

Permian plume beneath Tarim from receiver functions

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Abstract

Receiver functions for the central Tien Shan and northern Tarim in central Asia reveal a pronounced depression on the 410-km discontinuity beneath the Permian basalts in Tarim. The depression may most likely be caused by elevated temperature. The striking spatial correlation between the anomaly of the MTZ and the Permian basalts suggests that both may be effects of the same plume. This relation can be reconciled with reconstructed positions of paleo-continents since the Permian by assuming that the mantle layer which translated coherently with the Tarim plate extended to a depth of 410 km or more. Alternatively, lithosphere and the underlying mantle are decoupled at a depth of ~ 200 km, but a cumulative effect of the Tarim plate motions since the Permian is by an order of magnitude less than predicted by the paleo-reconstructions. A similar explanation is applicable to the Siberian traps.

1. Introduction.

Theoretical considerations predict decoupling of the rigid lithosphere and the underlying ductile upper mantle (asthenosphere) at the lithosphere-asthenosphere boundary (Eaton et al., 2009). The depth to the lithosphere-asthenosphere boundary (LAB) ranges from a few tens kilometers for a young lithosphere to about 300 km for Precambrian cratons (e.g. Artemieva and Mooney, 2001). Another idea postulates that the layer which translates coherently with the continental plate (tectosphere) may extend to a depth of at least 400 km (Jordan, 1978).

25 Examples of successful application of the concept of tectosphere to geophysical data are few. We test this idea by comparing the locations of possible remnants of extinct mantle plumes in the mantle transition zone (MTZ) and the related basaltic outcrops at the Earth's surface.

Recently this test was applied to the Siberian Large Igneous Province (LIP). The Siberian traps present the result of gigantic basalt eruptions which took place near the Permo-Triassic
30 boundary at about 250 Ma (Fedorenko et al., 1996). The analysis of structure of the mantle beneath the Siberian LIP was conducted with the aid of receiver function techniques that were applied to the recordings of seismograph station Norilsk (NRIL) within the Siberian LIP (Vinnik et al., 2017). This analysis has shown that the seismic boundary at the top of the MTZ with a standard depth of 410 km is depressed in the vicinity of NRIL by 10 km. The diagram of olivine
35 - wadsleyite phase transition may account for this depression by assuming about 100 K increase of the temperature.

In the depth range from 350 to 410 km, the S velocity beneath the Siberian LIP is reduced by 4 – 5% (Vinnik and Farra, 2007) relative to IASP91 model (Kennett and Engdahl, 1991). This is a likely effect of about 1 vol % melt (Hier-Majumder and Courtier, 2011) which is unusual for
40 cratons. Jasbinsek et al. (2010) speculated that the low velocity atop the 410-km discontinuity may be an effect of anisotropy or subducted oceanic crust but they failed to provide any supporting observation. Another low-velocity layer is found in the depth interval from 460 to 500 km. Previously this layer was found in the vicinities of several hot-spots (e.g., Vinnik et al., 2012). The low S-wave velocity coincides in depth with the abrupt decrease of the solidus
45 temperature of carbonated mantle (Keshav et al., 2011) and may also be related to melting. The Siberian Craton shifted in the last 250 Myr by about 2000 km to the east (Torsvik et al., 2008). The anomalies of the MTZ might preserve their position beneath the Siberian LIP in spite of the plate motion if they translated coherently with the Siberian plate.

A similar conclusion is obtained for Greenland by Kraft et al. (2018). Arrival times of
50 P660s and P410s mode converted phases in P receiver functions (PRFs) were measured at 24

seismograph stations in central-eastern Greenland. In two regions corresponding to basaltic outcrops about 55 Myr old, the differential time between P660s and P410s seismic phases is reduced by more than 2 s relative to IASP91 reference model. The 410-km discontinuity in these regions is depressed by more than 20 km. The depression can be explained by elevated
55 temperature. The basaltic outcrops and the related temperature anomalies are likely related to the passage of Greenland over the Iceland hot-spot. This explanation is consistent with the concept of tectosphere and implies that the upper mantle beneath Greenland to a depth of at least 430 km translated coherently with the Greenland plate.

Here we describe a similar analysis for the central Tien Shan and Tarim in central Asia and
60 discuss possible implications of these observations.

2. Seismic structure of the MTZ beneath the central Tien Shan and Tarim.

This section presents in condensed form the results of the recent seismic study (Kosarev et al., 2018) of the MTZ beneath the central Tien Shan and northern Tarim (Fig.1). The ongoing orogenesis in central Asia is a likely far-field effect of the India-Eurasia collision (Molnar and
65 Tapponnier, 1975). Previous mountain-building episodes in the region of the Tien Shan took place in the Paleozoic (e.g., Windley et al., 1990), but for about 100 Myr prior to the onset of the present-day mountain building the lithosphere of the Tien-Shan was quiet. Tectonic activity resumed at about 25-20 Ma in the southern Tien Shan (Sobel and Dumitru, 1997) and at 11 Ma in the north (Bullen et al., 2001). The lithosphere of Tarim underthrusts the relatively weak
70 lithosphere of the Tien Shan at a rate of about 20 mm/yr (Reigber et al., 2001).

Teleseismic recordings of 64 broad-band stations in Fig. 1 were low-pass filtered with a corner at 6s and transformed into PRFs. The PRFs were calculated by using the LQ coordinate system, where L is parallel to the principal motion direction of the P wave and Q is normal to L in the wave propagation plane. The Q components were deconvolved by the L components in
75 time domain and stacked to reduce noise. In the context of our study the most important elements of the PRFs are P660s and P410s mode converted seismic phases. The 410-km and 660-km

discontinuities mark the top and bottom of the MTZ and their depths are sensitive to the temperature and composition.

The times of P660s and P410s seismic phases depend not only on topography of the 660-km
80 and 410-km discontinuities but also on volumetric velocity heterogeneities above the 410-km
boundary. Separation of these two effects is the main problem of interpreting the observations of
P660s and P410s phases. This problem is solved by calculating the time difference (differential
time) between the arrivals of P660s and P410s phases. The ray paths of P660s and P410s phases
in the crust and upper mantle are close to each other for the same seismic recording, and, as a
85 result, the differential time is insensitive to the properties of the Earth's medium above the MTZ.

To detect P660s and P410s phases and to map the differential time, a large number of the
PRFs should be stacked. One possibility is to apply a version of CCP (Common Conversion
Point) stacking: to divide the Earth's surface into cells and to stack with appropriate move-out
time corrections the PRFs, the projections of the conversion points of which fall into the same
90 cell. However, the surface projections of the conversion points of P410s and P660s phases for
the same recording are at different distances (around 1° and 2°, respectively) from the
seismograph station, and the set of PRFs thus selected for the detection of P410s phase may
differ from that for P660s phase. Then the differential time of stacked P660s and P410s phases
can be affected by lateral heterogeneity of the crust and mantle above the MTZ. This can be
95 avoided by locating the conversion points in the middle of the MTZ (at a depth of 535 km) and
stacking those PRFs, the projections of the conversion points of which are located within the
same cell. Then P410s and P660s phases for each cell are detected in the same set of PRFs and
the effect of lateral heterogeneity above the 410-km discontinuity is minimized.

Epcenters of seismic events of sufficient magnitude in a distance range from 35° to 90° are
100 abundant in a broad azimuth range. Surface projections of the conversion points at a depth of 535
km cover the area between 38°N and 44°N and between 72°E and 82°E. The cells were chosen
in the form of a rectangular box. The size of the box affects lateral resolution and, through the

number of stacked PRFs, accuracy of the estimates of the differential time. The individual PRFs were visually inspected and only those of the best quality were stacked. The optimum size of the box (2° for NS and EW or 220 km and 160 km, respectively) was found by trial and error. The largest number of the stacked PRFs exceeds 1750, the smallest is 48 (See Fig. 3 Table 1). These numbers are sufficient for a robust detection of P660s and P410s phases (see example in Fig. 2). The accuracy of the estimates of the differential time (confidence interval of 66%) which was determined by bootstrap resampling (Efron, Tibshirani, 1991) is typically 0.2 s. For most boxes the residuals of the differential time with respect to the IASP91 value (23.9 s) are on the order of a fraction of a second (Fig. 3). Large residuals (more than 1.0 s) are obtained for three boxes: ($40^\circ - 42^\circ\text{N}$, $76^\circ - 78^\circ\text{E}$, +1.5 s), ($40^\circ - 42^\circ\text{N}$, $72^\circ - 74^\circ\text{E}$, -1.1 s) and ($38^\circ - 40^\circ\text{N}$, $80^\circ - 82^\circ\text{E}$, -1.5 s). Further on these boxes are referred as a, b and c. The resulting anomalies of thickness of the MTZ for a, b and c are +15 km, -11 km, and -15 km, respectively. These anomalies are located beneath the south-central Tien Shan, Fergana Basin and Tarim. We note that while the number of stacked PRFs for c is minimal (48), quality of the PRFs (signal-noise ratio) in this box is very high and the accuracy of the differential time is comparable with the other boxes.

The further analysis (Kosarev et al., 2018) demonstrates that the increased thickness of the MTZ in a is the effect of an uplift of the 410-km discontinuity and a depression of the 660-km discontinuity. The MTZ might be cooled by a detached and sinking mantle lithosphere. The thinned MTZ in b and c is the effect of a depressed 410-km discontinuity and a stable 660-km discontinuity. The depressed 410-km discontinuity beneath b and c is likely a result of a temperature anomaly of about $+100^\circ\text{C}$. The elevated temperature in b may be related to a plume which is responsible for small-scale basaltic volcanism in the Tien Shan from 72 Ma to 60 Ma. Possible origin of the anomaly in c (Tarim) is discussed in next Section.

3. Possible origin of the anomalous MTZ beneath Tarim.

Tarim can be characterized as an Archean craton (Yuan et al., 2004) with a complex evolutionary history (Zhang et al., 2013; Deng et al., 2017). In the Permian, basalts with the areal

extent of about 200000 km² erupted in the west of the Tarim basin (Fig. 4). The thickness of
130 basalt reaches 800 m. The age span of the magmatism extends from about 292 Ma to 272 Ma
with two peaks at 279 Ma and 289 Ma (Wei et al., 2014). The magmatism is interpreted as
plume-induced (Zhang et al., 2010; Xu et al., 2014). Evidence for the mantle plume beneath
Tarim includes the large volume of the Permian mafic rocks, OIB-like trace element signatures,
Permian crustal doming and the high zircon saturation temperatures (Zhang et al., 2008, 2010).
135 No magmatic activity is known after the Permian (Zhang et al., 2013; Deng et al., 2017).

Fig. 4 demonstrates a striking spatial correlation of the depressed 410-km discontinuity and
the Permian magmatic province in Tarim, with implication of a causal relation between them. An
alternative interpretation suggests that the topography on the 410-km discontinuity, though
spatially correlated with the Permian basalts is caused by another, relatively young plume.
140 However, this seems unlikely, as recently erupted (post-Permian) basalts are unknown in Tarim.
The depressed 410-km discontinuity and the stable 660-km discontinuity are typical for hotspots
and plumes (e.g. Du et al., 2006), though there are some exceptions (e.g. Vinnik et al., 2012). The
stable depth of the 660-km discontinuity is either the result of a zero temperature anomaly at the
base of the MTZ or an effect of two phase transitions at nearly the same depth but with opposite
145 Clapeyron slopes (Hirose, 2002).

The assumed causal relation between the Permian basalts and the present-day anomaly
implies that the anomaly at a depth of ~400 km may exist for ~300 Myr. To check this
possibility we calculated the temperature for 1D conductive medium by using the well known
expression (e.g., Zharkov et al., 1969) $T(r,t) = Q \exp(-r^2/4\alpha t)/2\sqrt{\pi\alpha t}$, where T is temperature, t is
150 time, r is distance, α is diffusivity, Q is constant, and the initial temperature anomaly distribution
is taken in the form of δ -function at $r = 0$ and $t = 0$. The diffusivity α is taken equal to 32
km²/m.y. (e.g., Morgan and Sass, 1984). The results (Fig.5a) demonstrate that the temperature
anomaly in the time interval of 300 m.y. (between 100 m.y. and 400 m.y.) is halved. The
maximum temperature anomaly in plumes is ~300 ±100°C (Campbell, 2005), which means that

155 the temperature anomaly after 300 m.y. may be around 150°C, close to the seismic estimate. A comparable result is obtained for 2D conductive medium (Fig. 5b). These calculations suggest that the thermal anomaly at a depth of 400 km may survive for a few hundred million years.

It is also possible that the anomalous depth of the 410-km discontinuity is an effect of anomalous composition. The pressure of the phase transition in $(\text{Mg,Fe})_2\text{SiO}_4$ depends on the
160 Mg content (Mg#) relative to Fe (Fei and Bertka, 1999). Increasing Mg# from 89 to 92 results in up to 10-km deepening of the 410-km discontinuity (Schmerr and Garnero, 2007). The depleted composition and increased Mg# are commonly interpreted as effects of melting (e.g., Boyd, 1989).

Relative positions of the present-day thermal anomaly in the MTZ and the Permian basalt
165 eruptions depend on plate motions in the last ~300 Myr. Reconstruction of positions of old continents is difficult for the time exceeding the age of the oldest hot-spot trails (130 Ma). There are abundant paleomagnetic data for the earlier times, but they do not constrain paleo-longitudes. The motions of Tarim are constrained by paleomagnetic data. According to Zhao et al. (1996) Tarim might be attached to Eurasia since the Late Paleozoic time, and there are paleomagnetic
170 indications of displacements of Tarim relative to Eurasia after the Cretaceous, apparently owing to the India-Eurasia collision (Zhao et al., 1996). The uncertainty of the paleoreconstructions for the Mesozoic can be minimized by selecting Africa as a reference continent that was most stable longitudinally (Torsvik et al. 2008). In this reference frame the Siberian traps shifted to the east by nearly 2000 km since they were erupted at 250 Ma (Torsvik et al., 2008). On the assumption
175 that Tarim and the Siberian craton were parts of the same continental plate in the past 300 Myr, 2000 km can be used as a rough estimate of the shift of Tarim.

The spatial correlation between the anomaly in the MTZ and the basalt eruptions in Tarim
(Fig. 4) in spite of the shift of the Tarim craton to the east and north-east by a few thousand kilometers is possible if the layer which translates coherently with the plate includes the top of
180 the MTZ. Alternatively this is possible without the recourse to the deep tectosphere, if the

available paleo-reconstructions for Asia are too rough and the actual shift of Tarim is by an order of magnitude less than predicted. This would also be true for the Siberian traps.

4. Conclusions

The striking spatial coincidence of the Permian basalts and a depression on the 410-km discontinuity beneath Tarim (Fig. 4) suggests that both may be related to the same mantle plume. This relation allows a dual interpretation. Recent reconstructions (Torsvik et al., 2008) demonstrate a shift of Tarim of about 2000 km in the past 300 Myr. Then the observed relation between the deep and shallow features can be explained by a coherent translation of the crust and mantle to a depth of 430 km. Alternatively the spatial coincidence of the deep and shallow features is possible without the recourse to the deep tectosphere if the actual shift of Tarim is by an order of magnitude less than predicted by the reconstructions. Practically similar conclusions would apply to the Permo-Triassic traps of the Siberian Craton.

It would be useful in the future to find other evidence that may indicate whether tectosphere extends to over 400-km depth. For example, it would be interesting to look at the strength and direction of azimuthal anisotropy in the 100-400 km depth range to investigate if there is evidence for flow related to absolute plate motion shallower than the MTZ. It is difficult to do this with the available seismic data. The Tarim basin has the largest desert area in China, practically devoid of seismogram stations, but more data will be available in future.

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300 **Figure captions**

Figure 1. Topographic map of the study region and the seismograph network.

Figure 2. Stacked PRFs for the box with the coordinates: 38 N, 40N, 80 E and 82 E. Trial conversion depths in kilometers for each trace are shown on the left-hand side. The detected P410s and P660s phases are marked by arrows. Note that the largest amplitudes of P410s and P660s phases are observed at appropriate trial depths (around 400-500 km and 600=700 km, respectively).

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Figure 3. Residuals of the differential time between P660s and P410s phases in seconds relative to IASP91. Strongly anomalous boxes are in south-central Tien Shan (1.5 s, blue, a), Fegana

310 basin (-1.1 s, red, b) and Tarim (-1.5 s, red, c). Light shading indicates elevations greater than
 1500 m, intermediate shading elevations greater than 3000 m. The number of stacked receiver
 functions in each box is shown by italics.

Figure 4. Superimposed Permian basalts in Tarim (orange) and the anomalous region on the 410-
 km discontinuity.

315 **Figure 5.** Temperature anomaly distributions in 1D (a) and 2D (b) conductive media with an
 interval of 300 million years.

Table 1. Numbers of piercing points in the boxes in Fig. 3.

| lat1 | lat2 | lon1 | lon2 | number of pp |
|------|------|------|------|--------------|
| 38 | 40 | 72 | 74 | 132 |
| 38 | 40 | 74 | 76 | 267 |
| 38 | 40 | 76 | 78 | 402 |
| 38 | 40 | 78 | 80 | 96 |
| 38 | 40 | 80 | 82 | 48 |
| 40 | 42 | 72 | 74 | 414 |
| 40 | 42 | 74 | 76 | 1130 |
| 40 | 42 | 76 | 78 | 1512 |
| 40 | 42 | 78 | 80 | 616 |
| 40 | 42 | 80 | 82 | 322 |
| 42 | 44 | 72 | 74 | 317 |
| 42 | 44 | 74 | 76 | 757 |
| 42 | 44 | 76 | 78 | 1766 |
| 42 | 44 | 78 | 80 | 533 |
| 42 | 44 | 80 | 82 | 332 |
| 44 | 46 | 74 | 76 | 120 |