GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G46889.1

Manuscript received 20 August 2019
Revised manuscript received 23 October 2019
Manuscript accepted 29 October 2019

Published online 9 December 2019

Foundered lithospheric segments dropped into the mantle transition zone beneath southern California, USA

Youqiang Yu[1], Stephen S. Gao[2], Kelly H. Liu[2] and Dapeng Zhao[3]
[1]State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
[2]Geology and Geophysics Program, Missouri University of Science and Technology, Rolla, Missouri 65409, USA
[3]Department of Geophysics, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

ABSTRACT

The diverse range of active tectonics occurring in southern California, USA, offers an opportunity to explore processes of continental deformation and modification in response to the instability of the Pacific and Farallon plates. Here, we present a high-resolution receiver-function image of the mantle transition zone (MTZ). Our result reveals significant lateral heterogeneities in the deep mantle beneath southern California. Both seismic tomography and MTZ discontinuity deflections reveal foundered lithospheric segments that have dropped into the MTZ beneath the western Transverse Ranges, the Peninsular Ranges, and part of the southern Sierra Nevada. Water dehydrated from these foundered materials may contribute to the observed MTZ thickening. Our observations, combined with previous tomography and geochemical results, indicate that lithospheric foundering of fossil arc roots provides a way for geochemical heterogeneities to be recycled into the underlying mantle, and suggest that the foundered materials can play a significant role in inducing lateral variations of MTZ structure.

INTRODUCTION

Abundant seismicity, and the availability of a wide range of other geological and geophysical data make southern California, USA (Fig. 1) one of the best-studied regions in the world with respect to crustal and mantle structure and dynamics. While the crust and shallow upper mantle in this area of California are comparatively well documented, structures at greater depths, especially the mantle transition zone (MTZ), have not been explored in great detail, leading to considerable uncertainties regarding mass exchange between the shallow and deep mantle layers. Several tectonic issues are still under debate, including the fate of the removed lithospheric root beneath the southern Sierra Nevada, the origin of the Isabella anomaly (imaged as a high-velocity anomaly [HVA] in the upper mantle under the Great Valley), and the depth extent of the high-velocity mantle lithosphere beneath the Transverse Ranges (e.g., Humphreys and Hager, 1990; Saleeby et al., 2003; Zandt et al., 2004; Schmandt and Humphreys, 2010; Wang et al., 2013; Cox et al., 2016; Jiang et al., 2018; Yu and Zhao, 2018).

Questions arise about where the removed lithospheric pieces now reside, and whether these foundered lithospheric segments have entered the MTZ or the lower mantle. The MTZ is bounded by the 410 km (d410) and 660 km (d660) discontinuities, which represent phase transitions from olivine to wadsleyite and ringwoodite to bridgmanite, respectively (Ringwood, 1975). Under normal temperature and anhydrous conditions, the depths of the d410 and d660 are sensitive to lateral temperature variations, and have positive and negative Clapeyron slopes, respectively (e.g., Ringwood, 1975; Bina and Helffrich, 1994). The existence of a cold subducted slab or upwelling hot material, would lead to a thicker or thinner MTZ, respectively (Ringwood, 1975). In addition, compositional or water content variations can also disturb the topography of the d410 and d660 (Litasov et al., 2005). Thus, the topography of the MTZ discontinuities can be used to infer physical properties of the MTZ.

There are significant discrepancies among pre-USArray seismic observatory (http://www.usarray.org/) MTZ studies in southern California, most likely due to the low number of receiver functions (RFs) used in the studies (Gurrola and Minster, 1998; Ramesh et al., 2002; Lewis and Gurrola, 2004; Vinnik et al., 2010). On the other hand, more recent RF studies using USArray data are focused on the western or the entire United States with resolutions that are not high enough for identifying finer MTZ features in southern California (e.g., Tauzin et al., 2013; Gao and Liu, 2014b). In this study, we employed the RF method to conduct a comprehensive investigation of the MTZ structure beneath southern California with an unprecedented spatial resolution by taking full advantage of the dense seismic station coverage, which is among the highest in the world. The high-resolution RF observations, when combined with results of seismic tomography studies, provide critical constraints on some of the aforementioned long-lasting questions about the deformation and lithospheric modification occurring under southern California.

LATERAL VARIATIONS IN MTZ STRUCTURE

All the seismograms used in this study were selected by employing a signal-to-noise ratio–based procedure and were band-pass filtered in the frequency band of 0.02–0.2 Hz (Gao and Liu, 2014a). The filtered seismograms were further converted into radial RFs using the frequency-domain water-level deconvolution procedure (Ammon, 1991). Stacking of RFs in successive circular bins with a radius of 0.3° under the non-plane-wave assumption (Gao and Liu, 2014a) revealed that robust P-to-S conversions from either the d410 or the d660 are clearly identifiable in a total of 599 bins (see the GSA Data Repository[1] for details on the data and methods).

[1]GSA Data Repository item 2020056, Figures DR1–DR8 and Table DR1 (results of receiver function stacking for each of the bins), is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

CITATION: Yu, Y., Gao. S.S., Liu, K.H., and Zhao, D., 2020, Foundered lithospheric segments dropped into the mantle transition zone beneath southern California, USA: Geology, v. 48, p. 200–204, https://doi.org/10.1130/G46889.1

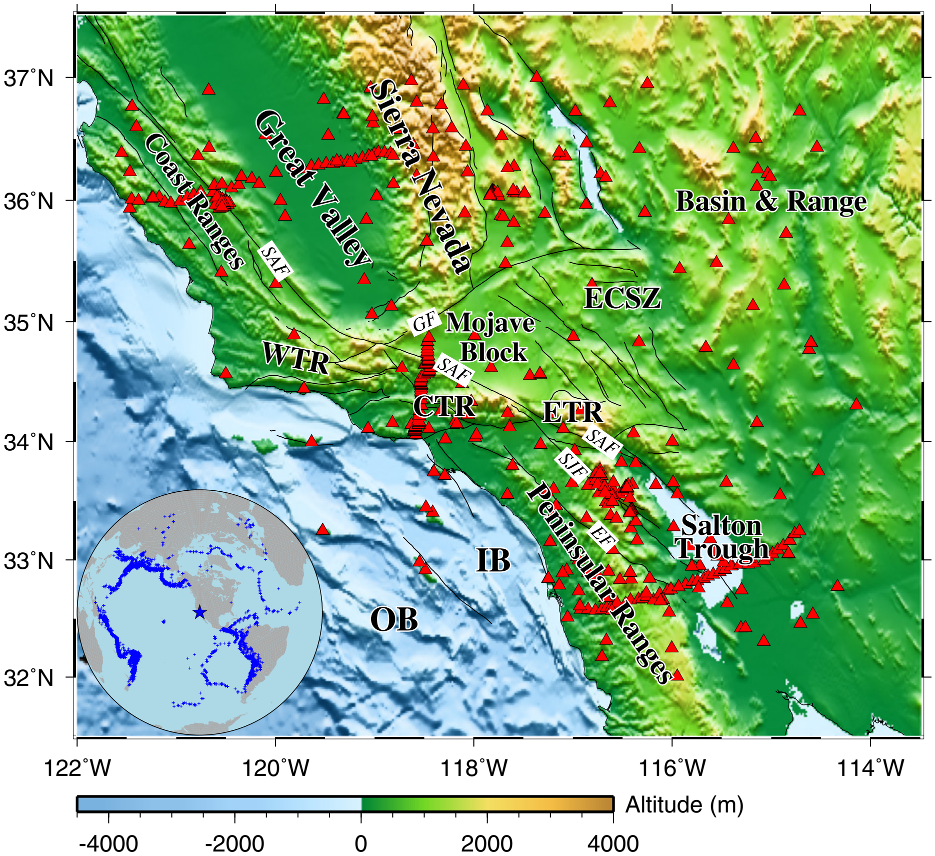

Figure 1. Topographic map showing the distribution of 476 broadband seismic stations (red triangles) in southern California, USA, used in this study. Black lines indicate major faults. CTR—central Transverse Ranges; ECSZ—Eastern California shear zone; EF—Elsinore fault; ETR—eastern Transverse Ranges; GF—Garlock fault; IB—Inner Borderland; OB—Outer Borderland; SAF—San Andreas fault; SJF—San Juan fault; WTR—western Transverse Ranges. Inset map displays distribution of teleseismic events (blue plus signs) used to calculate receiver functions. Blue star represents the center of the study area.

The resulting MTZ discontinuity depths are apparent, rather than true depths, due to our use of the one-dimensional (1-D) IASP91 (International Association of Seismology and Physics of the Earth's Interior) Earth model (http://ds.iris.edu/ds/products/emc-iasp91/) to moveout-correct the RFs. Accurately determined absolute P- and S-wave velocity (Vp, Vs) models above the d660 are required to calculate the true depths. Because such high-resolution velocity models are not available for the study area, the apparent, rather than velocity-corrected, depths are discussed in the following.

The apparent depths of both the d410 and d660 are revealed to have remarkable lateral variations ranging from 399 to 444 km and from 657 to 698 km, respectively (Fig. 2; Table DR1 in the Data Repository), leading to substantial perturbations of the MTZ thickness from 223 to 282 km, with a mean value of 247 ± 7 km. The average depth of the d410 is calculated to be 429 ± 7 km, and that of the d660 is 677 ± 8 km, which are significantly deeper than the anticipated values of 410 km and 660 km, respectively, in the IASP91 Earth model, and are indicative of the overall slow velocities above the d410. The average Vp anomaly from the surface to the d410 is estimated to be −1.26% (Fig. 2D), if we assume the true d410 depth to be 410 km (see the Data Repository for details). The estimated magnitude of the velocity anomaly is consistent with previous seismic tomographic results (e.g., Raikes, 1980; Humphreys et al., 1984; Zhao et al., 1996; Schmandt and Humphreys, 2010). Significant depressions of the MTZ discontinuities have also been revealed by previous RF studies using a smaller number of RFs (Ramesh et al., 2002; Vinnik et al., 2010) or a lower spatial resolution (Gao and Liu, 2014b).

The cross-correlation coefficient (XCC) between the resulting apparent depths of d410 and d660 is 0.47 (Fig. DR2), which is much smaller than that (0.84) for the contiguous United States (Gao and Liu, 2014b). Considering the significant low-velocity anomalies (LVAs) above the d410, the low XCC may suggest the existence of thermal or compositional (including water-content) anomalies in the MTZ. The western Transverse Ranges, Peninsular Ranges, and part of the southern Sierra Nevada are characterized by significant MTZ thickening, which is further confirmed by RF stacking within each subarea (Fig. DR3) and results from a larger bin size of 0.5° (Fig. DR4). In contrast, most parts of the Great Valley, the Outer Borderland, and the Basin and Range Province are dominated by an obviously thinner-than-normal MTZ.

FOUNDERED LITHOSPHERIC MATERIALS IN THE MTZ

The resulting thicker-than-normal MTZ beneath the western Transverse Ranges (265 ± 8 km), the Peninsular Ranges (258 ± 4 km), and part of the southern Sierra Nevada (256 ± 3 km) is generally consistent with the distribution of the HVAs around the MTZ (Fig. 3; Fig. DR5) revealed by seismic tomography (e.g., Schmandt and Humphreys, 2010; Yu and Zhao, 2018). While HVAs in the MTZ are usually interpreted as subducted oceanic slabs, the slabs of the latest subduction event of the Farallon plate are imaged at 300–700 km depth beneath the central and eastern United States, which is outside our study area (e.g., Schmandt and Lin, 2014; Burdick et al., 2017; Wang et al., 2019a). In addition, analysis of silica-rich glasses from the southern Sierra Nevada indicated that some of the trace elements are sourced from lower-crustal rocks, instead of having a subduction-related origin (Ducea and Saleeby, 1998). These observations, together with the absence of currently active subduction, suggest that the observed HVAs beneath southern California could represent foundered lithospheric segments dropped into the MTZ, rather than subducted oceanic slabs (Fig. 3).

Seismic experiments, numerical modeling, and xenolith studies support the loss of the crustal root beneath the southern Sierra Nevada since the Miocene, and its lithospheric mantle here is characterized by significant LVAs (e.g., Saleeby et al., 2003; Boyd et al., 2004; Gilbert et al., 2012; Yu and Zhao, 2018), indicative of lithospheric foundering (Fig. 3), which is estimated to have occurred at 3.5 Ma based on a sudden pulse of mafic potassic magmatism (Manley et al., 2000). The removed lithospheric material beneath the southern Sierra Nevada has been interpreted to have convectively descended or foundered into the asthenosphere beneath the southern Great Valley, forming the high-velocity Isabella anomaly (e.g., Saleeby et al., 2003; Boyd et al., 2004; Zandt et al., 2004; Gilbert et al., 2012; Jones et al., 2014), which extends from near the base of the crust to at least ~300 km depth (Fig. 3A). However, recent observations on the position (Wang et al., 2013; Jiang et al., 2018), geometry (Cox et al., 2016), and lithospheric anisotropy (Yu and Zhao, 2018) of the Isabella anomaly are more consistent with a fossil slab hypothesis for its origin, probably as a remnant of Miocene subduction termination that is still attached to the Monterey slab translating northward with the Pacific plate (Wang et al., 2013; Cox et al.,

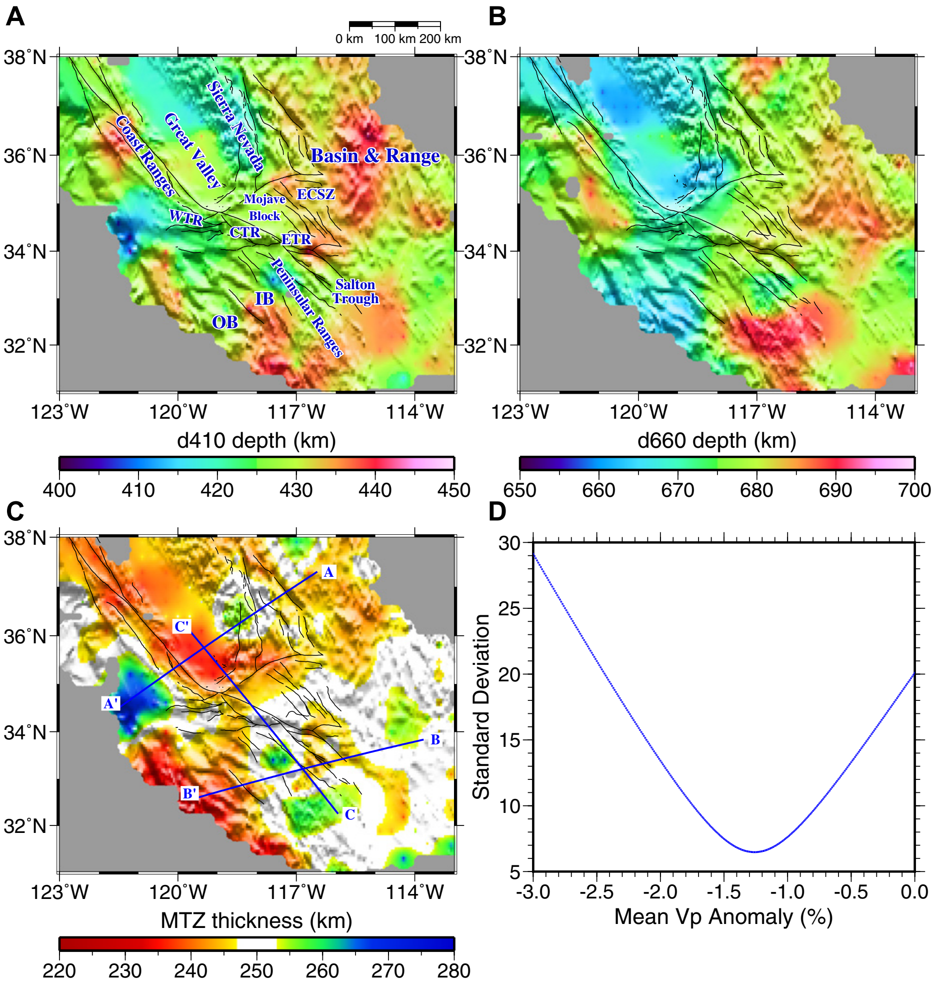

Figure 2. Results of receiver function (RF) stacking and average P-wave seismic velocity (Vp) anomaly relative to the IASP91 Earth model (International Association of Seismology and Physics of the Earth's Interior, http://ds.iris.edu/ds/products/emc-iasp91/) in southern California, USA. (A) Spatial distribution of the resulting apparent 410 km discontinuity (d410) depth. (B) Same as A, but for the 660 km discontinuity (d660). (C) Mantle transition zone (MTZ) thickness measurements. (D) Estimation of mean Vp anomaly above the d410 depth calculated based on results in A (see the Data Repository for details [text footnote 1]). See Figure 1 for abbreviations.

2016). The fact that the MTZ beneath the Isabella anomaly has a thinner-than-normal thickness (Fig. 3A), which indicates the existence of a high-temperature anomaly, suggests that the HVA, usually featured as a low-temperature anomaly, does not extend to the MTZ and is consistent with the hypothesis that the Isabella anomaly is a fossil slab existing in the upper mantle. In contrast, beneath the southern Sierra Nevada, the observed thicker-than-normal MTZ and the tomographically revealed HVAs suggest that the foundered cold lithosphere has sunk into the MTZ (Fig. 3D). The proposed downward movement of the foundered lithosphere is consistent with the overwhelmingly negative radial anisotropy (indicative of a faster velocity in the vertical direction than in the horizontal direction) associated with the HVAs (Fig. 3).

A positive arrival at the depth of ~740 km was observed in some areas, such as the southern Sierra Nevada (Fig. 3A; see also Simmons and Gurrola, 2000), and could be associated with a garnet phase change (Simmons and Gurrola, 2000). Geochemical studies indicate that garnet clinopyroxenite constitutes a significant component of the Sierran mantle lithosphere, and these garnet-rich rocks are of the order of 0.2 g/cm^3 denser than typical mantle peridotite (Saleeby et al., 2003). Thus, the discontinuity at ~740 km may reflect that some of the foundered lithospheric segments discussed above may have dropped into the lower mantle. The foundered lithosphere would have dropped down, leaving space for inflow of buoyant asthenosphere (Saleeby et al., 2003; Zandt et al., 2004), which may have instigated the development of a small-scale mantle convection system (Fig. 3D). Extensive MTZ thinning (Fig. 2) observed beneath the Great Valley (240 ± 5 km) and the Outer Borderland (238 ± 7 km) is possibly associated with the upwelling branch of the convection system (Fig. 3D).

CONTRIBUTION OF DEHYDRATED WATER TO MTZ THICKENING

The presence of water may also play a role in the observed deflections of the MTZ discontinuities (e.g., van der Meijde et al., 2003; Cao and Levander, 2010) in addition to thermal anomalies. Observational and experimental studies suggest that hydration of the MTZ decreases seismic velocities (Inoue et al., 1998; Cao and Levander, 2010) and increases MTZ thickness (Litasov et al., 2005). Small-scale heterogeneities of low-velocity bodies have recently been revealed in the MTZ based on RF images of the North American MTZ and interpreted as water-enriched harzburgites (Wang et al., 2019b). In addition, regional and continental-scale tomographic studies commonly show LVAs either around the d410 or in the MTZ at places where significant MTZ thickening is observed beneath southern California (Fig. 3; Figs. DR5–DR7), suggesting possible contributions of an anomalously high amount of water to the observed MTZ thickening. The existence of an excessive amount of water-rich minerals in the MTZ is further supported by the negative arrivals immediately atop the d410 (Bercovici and Karato, 2003) and the relatively smaller stacking amplitude of the d410 (Fig. DR8; van der Meijde et al., 2003), especially beneath the Peninsular Ranges. Additionally, a discontinuity at a depth of ~520 km (d520) may represent the phase transition from wadsleyite to ringwoodite (Fig. 3), which is frequently observed in areas with a hydrous MTZ (van der Meijde et al., 2003; Deuss and Woodhouse, 2001; Tauzin et al., 2013; Maguire et al., 2018). Experimental and thermodynamic studies indicate that a sharp d520 would be preferentially detected in colder- and more hydrated-than-average regions (Inoue et al., 1998; Xu et al., 2008). In addition, splitting of the d520 (Fig. 3) might be expected with an increased water content or the exsolution of calcium-perovskite in the MTZ (Deuss and Woodhouse, 2001; van der Meijde et al., 2003). Previous investigations suggested that 2.0 wt% of water can result in 25–45 km thickening of the MTZ (Cao and Levander, 2010). Thus, the maximum amount of water beneath southern California is ~1.0 wt%, if the resulting MTZ thickening is dominantly attributed to water effects. A plausible source of the water is dehydration of the foundered lithospheric segments widely revealed in the upper mantle (Fig. 3D). The silica-rich glasses from the Sierra Nevada have been proposed to be associated with dehydration melting of hornblende-bearing areas along the edges of foundered segments (Ducea and Saleeby, 1998). The lithosphere of these fossil arcs, such as under the Sierra Nevada and the Peninsular Ranges (e.g., DePaolo, 1981), may have been saturated by hydrous upwelling from the slab interface during the subduction of the Farallon plate. Numerical modeling and geochemical results show that the

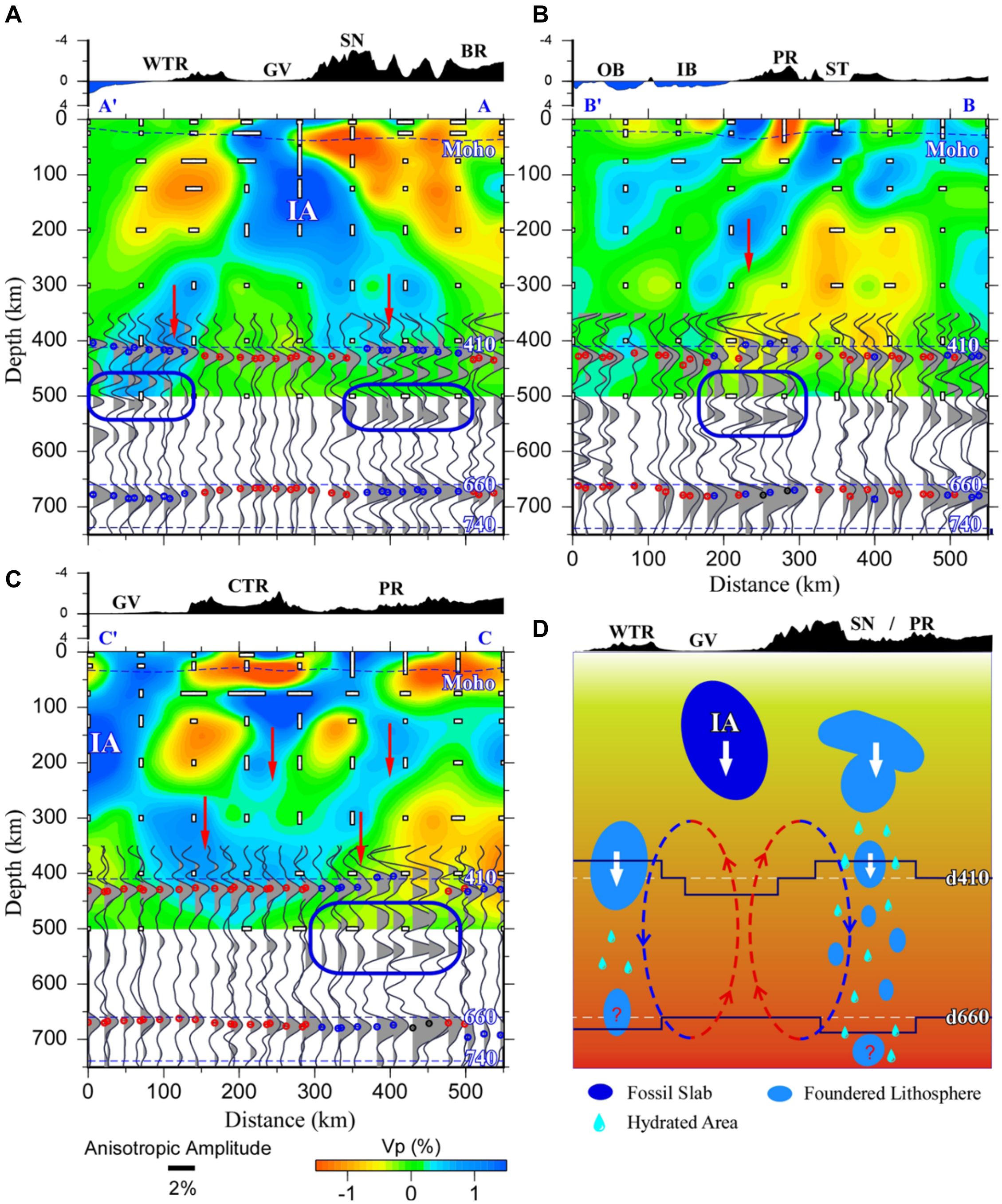

Figure 3. (A–C) Cross sections of receiver function (RF) traces, P-wave isotropic tomography, and radial anisotropy (white bars; Yu and Zhao, 2018) along the three profiles shown in Figure 2C in southern California, USA, and (D) interpretative cartoon. Thick blue circular lines highlight the sharp or split 520 km discontinuity. Horizontal white bars represent a horizontal velocity faster than vertical velocity, and vice versa for vertical bars. Length of white bars denotes amplitude of radial anisotropy. Small circles indicate well-determined peaks of the 410 km discontinuity (d410) and 660 km discontinuity (d660). Blue and red circles display mantle transition zone (MTZ) thickness with values larger/equal to or less than 250 km, respectively. Note that the maximum depth of the Yu and Zhao (2018) model is 500 km. Red arrows indicate downwelling of foundered lithospheric segments. BR—Basin and Range; IA—Isabella anomaly; GV—Great Valley; PR—Peninsular Ranges; SN—Sierra Nevada; ST—Salton Trough; WTR—western Transverse Ranges; CTR—central Transverse Ranges; IB—Inner Borderland; OB—Outer Borderland.

lithosphere altered from arc magmatism is likely to be 1%–5% denser than its surrounding mantle, and would possess a weak lower crust due to eclogitization with the aid of water dehydrated from the slab interface (e.g., Saleeby et al., 2003; Elkins-Tanton, 2005). Such a density contrast would be sufficient to drive gravitational instability (Elkins-Tanton, 2005; West et al., 2009).

CONCLUSIONS

This study reveals significant lateral heterogeneities in the deep mantle beneath southern California. Both seismic tomography and MTZ discontinuity deflections reveal foundered lithospheric segments that have dropped into the MTZ beneath the western Transverse Ranges, the Peninsular Ranges, and part of the southern Sierra Nevada. Our observations provide new evidence to support the hypothesis that foundering of a fossil arc lithosphere root may induce small-scale mantle convection, produce a heterogeneous and locally hydrous upper mantle, and lead to short-duration eruptive episodes of hydrous, alkali-rich magmas in southern California (Elkins-Tanton and Grove, 2003).

ACKNOWLEDGMENTS

Data used in this study are archived at, and were provided by, the Incorporated Research Institutions for Seismology Data Management Center (https://ds.iris.edu/ds/nodes/dmc/). Constructive comments from editor Dennis Brown, Donald Forsyth, and four anonymous reviewers significantly improved the manuscript. This work was supported by the National Natural Science Foundation of China (grant 41606043) and the National Program on Global Change and Air-Sea Interaction (grant GASI-GEOGE-05 to Y. Yu), the Japan Society for the Promotion of Science (grant 19H01996 to D. Zhao), and the American Chemical Society (grant PRF-60281-ND8 to S. Gao).

REFERENCES CITED

Ammon, C.J., 1991, The isolation of receiver effects from teleseismic P waveforms: Bulletin of the Seismological Society of America, v. 81, p. 2504–2510.

Bercovici, D., and Karato, S.I., 2003, Whole-mantle convection and the transition-zone water filter: Nature, v. 425, p. 39–44, https://doi.org/10.1038/nature01918.

Bina, C.R., and Helffrich, G., 1994, Phase transition Clapeyron slopes and transition zone seismic discontinuity topography: Journal of Geophysical Research, v. 99, no. B8, p. 15853–15860, https://doi.org/10.1029/94JB00462.

Boyd, O.S., Jones, C.H., and Sheehan, A.F., 2004, Foundering lithosphere imaged beneath the southern Sierra Nevada, California, USA: Science, v. 305, p. 660–662, https://doi.org/10.1126/science.1099181.

Burdick, S., Vernon, F.L., Martynov, V., Eakins, J., Cox, T., Tytell, J., Mulder, T., White, M.C., Astiz, L., Pavlis, G.L., and van der Hilst, R.D., 2017, Model update May 2016: Upper-mantle heterogeneity beneath North America from traveltime tomography with global and USArray data: Seismological Research Letters, v. 88, no. 2A, p. 319–325, https://doi.org/10.1785/0220160186.

Cao, A., and Levander, A., 2010, High-resolution transition zone structures of the Gorda slab beneath the western United States: Implication for deep water subduction: Journal of Geophysical Research, v. 115, no. B7, B07301, https://doi.org/10.1029/2009JB006876.

Cox, P., Stubailo, I., and Davis, P., 2016, Receiver function and geometric tomography along the Monterey microplate to test slab delamination or lithospheric drip models of the Isabella anomaly, California: Bulletin of the Seismological Society of America, v. 106, p. 267–280, https://doi.org/10.1785/0120140339.

DePaolo, D.J., 1981, A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California: Journal of Geophysical Research, v. 86, no. B11, p. 10470–10488, https://doi.org/10.1029/JB086iB11p10470.

Deuss, A., and Woodhouse, J., 2001, Seismic observations of splitting of the mid-transition zone discontinuity in Earth's mantle: Science, v. 294, p. 354–357, https://doi.org/10.1126/science.1063524.

Ducea, M., and Saleeby, J., 1998, Crustal recycling beneath continental arcs: Silica-rich glass inclusions in ultramafic xenoliths from the Sierra Nevada, California: Earth and Planetary Science Letters, v. 156, p. 101–116, https://doi.org/10.1016/S0012-821X(98)00021-1.

Elkins-Tanton, L.T., 2005, Continental magmatism caused by lithospheric delamination, *in* Fougler, G.R., et al., eds., Plates, Plumes, and Paradigms: Geological Society of America Special Papers, v. 388, p. 449–461, https://doi.org/10.1130/2005.2388(27).

Elkins-Tanton, L.T., and Grove, T.L., 2003, Evidence for deep melting of hydrous, metasomatized mantle: Pliocene high potassium magmas from the Sierra Nevadas: Journal of Geophysical Research, v. 108, p. 2350, https://doi.org/10.1029/2002JB002168.

Gao, S.S., and Liu, K.H., 2014a, Imaging mantle discontinuities using multiply-reflected P-to-S conversions: Earth and Planetary Science Letters, v. 402, p. 99–106, https://doi.org/10.1016/j.epsl.2013.08.025.

Gao, S.S., and Liu, K.H., 2014b, Mantle transition zone discontinuities beneath the contiguous United States: Journal of Geophysical Research, v. 119, p. 6452–6468, https://doi.org/10.1002/2014JB011253.

Gilbert, H., Yang, Y., Forsyth, D.W., Jones, C.H., Owens, T.J., Zandt, G., and Stachnik, J.C., 2012, Imaging lithospheric foundering in the structure of the Sierra Nevada: Geosphere, v. 8, p. 1310–1330, https://doi.org/10.1130/GES00790.1.

Gurrola, H., and Minster, J.B., 1998, Thickness estimates of the upper-mantle transition zone from bootstrapped velocity spectrum stacks of receiver functions: Geophysical Journal International, v. 133, p. 31–43, https://doi.org/10.1046/j.1365-246X.1998.1331470.x.

Humphreys, E.D., and Hager, B.H., 1990, A kinematic model for the late Cenozoic development of southern California crust and upper mantle: Journal of Geophysical Research, v. 95, no. B12, p. 19747–19762, https://doi.org/10.1029/JB095iB12p19747.

Humphreys, E., Clayton, R.W., and Hager, B.H., 1984, A tomographic image of mantle structure beneath southern California: Geophysical Research Letters, v. 11, p. 625–627, https://doi.org/10.1029/GL011i007p00625.

Inoue, T., Weidner, D.J., Northrup, P.A., and Parise, J.B., 1998, Elastic properties of hydrous ringwoodite (γ-phase) in Mg_2SiO_4: Earth and Planetary Science Letters, v. 160, p. 107–113, https://doi.org/10.1016/S0012-821X(98)00077-6.

Jiang, C., Schmandt, B., Hansen, S.M., Dougherty, S.L., Clayton, R.W., Farrell, J., and Lin, F.C., 2018, Rayleigh and S wave tomography constraints on subduction termination and lithospheric foundering in central California: Earth and Planetary Science Letters, v. 488, p. 14–26, https://doi.org/10.1016/j.epsl.2018.02.009.

Jones, C.H., Reeg, H., Zandt, G., Gilbert, H., Owens, T.J., and Stachnik, J., 2014, P-wave tomography of potential convective downwellings and their source regions, Sierra Nevada, California: Geosphere, v. 10, p. 505–533, https://doi.org/10.1130/GES00961.1.

Lewis, J., and Gurrola, H., 2004, Evidence for localized down welling of lithospheric material through the upper mantle transition zone beneath southern California: San Francisco, California, American Geophysical Union, Fall Meeting supplement, abstract S53B-0207.

Litasov, K.D., Ohtani, E., Sano, A., Suzuki, A., and Funakoshi, K., 2005, Wet subduction versus cold subduction: Geophysical Research Letters, v. 32, L13312, https://doi.org/10.1029/2005GL022921.

Maguire, R., Ritsema, J., and Goes, S., 2018, Evidence of subduction-related thermal and compositional heterogeneity below the United States from transition zone receiver functions: Geophysical Research Letters, v. 45, p. 8913–8922, https://doi.org/10.1029/2018GL078378.

Manley, C.R., Glazner, A.F., and Farmer, G.L., 2000, Timing of volcanism in the Sierra Nevada of California: Evidence for Pliocene delamination of the batholithic root?: Geology, v. 28, p. 811–814, https://doi.org/10.1130/0091-7613(2000)28<811:TOVITS>2.0.CO;2.

Raikes, S.A., 1980, Regional variations in upper mantle structure beneath southern California: Geophysical Journal International, v. 63, p. 187–216, https://doi.org/10.1111/j.1365-246X.1980.tb02616.x.

Ramesh, D.S., Kind, R., and Yuan, X., 2002, Receiver function analysis of the North American crust and upper mantle: Geophysical Journal International, v. 150, p. 91–108, https://doi.org/10.1046/j.1365-246X.2002.01697.x.

Ringwood, A.E., 1975, Composition and Petrology of the Earth's Mantle (1st ed.): New York, McGraw-Hill, 672 p.

Saleeby, J., Ducea, M., and Clemens-Knott, D., 2003, Production and loss of high-density batholithic root, southern Sierra Nevada, California: Tectonics, v. 22, p. 1064, https://doi.org/10.1029/2002TC001374.

Schmandt, B., and Humphreys, E., 2010, Seismic heterogeneity and small-scale convection in the southern California upper mantle: Geochemistry Geophysics Geosystems, v. 11, Q05004, https://doi.org/10.1029/2010GC003042.

Schmandt, B., and Lin, F.C., 2014, P and S wave tomography of the mantle beneath the United States: Geophysical Research Letters, v. 41, p. 6342–6349, https://doi.org/10.1002/2014GL061231.

Simmons, N.A., and Gurrola, H., 2000, Multiple seismic discontinuities near the base of the transition zone in the Earth's mantle: Nature, v. 405, p. 559–562, https://doi.org/10.1038/35014589.

Tauzin, B., Van Der Hilst, R.D., Wittlinger, G., and Ricard, Y., 2013, Multiple transition zone seismic discontinuities and low velocity layers below western United States: Journal of Geophysical Research, v. 118, p. 2307–2322, https://doi.org/10.1002/jgrb.50182.

van der Meijde, M., Marone, F., Giardini, D., and Van der Lee, S., 2003, Seismic evidence for water deep in Earth's upper mantle: Science, v. 300, p. 1556–1558, https://doi.org/10.1126/science.1083636.

Vinnik, L., Ren, Y., Stutzmann, E., Farra, V., and Kiselev, S., 2010, Observations of S410*p* and S350*p* phases at seismograph stations in California: Journal of Geophysical Research, v. 115, no. B5, B05303, https://doi.org/10.1029/2009JB006582.

Wang, H., Zhao, D., Huang, Z., and Wang, L., 2019a, Tomography, seismotectonics and mantle dynamics of central and eastern United States: Journal of Geophysical Research, v. 124, p. 8890–8907, https://doi.org/10.1029/2019JB017478.

Wang, Y., Forsyth, D.W., Rau, C.J., Carriero, N., Schmandt, B., Gaherty, J.B., and Savage, B., 2013, Fossil slabs attached to unsubducted fragments of the Farallon plate: Proceedings of the National Academy of Sciences of the United States of America, v. 110, p. 5342–5346, https://doi.org/10.1073/pnas.1214880110.

Wang, Y., Pavlis, G.L., and Li, M., 2019b, Heterogeneous distribution of water in the mantle transition zone inferred from wavefield imaging: Earth and Planetary Science Letters, v. 505, p. 42–50, https://doi.org/10.1016/j.epsl.2018.10.010.

West, J.D., Fouch, M.J., Roth, J.B., and Elkins-Tanton, L.T., 2009, Vertical mantle flow associated with a lithospheric drip beneath the Great Basin: Nature Geoscience, v. 2, p. 439–444, https://doi.org/10.1038/ngeo526.

Xu, W., Lithgow-Bertelloni, C., Stixrude, L., and Ritsema, J., 2008, The effect of bulk composition and temperature on mantle seismic structure: Earth and Planetary Science Letters, v. 275, p. 70–79, https://doi.org/10.1016/j.epsl.2008.08.012.

Yu, Y., and Zhao, D., 2018, Lithospheric deformation and asthenospheric flow associated with the Isabella anomaly in southern California: Journal of Geophysical Research, v. 123, p. 8842–8857, https://doi.org/10.1029/2018JB015873.

Zandt, G., Gilbert, H., Owens, T.J., Ducea, M., Saleeby, J., and Jones, C.H., 2004, Active foundering of a continental arc root beneath the southern Sierra Nevada in California: Nature, v. 431, p. 41–46, https://doi.org/10.1038/nature02847.

Zhao, D., Kanamori, H., and Humphreys, E., 1996, Simultaneous inversion of local and teleseismic data for the crust and mantle structure of southern California: Physics of the Earth and Planetary Interiors, v. 93, p. 191–214, https://doi.org/10.1016/0031-9201(95)03076-X.

Printed in USA