effective strategy. Specifically, we involve broadband direct converted waves (e.g., P410s, P660s) and the topside reflections (the multiples, e.g., PpP410s, PpP660s) in the context of P-wave receiver function technique. Such a tactic not only minimizes tradeoffs between velocity and density jumps, but also allows self-consistent estimates of the shear velocity jump, the density jump, the transition width and the velocity/density gradient near the boundary. We will detail our first attempt near the region of stagnant slab beneath China. These new observations, along with the thermodynamic framework, HeFESTo, allow us to test and validate hypotheses including the state of mantle mixing and equilibrium, compositional heterogeneities and the degree of hydration in the TZ.

Keywords: transition zone, receiver function, mantle mixing

Seismic Structure of the Mantle Discontinuities beneath Japan Sea and Adjacent Regions

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Seismic structure of the upper mantle discontinuities is important for understanding the thermal structure, composition of the mantle, and scales of mantle circulation as well. Northwest Pacific region is one of the ideal locations to study the interaction between a subducting slab and the upper mantle discontinuities. Seismic tomography images show that beneath the Japan Sea, the subducting slab has entered the depth of 400 km and has been trapped as a stagnant slab in the MTZ. Due to the sparse distribution of seismic stations in the sea, investigation of deep mantle structure beneath the broad sea regions is very limited. In this study, we applied the long-period multiple-ScS reverberations analysis to waveforms recorded by F-net. We took advantage of the dense distribution of stations and spatial clusters of intermediate and deep earthquakes occurred beneath Okhotsk Sea, Russia and Northeast China, and conducted a common-reflection-point (CRP) stacking to the data, that allows us to map the topography of the 410-km and 660-km discontinuities beneath Japan Sea. A series of systematic synthetic experiments have been conducted to test the validity and effectiveness of the ScS reverberation method and its resolution. Detailed topography variation features of the upper mantle discontinuities are revealed beneath the Japan Sea. The associated thermal structure and underlying geodynamic implications are discussed. Our results are not only consistent for the major features of the 410 and 660 beneath the Japan islands with previous short-period seismic wave studies, but also give a more comprehensive and complete image of the topography of the upper mantle discontinuities beneath a much broader sea region.

Keywords: Mantle Transition Zone, Mantle Discontinuities, Multiple-ScS Reverberations, Northwest Pacific Subduction region, Japan Sea

A sporadic low-velocity layer atop the 410-km discontinuity beneath the Pacific Ocean

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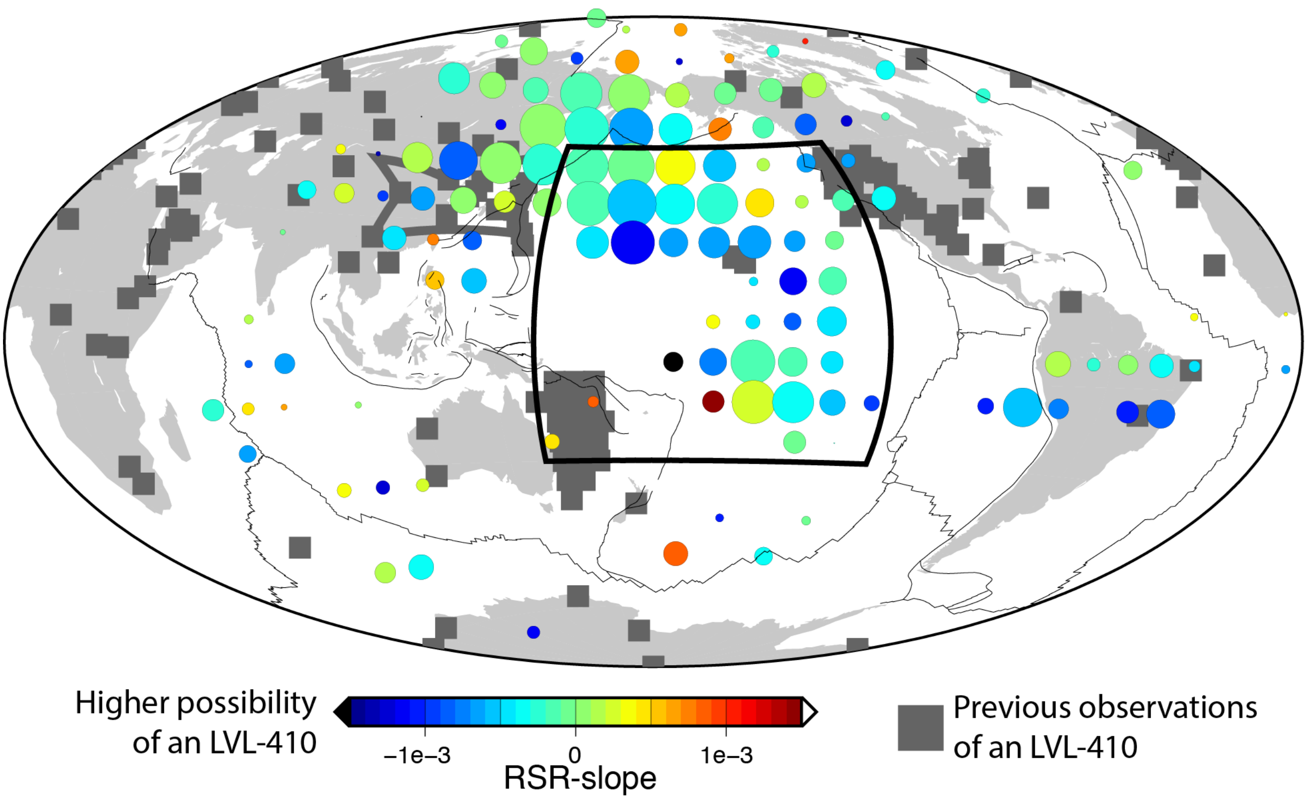
The seismic discontinuity at 410 km depth is usually attributed to an isochemical phase transformation from olivine to wadsleyite. In addition to this globally observed feature, a low-velocity layer immediately above it has been observed regionally in many places, mainly under continents and continental margins. This low-velocity layer is thought to represent partial melting due to dehydration of ascending mantle across the 410-km discontinuity. Here we present seismic observations of a sporadic low-velocity layer atop the 410-km discontinuity beneath the Pacific Ocean by stacking and analysing long-period seismic body waves. The lateral variations of this low-velocity layer show no geographical correlation with 410-km discontinuity topography or tomographic models of seismic velocity, suggesting that it is not caused by regional thermal anomalies. If this low-velocity layer indeed indicates dehydration melting across the 410-km discontinuity, its strong lateral heterogeneity needs to be taken into account in future geodynamic models of mantle convection and the deep water cycle.

Keywords: 410-km discontinuity, SS precursor, Partial melting



Persistence of Strong Silica-Enriched Domains in the Earth's Lower Mantle

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The composition of the Earth's lower mantle is poorly constrained. Among the major elements, the lower-mantle Mg/Si ratio remains controversial, ranging from upper-mantle “pyrolite” composition (Mg/Si 1.2~1.3) to a “perovskititic” composition similar to primitive chondrites and the Sun's photosphere (Mg/Si 0.9~1.1). Geophysical evidence for deep subduction of lithospheric slabs into the lower mantle implies that whole-mantle convection and mixing may have homogenized the entire mantle. However, previous models did not consider the effects of variable Mg/Si upon the viscosity of lower-mantle rocks. Here we use geodynamical models to show that rocks with Mg/Si smaller than pyrolite can avoid efficient mixing throughout Earth's history owing to an intrinsically high viscosity in the lower mantle. In the lower mantle, rocks with relatively low Mg/Si are mostly composed of the strong mineral bridgmanite. We find a new style of whole-mantle convection that consists of viscous cores of “bridgmanite-enriched ancient mantle structures” (BEAMS) in the lower mantle (at 1000~2200 km depth), separated by conduits of relatively weak pyrolitic rocks that circulate between the shallow and deep mantle. The resultant pattern of convection is stable over time-scales longer than the age of the Earth, and sustains significant differences in Mg/Si between the lower and upper mantles. The BEAMS model provides a physical mechanism to explain the hypothesized long-term stability of deep-mantle convection patterns and the geographical fixity of upwelling centers. It can also account for the deflection of upwelling plumes in the uppermost lower mantle, since mantle “wind” is predicted to circulate around BEAMS. Analogously, the BEAMS model with large-scale lateral heterogeneity in the lower mantle can readily explain why some (but not all) slabs stagnate at ~1000 km depth. The presence of BEAMS in the lower mantle can further account for the inferred “viscosity hill” in the mid mantle, as well as differences in the long-wavelength seismic structure between the shallow and deep mantle. Possibly, organization of mantle wind around BEAMS may even contribute to anomalous mountain-building events due to heterogeneous coupling between the lithosphere and mesosphere. Finally, BEAMS may help to balance the Earth's silicon budget, and could host “primordial” noble-gas and/or $^{182}W/^{184}W$ reservoirs over billions of years despite persistent whole-mantle convection.

Keywords: Mantle Convection, Slab Stagnation, Primordial Reservoirs

Tracing plume morphology through the mantle using seismic tomography

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The behaviour of plumes in the mantle has the ability to tell us about the vigour of mantle convection, net rotation of the mantle, the roll of thermal versus chemical anomalies and the important bulk physical properties of the mantle such as viscosity structure. Understanding the journey of plumes through the mantle will help us understand the structure of the mantle and the links between the deep mantle and surface. We have developed an algorithm to trace plume-like features in shear-wave (Vs) seismic tomography models based on picking local minima in the velocity and searching for continuous features with depth. We apply this method to recent tomographic models and recover 60 or more continuous plume conduits that are >750 km long. Around a third of these can be associated with a known hotspot at the surface.

We study the morphology of these plume chains and find that the largest lateral deflections occur near the base of the lower mantle and in the upper mantle. We analyze the preferred orientation of the plume deflections and their gradient to infer large scale mantle flow patterns and the depth of viscosity contrasts in the mantle respectively. We find no preferred azimuthal direction to the plume conduits in the mantle. Increases in the plume gradients correspond to the lower transition zone and 1000 km depth (Bullen's layer C). We infer viscosity structure from these deflections and explore the dynamics of a plume travelling through these viscosity jumps. We also retrieve Vs profiles for our traced plumes and compare with velocity profiles predicted for different mantle adiabat temperatures. We use this to constrain the thermal anomaly associated with these plumes. We use these thermal anomalies in conjunction with our measured plume tilts/deflections to further explore the dynamics of plume conduits in the lower mantle and transition zone.

Keywords: plume, seismic tomography, viscosity

High-resolution mapping of seismic properties across upper mantle discontinuities in the stagnant slab region beneath Korea

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Plate tectonic processes operating over much of the Earth’ s history induce long-term mantle mixing of chemical heterogeneities, recycling of volatiles into the mantle and regulate basalt geochemistry. Fundamental questions relevant to the mantle transition zone concern the nature of phase transition, the distribution of chemical heterogeneities (e.g., harzburgite, basalt), the temperature gradient, as well as the degree and extent of hydration and melting. One particularly important question is how the slab stagnation may be influenced by hydration or/and basalt enrichment in the mantle transition zone. To help answer these questions, we aim to detail upper mantle seismic discontinuity properties, including the shear velocity contrast, the density contrast, the transition sharpness and the gradient using high-quality receiver functions using broadband data in South Korea, which is located in the immediate vicinity of the imaged stagnant slab near northeast China.

Our approach involves broadband observation and amplitude analysis of direct converted waves (Pds) and multiples (PpPds) from the 410 and 660 seismic discontinuities, following our previous effort in a similar analysis in China. We processed waveforms from available broadband seismic stations of the Korea seismic array using an automatic scheme to remove noisy waveforms and retained close to ~12,000 high quality receiver functions. After gathering receiver functions as a function of epicentral distance, we perform slowness stacking of direct converted waves and the multiples, respectively, at several discrete frequency bands between 1 sec and 15 sec.. To avoid interferences from other mantle waves (PP, PPP, PcP, PP410s, PP660s), we stack receive functions across epicentral distances of 74-90 (62-76) degrees for the 410 (660) seismic discontinuity and obtain amplitude estimates and uncertainties through the bootstrap method. To properly calibrate the amplitudes of receiver functions, we take into account the effect of incoherent stacking due to discontinuity topography and frequency-dependent attenuation. Preliminary result will be presented and contrasted against our previous work in east China.

Keywords: transition zone, receiver function

Imaging topography of 410km and 660km discontinuities in eastern North China Craton from ambient noise interferometry

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A sudden increase of both elastic wavespeeds and densities has been indicated near 410km and 660km depth, which are both interpreted as phase changes in the olivine system induced by pressure and temperature changes. And lateral variations of temperature and composition would lead to local topographic changes of both discontinuities. Usually, Ps and Sp conversions, SS precursors, and reflections of local high-frequency subduction zone earthquakes are utilized to study the regional or global topography of mantle discontinuities and the thickness of mantle transition zone. Here we present how to image the mantle transition zone discontinuities in eastern North China Craton with ambient noise interferometry. In the last decade, ambient noise correlation technique has made rapid developments and is increasingly used to extract body wave signals between receiver pairs, which are then used to explore the Earth’s interior structures. More correlations need to be stacked to improve the signal to noise ratio of retrieved body waves than surface waves due to their weaker amplitude. Hence, it is still difficult to obtain high-resolution topographic images of 410km and 660km discontinuities from ambient noise interferometry. In this research, about two years long continuous vertical component records of a dense array (~200 stations) deployed in eastern North China Craton were used to calculate ambient noise cross-correlations. All the cross-correlations were corrected to the zero-offset traces by removing the time delay caused by the inter-station distance as well as 3-D lateral heterogeneities using 3-D velocity models. Then the study area was divided into a grid network and each grid point was regarded as the center of a circle bin. And all the corrected cross-correlations were stacked using a phase-weighted stacking method if their reflection points (the middle points of station pairs) are located within the same bin. And all the stacked traces within each bin were used to map the topography of mantle discontinuities. The result determined by the reflected P phases extracted from ambient noise interferometry was compared with that determined by teleseismic Ps conversions at the same region. Both results indicate shallower depth of 410km discontinuity in the northeastern part of the study region, however, deeper depth in the southwestern part. The overall pattern of the topography of 660km discontinuity is similar with 410km discontinuity but more complicated. Both studies reveal thinner transition zone beneath Taihang Mountain area, possibly implying higher temperature caused by small-scale mantle upwelling. The similarity between the results from these two methods proves the reliability of this interferometric method. In addition, relative amplitude ratios between the 410km and 660km reflected P phases vary in different regions, which implies lateral changes of phase transition thickness of these two discontinuities.

Keywords: Ambient noise interferometry, Mantle discontinuities, Body waves

The Impact of the Iron Spin-transition on Seismic Signatures in Bullen's C-Layer

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Bullen's C-Layer lies between 660 km and 1200 km and has distinctive signatures characterized by discontinuities which may have geodynamical origins. The high-spin to low spin transition of Fe^{++} in iron-magnesium oxides in the lower mantle is a second-order phase transition which causes changes in the density, and elastic properties. They are likely to occur below ~1200 km depth with the highest degrees of influence at about 1800 km depth, depending on the local temperature conditions. We have investigated the dynamical consequences with a compressible spherical convection model, where this transition has been included. Depending on the magnitude of this second-order transition, the sinking slabs may be stagnated at mid mantle depths (~1600 km) or be slowed at the shallower depths. Similarly the rising plumes can be stagnated below ~1600 km depth; resulting a layered convection in the lower mantle. Our results show the potential importance of the high-spin to low spin transition in creating visible seismic signatures in the Bullen’ s C-layer and the D-layer.

Keywords: iron spin transition, mantle mixing, slab stagnation

Oceanic crust-like structures in the mid-mantle below subduction zones seen by source-sided S-to-P conversions.

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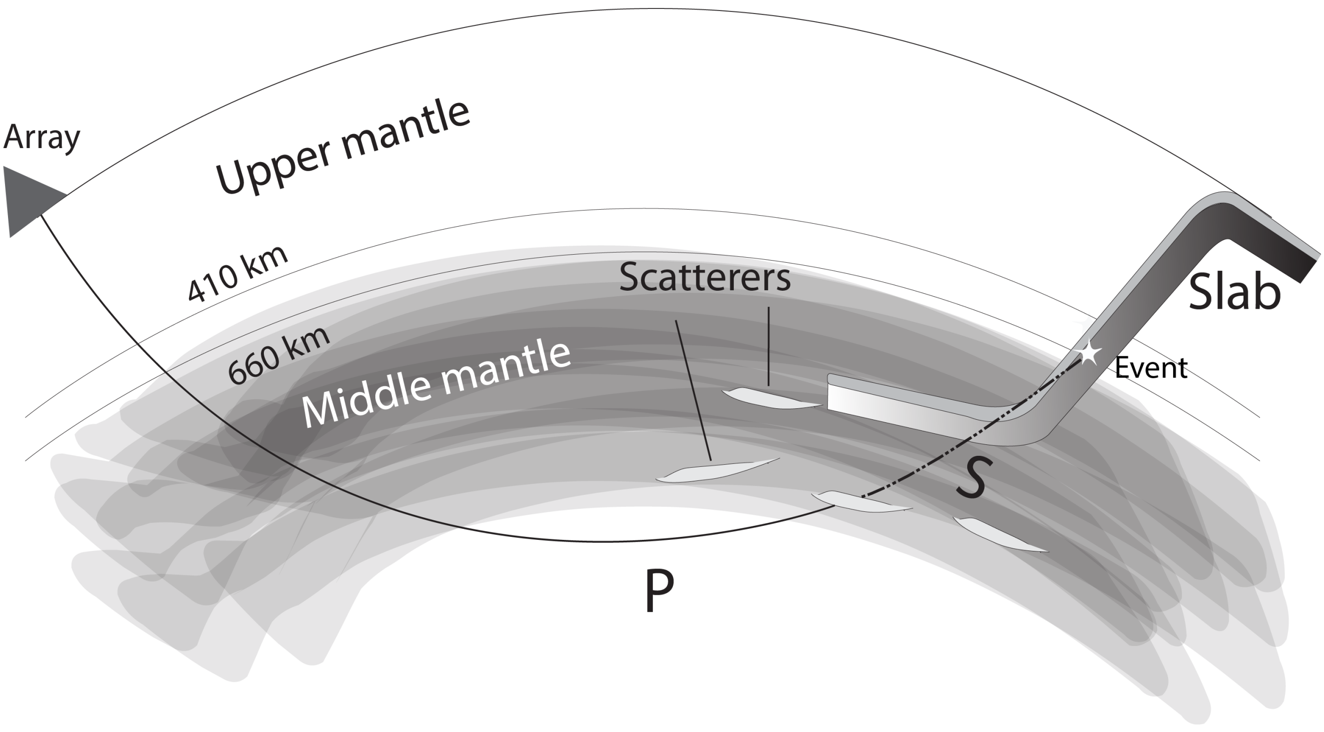
The fate of a subducted slab is a key ingredient in the context of plate tectonics, yet it remains enigmatic especially in terms of its crustal component. In this study, our efforts are devoted to resolve slab-related structures in the mid-mantle below eastern Inonesia, the Izu-Bonin area, and the Solomon-Tonga region by employing seismic array analysing techniques on high frequency waveform data from F-net in Japan, the Alaska regional network in North America and NECESSArray in Northeast China. A pronounced arrival after the direct P wave is observed in the recordings of eight deep earthquakes (greater than 400 km) mostly sourced from western Pacific subduction systems. This later arrival displays a slightly lower slowness compared to the direct P wave and its back-azimuth deviates somewhat from the great circle direction. We explain it as an S-to-P conversion at a deep scatterer below the sources in the earthquake regions. In total nine scatterers are seen at depths ranging from ~700-1110 km. Our waveform forward modelling reveals that those scatterers are characterized by an ~ 7 km thick low-velocity layer compared to the ambient mantle. Combined evidence from published mineral physical analysis suggests that past subducted oceanic crust, possibly fragmented, is most likely responsible for these thin-layer compositional heterogeneities trapped in the mid-mantle beneath the study regions.

Keywords: Oceanic crust, Seismic array, S-to-P conversions, mid-mantle



Discontinuity image of the upper mantle transition zone beneath eastern and southeastern Tibet

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We present new constraints on the upper mantle transition zone structure beneath eastern and southeastern Tibet based on P-wave receiver functions for a large broadband data set from two very dense seismic arrays. The northern array, installed during 2007 to 2009, consisted of 288 broadband stations spaced at 10–30 km intervals, mainly across the Qiangtang and Songpan-Ganzi blocks and the Sichuan Basin. The southern array consisted of 350 broadband stations with an average spacing of ˜35 km, and was deployed mainly in SE Tibet by the ChinArray project from 2011 to 2014. To apply the receiver function technique, we collected events with body wave magnitudes > 5.0 and at epicentral distances of 30–90˚. We computed a dataset of 195,000 high-quality receiver functions from 1,360 teleseismic events. Our results show a clear depression of both the 410-km and 660-km discontinuities west of the Red River fault relative to the east. The same amount depression of the two discontinuities results in a normal transition zone beneath the Tengchong volcano. Moreover, a significant depression of the 660-km discontinuity is detected beneath the western Yangtze Craton. In contrast, that the transition zone thickness beneath much of the Sichuan Basin is similar to the global average. These result not only provide new constraints on the mechanism of the Tengchong volcano but also shed light into the depth extent of the Red River fault and the possible presence of detached lithosphere below the western Yangtze Craton, which are key to understanding the tectonic evolution of eastern and SE Tibet.

Acknowledgments

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Keywords: Tibet, receiver function, Red River fault zone, Tengchong volcano

