Weak and vanishing upper mantle discontinuities generated by large-scale lithospheric delamination in the Longmenshan area, China

Chuansong He (hechuansong@aliyun.com)
Institute of Geophysics, CEA

Research Article

Keywords: Longmenshan, lithospheric delamination, tomography, CCP stacking of receiver functions, 410 km discontinuity, 660 km discontinuity

Posted Date: July 13th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-710024/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Weak and vanishing upper mantle discontinuities generated by large-scale lithospheric delamination in the Longmenshan area, China

Chuansong He
Institute of geophysics, China Earthquake Administration, 100081, Beijing

Abstract: A large amount of high-quality teleseismic data is used for common conversion point (CCP) stacking of receiver functions in the Longmenshan area. The results show that a large-scale high-velocity anomaly or lithospheric delamination can completely destroy upper mantle discontinuities or erase the phase boundary of olivine, which is a very important finding and can be used to assess stagnant slabs in the mantle transition zone globally. The deepening region of the 660 km discontinuity beneath the Songpan-Ganzi terrane might indicate that the large-scale high-velocity anomaly in the mantle transition zone is a cold domain and can affect the topography of upper mantle discontinuities.

Key words: Longmenshan, lithospheric delamination, tomography, CCP stacking of receiver functions, 410 km discontinuity, 660 km discontinuity.

* Corresponding author: Chuansong He (hechuansong@aliyun.com)
Plain language summary: In this study, a large amount of high-quality teleseismic data is used for CCP stacking of receiver functions in the Longmenshan area. The results imply a very important finding that a high-velocity anomaly can completely destroy upper mantle discontinuities or greatly erase the phase change in olivine. The deepening region of the 660 km discontinuity beneath the Songpan-Ganzi terrane might indicate that the large-scale high-velocity anomaly in the mantle transition zone is a cold domain and can affect the topography of upper mantle discontinuities.

1. Introduction

The Longmenshan region has undergone two orogenic events since the Mesozoic: east-west deformation induced by the Indosinian orogeny in the Late Triassic–Early Jurassic (Roger et al., 2008) and south-north deformation linked to the collision between the Indian and Asian continents in the Cenozoic (Zhang et al., 2020; Tong et al., 2021). This collision has subsequently led to large-scale crustal shortening across Asia and greatly deformed the Longmenshan area (e.g., Molnar and Tapponnier, 1975; Chatterjee et al., 2013; Searle, 1995; Huang et al., 2005).
GPS studies have reported that crustal materials are moving eastward from the Tibetan Plateau into the Longmenshan area in the Cenozoic (Zhang et al., 2004), but they are obstructed by the rigid crust and lithosphere of the Yangtze block or the Sichuan Basin (e.g., Copley and McKenzie, 2007; Oskin, 2012). This might result in stress accumulation and release in this area (He et al., 2019) and lead to several devastating earthquakes in the Longmanshan area, such as the 2001 Mw 7.8 Kunlun, the 2008 Mw 7.9 Wenchuan, the 2010 Mw 6.9 Yushu and the 2013 Ms 7.0 Lushan earthquakes.

Tomography has revealed the absence of the lithosphere beneath the Songpan-Ganzi terrane and large-scale lithospheric delamination in the Longmenshan area (He et al., 2019), which might have played a key role in stress accumulation and release and facilitated the eastern extrusion of the Tibetan Plateau (Tian et al., 2021) as well as ductile crustal thickening (Burchfiel et al., 2008; Chang et al., 2012). However, this work provides only one piece of evidence. Therefore, it is necessary to further investigate and confirm this deep process.

Based on tomographic images, the lithospheric structure (or a large-scale low-velocity structure) has delaminated into the MTZ beneath the Songpan-Ganzi terrane (He et al., 2019). Generally, a high-velocity anomaly is a cold domain, which might induce structural variations in the mantle transition zone (MTZ) (Foulger, 2012). The receiver
function technique is an effective tool that can be used to detect the structure of the MTZ.

Accordingly, I collected a large amount of high-quality teleseismic data, carried out common conversion point (CCP) stacking of receiver functions and imaged the structure of the MTZ. The results show that a large-scale high-velocity anomaly can result in weak and vanishing upper mantle discontinuities and demonstrate that the lithosphere has delaminated into the MTZ.

2. Data and method

Fig. 1 Left panel: location of the study region; inset figure: distribution of events used in this study. Right panel: distribution of seismic stations and tectonic framework; white lines: boundaries of geological units; red lines: profiles for CCP stacking of receiver functions; profiles b and c also show P-wave velocity perturbations (He et al., 2019).
In total, 684 teleseismic events were collected from 406 permanent seismic stations recorded during 2007-2020 (Fig. 1), with earthquake epicentral distances ranging from 30° to 90° for individual event-station pairs and Ms > 6.0 (Fig. 1, insert in left panel). The raw record was cut from 15 s before to 200 s after the P-wave arrival and filtered by a Butterworth bandpass filter between 0.05 and 1 Hz. To select consistent raw data for the waveforms, a cross-correlation technique (VanDecar and Crosson, 1990) was used for data processing (for example, see Fig. S1). Finally, 16258 high-quality receiver functions were extracted by a modified frequency-domain deconvolution (0.01 water level and 1 Hz Gaussian filter) (Zhu and Kanamori, 2000; Langston, 1979) (for example, see Fig. S2).

The technique of CCP stacking of receiver functions is employed to define the topographies of the 410 and 660 km discontinuities (e.g., Eagar et al., 2010; Zhu, 2000; Xu et al., 2018), and spherical coordinates are established to calculate the Ps-P differential time $T_{Ps}$ (Eagar et al., 2010):

$$T_{Ps} = \sum_{i}^{N} \left( \sqrt{\left( \frac{R_{i}}{V_{Ps}} \right)} - p_{Ps} \right) - \sqrt{\left( \frac{R_{i}}{V_{P}} \right)} - p_{P} \frac{\Delta r}{R_{i}} \quad (1)$$
where the ray parameters of the direct Ps and P phases are represented as \( p_{Ps} \) and \( p_P \), respectively. \( V_{Pi} \) and \( V_{Si} \) are the P- and S-wave velocities in the \( i \)th layer, and \( R_i \) and \( \Delta r \) represent the Earth’s semidiameter at each \( i \)th depth shell \( (r_i) \) and depth interval. A 3-D global P- and S-wave velocity model by Lu et al. (2019) is used to remove the velocity heterogeneity effects in the upper mantle. The Ps-P differential times in the 3-D model are presented as follows:

\[
T_{Ps3D} = T_{Ps} + \Delta T \quad (2)
\]

where \( \Delta T \) is related to the travel-time correction or the 3-D velocity perturbations. The high- and low-velocity anomalies in the upper mantle can result in a travel-time increase or decrease \( (\Delta T) \) of a ray and lead to deviations in the real depths of the 410 and 660 km discontinuities. In the CCP stacking of receiver functions, the lateral grid interval and depth interval are designed as 0.5° and 1 km, respectively, and the search radius (or bin) of the migrated receiver functions is designated as 75 km (Xu et al., 2018). In each bin, bootstrap resampling with 2000 resampling iterations (Efron and Tibshirani, 1986) is used to calculate the mean value and standard deviation. Piercing points are calculated by the 1-D AK135 velocity model (Kennett et al., 1995), which shows good and reasonable piercing point distributions at the depths of the 410 and 660 km (Fig. S3).
3. Results and discussion

Fig. 2 CCP stacking profiles of receiver functions (a-d) corrected by a 3-D global P- and S-wave velocity model (Lu et al., 2019). Blue rectangular region: weak and vanishing 410 km and 660 km discontinuities. The yellow points are picked for the depths of both the 410 km and 660 km discontinuities on the CCP stacking of receiver functions. The bootstrapping method with 2000 stacked amplitudes is used to resample and calculate the dataset, and the final mean receiver functions corresponding to the 95% confidence level are calculated. Horizontal blue lines: depths of 410 and 660 km.

Four CCP stacking profiles of receiver functions were obtained (Fig. 2; for the locations of the profiles, see Fig. 1). The results show that the amplitude of the 410 km
discontinuity becomes small in the western part of profile a, whereas the 410 km
discontinuity almost vanishes in the western parts of profiles b, c and d. Moreover, the
local 660 km discontinuity also vanishes in the western parts of profiles b, c and d.

Fig. 3. Profiles b and c. Overlapping diagram of the P-wave velocity perturbation (He et al.,
2019) and the CCP stacking profiles (profiles c and d; see the locations in Fig. 1). A weak
or vanishing 410 km discontinuity corresponds to the high-velocity anomaly (Hv3) or
large-scale lithospheric delamination. The yellow points are picked for the depths of both
the 410 km and 660 km discontinuities in the CCP stacking of receiver functions. The
A bootstrapping method with 2000 stacked amplitudes is used to resample and calculate the dataset, and the final mean receiver functions corresponding to the 95% confidence level are calculated. Horizontal blue lines: depths of 410 and 660 km.

To further check this issue, P-wave velocity perturbation profiles overlap with the CCP stacking profiles (b and c) (Fig. 3). The results indicate that the vanishing 410 km discontinuity in the western parts of profiles b and c corresponds well to the high-velocity anomaly (Hv3) (He et al., 2019). Clearly, the large-scale high-velocity anomaly (Hv1) completely destroys the 410 km discontinuity or makes the phase boundary of olivine vanish. To date, no such case has been reported anywhere in the world.
Fig. 4. Left panel: CCP stacking points of receiver functions, which are corrected by a 3-D global P- and S-wave velocity model (Lu et al., 2019). A stacking point with more than 10 points can be used to calculate the depth of the 660 km discontinuity. Blue elliptical region: the deepening region of the 660 km discontinuity.

I have attempted to extract the topographies of the 410 km and 660 km discontinuities. However, due to the weak and vanishing 410 km discontinuity in the western part of the study region, obtaining the complete topography of the 410 discontinuity is very difficult. Accordingly, I extract the topography of only the 660 km discontinuity in this area (Fig. 4). The results show that the 660 km discontinuity beneath the Songpan-Ganzi terrane is deepened by an average of approximately 20-30 km (Fig. 4, right panel: blue elliptical region) compared to the global topography of the 660 km discontinuity (e.g., Flanagan and Shearer, 1999; Houser et al., 2008).

Experimental studies have revealed that upper mantle discontinuities might be associated with phase changes in olivine (Katsura and Ito, 1989; Ringwood, 1975). The 410 km discontinuity has a positive pressure-temperature slope that involves the olivine-to-wadsleyite transition (Helffrich, 2000), whereas the 660 km discontinuity exhibits a negative pressure-temperature gradient that involves the ringwoodite phase transformation to perovskite and magnesiowüstite (Helffrich, 2000; Bina and Helffrich,
A high-velocity anomaly is generally considered a lower-temperature domain than the surrounding mantle; thus, inferring that the deepening topography of the 660 km discontinuity beneath the Songpan-Ganzi terrane might be associated with the low-velocity anomaly (Hv3).

4. Conclusion

Weak and vanishing upper mantle discontinuities correspond well to large-scale high-velocity anomalies, which might indicate or demonstrate that the lithosphere has delaminated into the mantle transition zone. An important finding is that large-scale high-velocity anomalies or lithospheric delamination can completely destroy upper mantle discontinuities or make them vanish. This result can be used to understand or assess a stagnant slab in the mantle transition zone, which is an issue that generates great controversy.

Acknowledgments
I am grateful to the National K&D Plan of China (Grant No. 2017YFC601406). The raw data used for CCP stacking of receiver functions can be accessed at https://doi.org/10.5281/zenodo.5035828.

References

Bina, C. & Helffrich, G. (1994). Phase transition Clapeyron slopes and transition zone seismic discontinuity topography. *J Geoph. Res., 99*, 15853-15860.

Burchfiel, B. C., Royden, L. H., van der Hilst, R. D., Hager, B. H., Chen, Z., King, R. W., Li, C., Lu, J., Yao, H. & Kirby, E. (2008). A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, China. *GSA Today 18*(7), 4-11.

Chang, C. P., Chen, G. H., Xu, X. W., Yuan, R. M., Kuo, Y. T. & Chen, W. S. (2012). Influence of the pre-existing Xiaoyudong salient in surface rupture distribution of the Mw 7.9 Wenchuan earthquake, China. *Tectonophysics* *530–531*, 240-250.

Chatterjee, S., Goswaki, A. & Scotese, C. R. (2013). The longest voyage: Tectonic, magmatic, and paleoclimatic evolution of the Indian plate during its northward flight from Gondwana to Asia. *Gondwana Research* *23*, 238-267.
Copley, A. & McKenzie, D. (2007). Model of crustal flow in the India-Asia collision zone. *Geophysical Journal International* 169, 683-698.

Eagar, K. C., Fouch, M. J. & James, D. E. (2010). Receiver function imaging of upper mantle complexity beneath the Pacific Northwest, United States. *Earth Planet. Sci. Lett.*, 297, 141-153.

Efron, B. & Tibshirani, R. B. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Stat. Sci.*, 1, 54-75.

Flanagan, M. P. & Shearer, P. M. (1999). A map of topography on the 410-km discontinuity from PP precursors. *Geophys. Res. Lett.*, 26, 549-552.

Foulger, G. R. (2012). Are ‘hot spots’ hot spots?. *J. Geodyn.*, 58, 1-28.

He C. S., Dong, S. W. & Wang, Y. H. (2019). Lithospheric delamination and upwelling asthenosphere in the Longmenshan area: insight from teleseismic p-wave tomography. *Scientific Reports*, 9, 6967.

Helffrich, G. (2000). Topography of the transition zone seismic discontinuities. *Rev. Geophys.*, 38, 141-158.

Houser, C., Masters, G., Shearer, P. M. & Laske, G. (2008). Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms. *Geophys. J. Int.*, 174, 195-212.
Huang, B. C., Piper, J. D. A., Wang, Y. C., He, H. Y. & Zhu, R. X. (2005). Paleomagnetic and geochronological constraints on the post-collisional northward convergence of the southwest Tian Shan, NW China. *Tectonophysics, 409*, 107-124.

Katsura, T. & Ito, E. (1989). The systemMg2SiO4–Fe2SiO4 at high pressures and temperatures: precise determination of stabilities of olivine, modified spinel, and spinel. *J. Geophys. Res.*, 94, 15663-15670.

Kennett, B. L. N., Engdahl, E. R. & Buland, R. (1995). Constraints on seismic velocities in the Earth from traveltimes. *Geophys. J. Int.*, 122, 108-124.

Langston, C. A. (1979). Structure under Mount Rainier, Washington, inferred from teleseismic body waves. *J. Geophys. Res.*, 84, 4749-4762.

Molnar, P. & Tapponnier, P. (1975). Cenozoic tectonics of Asia: effects of a continental collision. *Science, 189 (4201)*, 419-426.

Oskin, M. E. (2012). Reanimating eastern Tibet. *Nature Geoscience, 5*, 597-598.

Owens, T. J., Zandt, G. & Taylor, S. R. (1984). Seismic evidence for an ancient rift beneath the Cumberland Plateau, Tennessee: a detailed analysis of broadband teleseismic P waveforms. *Journal of Geophysical Research 89*, 7783-7795.

Ringwood, A. (1975). Composition and Petrology of the Earth’s Mantle. McGraw-Hill, New York 618.
Roger, F., Jolivet, M. & Malavielle, J. (2008). Tectonic evolution of the Triassic fold belts of Tibet. *Comptes Rendus Geoscience, 340*, 180-189.

Searle, M. (1995). The rise and fall of Tibet. *Nature 374*, 17-18.

Tian, H. Y., He, C. S. & Santosh, M. (2021). S-wave velocity structure of the Sichuan-Yunnan region, China: implications for extrusion of Tibet Plateau and seismic activities. *Earth and Space Science*, accepted.

Tong, Y., Yang, Z., Pei, J., Wang, H., Wu, Z., & Li, J. (2021). Crustal clockwise rotation of the southeastern edge of the Tibetan Plateau since the late Oligocene. *Journal of Geophysical Research, 126*, e2020JB020153.

van der Meijde, M., van der Lee, S. & Giardini, D. (2005). Seismic discontinuities in the Mediterranean mantle. *Phys. Earth Planet. Inter., 148*, 233-250.

VanDecar, J. C. & Crosson, R. S. (1990). Determination of teleseismic relative phase arrival times using multi-channel cross-correlation and least squares. *Bull. Seismol. Soc. Am., 80*, 150-169.

Xu, M. J., Huang, H., Huang, Z. C., Wang, P., Wang, L. S., Xu, M.J., Mi, N., Li, H., Yu, D. Y. & Yuan, X. H. (2018). Insight into the subducted Indian slab and origin of the Tengchong volcano in SE Tibet from receiver function analysis. *Earth Planet. Sci. Lett., 482*, 567-579.
Zhang, C., Guo, Z., & Chen, Y. J. (2020). Lithospheric thickening controls the ongoing growth of northeastern Tibetan Plateau: Evidence from P and S receiver functions. *Geophysical Research Letters, 47*, e2020GL088972.

Zhang, P. Z., Shen, Z., Wang, M. & Gan, W. (2004). Continuous deformation of the Tibetan Plateau from Global Positioning System data. *Geology, 32*, 809-812.

Zhu, L. & Kanamori, H. (2000). Moho depth variation in southern California from teleseismic receiver functions. *J. Geophys. Res., 105*, 2069-2980.

Zhu, L. (2000). Crustal structure across the San Andreas Fault, southern California from teleseismic converted waves. *Earth Planet. Sci. Lett., 179*, 183-190.

**Author contributions**

H.C. conducted the analysis and wrote the first draft, and contributed to the interpretation of results and writing.

**Additional information**

Competing Interests: The author declare no competing interests.

**Electronic supplementary material**

Supplementary Information
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [20210628SupplementaryInformation.docx]