A second review of Permian plume beneath Tarim from receiver functions.

The revised version of this paper makes some improvements, but still has some significant weaknesses.

My primary concern is the possibility of move-out artifacts in the migration of the receiver functions. This is why I asked earlier about an event map to illustrate the azimuth and incidence distribution through the cells. Considering the distribution of stations is entirely to the northwest of the Tarim anomaly and that there is another anomaly (cell [a]) right in the center of the array, suggests move-out artifacts may be present. This concern is somewhat assuaged by the high amplitude of the anomalous cells, but I do worry the results may be skewed by these artifacts. This concern could be addressed by stacking geographic sub-arrays, such as one to the southeast, one to the northwest, one in the center, etc… and presenting in a multi-panel figure or single station stacking by ray-parameter and back-azimuth bins. I want to stress that I am not making this request because I doubt your algorithm, rather I am requesting this because I have run into similar issues with past experiences.

I still feel the exploration of alternative interpretations is not sufficient. The only lines I see addressing an alternative process-based interpretation is 136-138. This could be expanded by briefly discussing works that have suggested models of upper-mantle upwellings (e.g. James, Fouch, Carlson, and Roth, EPSL, 2011, Slab fragmentation, edge flow and the origin of the Yellowstone hotspot track; Tang Obayashi, Niu, Grand, Chen, Kawakatsu, Tanaka, Ning, and Ni, Nature Geoscience, 2014, Changbaishan volcanism in northeast china linked to subduction-induced mantle upwelling) which may result in a thinned MTZ in response to subduction processes. After setting up this alternative, you can then explain why this is not a likely interpretation due to the age of observed basalts and lack of evidence of subducting slabs in the region. The point is not to put forward unlikely interpretations, rather it is to show an exploration of alternatives and explain why those alternatives do not fit the data.

Line-by-line
Line 10: The term “most likely” is unnecessary
Line 21-22: “tens kilometers” should be “tens of kilometers”
Line 28-29: The transition from Siberian LIP to traps is not defined. This may confuse people not familiar with the terms. Simply adjust the prior sentence to something like: “Recently this test was applied to the Siberian traps Large Igneous Province (LIP).”
Line 38: “to IASP91” should be “to the IASP91” (see also line 51)
Line 52-53: “The depression can be explained by elevated temperature” should have a slight change, such as “Kraft et al., 2018 interpret this as due to elevated temperature”.
Line 62: “Asia is a likely far-field” should be “Asia is likely a far-field”
Line 73-74: “components in time domain” should be “components in the time domain”
Line 85-86: “CCP (Common Conversion Point)” should be “Common Conversion Point (CCP)”
Line 86-88: This sentence describing CCP stacking reads oddly. I’m not sure if it is technically grammatically incorrect, but I find myself tripping over reading it. I think a clearer sentence would be something like: “stacking. This process divides the Earth’s surface into cells and

stacks, after an appropriate move-out correction, the PRF amplitudes which project into the same cell."
Line 102: What metric was used to define "best quality"?
Line 111: I appreciate the labelling of boxes a, b, c as requested, but leaving them as lowercase letters blends into the regular text. Swap these out with capital A, B, and C to make them stand out more.
Line 116: "The further analysis (Kosareve et al., 2018)" should be "A broader in scope analysis by Kosarev et al., 2018," (or similar as the meaning of "further analysis" is not clear).
Line 120 (and other places to consider): The term "likely" suggests some statistical framework with a probability greater than 50% that doesn't seem possible in this context. For this line in particular, replacing likely with "may be" would remove that indication.
Line 123: "Possible…" should be "A possible…"
Line 126: "basalts with the areal" should be "basalts with an areal"
Line 132: "and the high zircon" should be "and high zircon"
Line 135: "with implication of" should be "and we infer"
Line 146: "for 1D" should be "for a 1D"
Line 146: "the well known" I think should be "a simple heat diffusion"
Line 153: Where does the seismic estimate of around 150˚C come from? I assume this is based on the depressed 410, but it could also be due to the velocity anomaly referenced earlier.
Line 154: "for 2D" should be "for a 2D"

Figure 2: I'm not sure what the string is on the top of the plot and the caption has a typo 600=700 km rather than 600-700 km

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).

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 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 - 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 cratons. 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 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 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 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.

Kraft et al., 2018 interpret this as due to…

Here we describe a similar analysis for the central Tien Shan and Tarim in central Asia and 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 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 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 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 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 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 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 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.

Epicenters of seismic events of sufficient magnitude in a distance range from 35° to 90° are 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 (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° - 42°N, 76° - 78°E, +1.5 s), (40° - 42°N, 72° - 74°E, -1.1 s) and (38° - 40°N, 80° - 82°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.

yes, better, but change to capital letters or enclose in braces to differentiate from normal text

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°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.

may be

A possible…

3. Possible origin of the anomalous MTZ beneath Tarim.

Tarim can be characterized as an Archean craton (Yuan et al., 2004) with a complex evolutional history (Zhang et al., 2013; Deng et al., 2017). In the Permian, basalts with the areal extent of about 200000 km^2 erupted in the west of the Tarim basin (Fig. 4). The thickness of 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). 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. 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 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 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 km^2/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 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 $(Mg,Fe)_2SiO_4$ depends on the 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 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 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 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 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.

Acknowledgment

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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).

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 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.

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

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

Figure 1

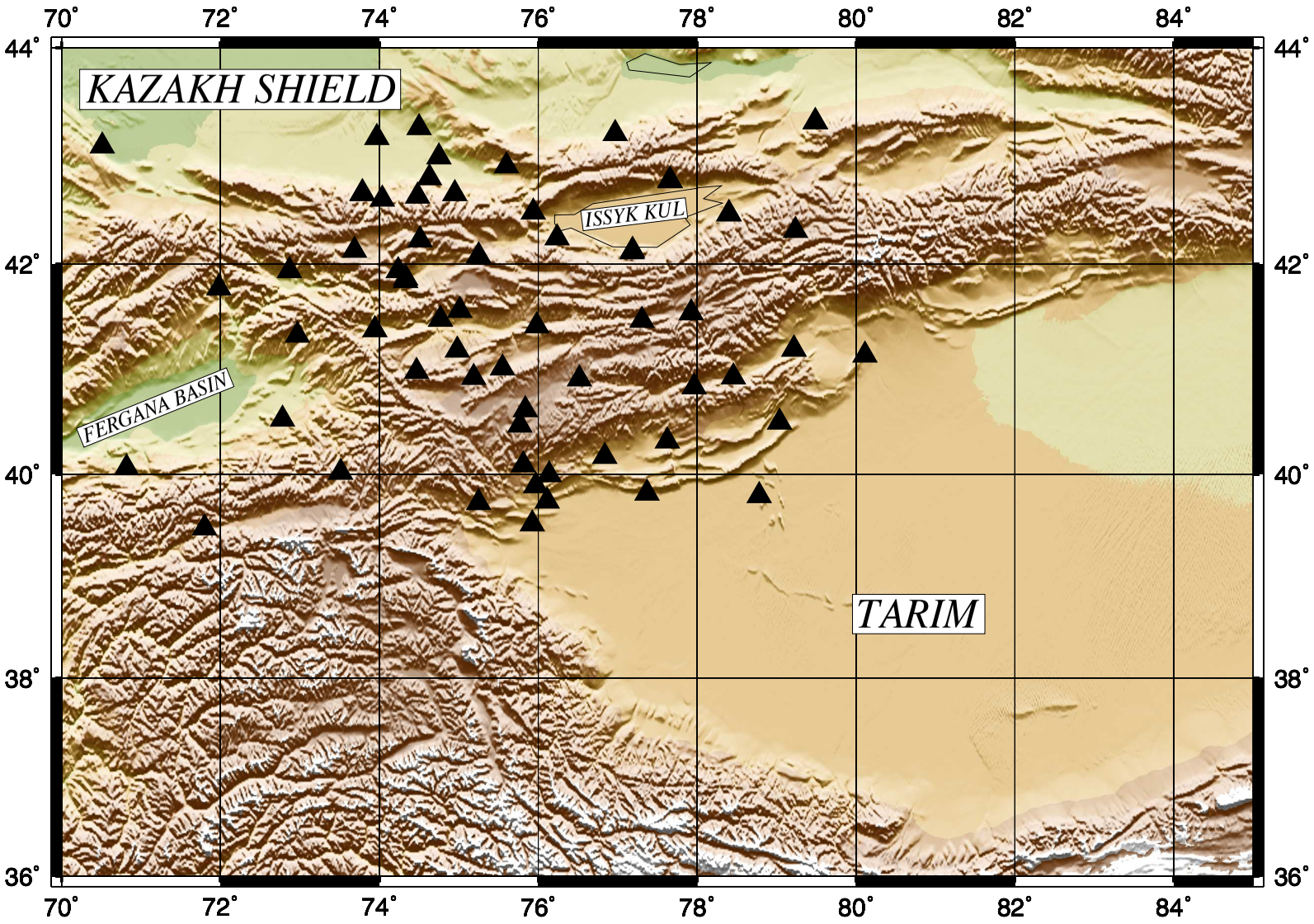

70°
72°
74°
76°
78°
80°
82°
84°
44°
42°
40°
38°
36°
KAZAKH SHIELD
ISSYK KUL
FERGANA BASIN
TARIM

Figure 2

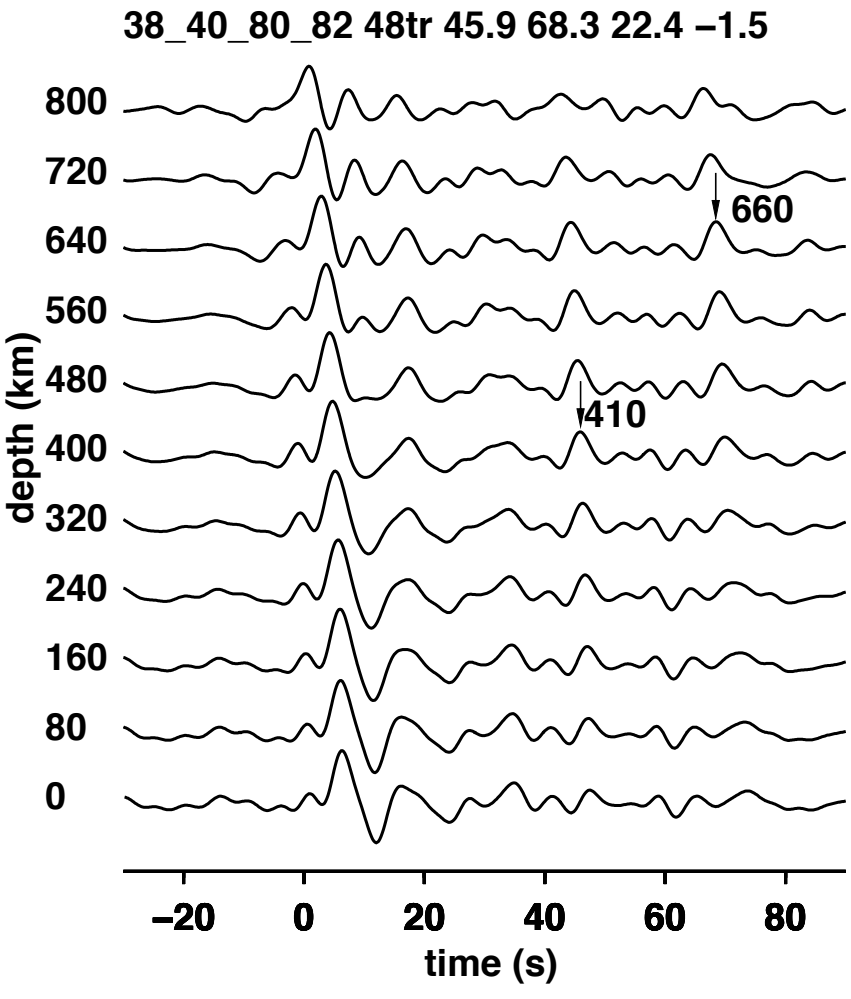

38_40_80_82 48tr 45.9 68.3 22.4 −1.5
800
720
640
560
480
400
320
240
160
80
0
660
410
depth (km)
−20
0
20
40
60
80
time (s)

Figure 3

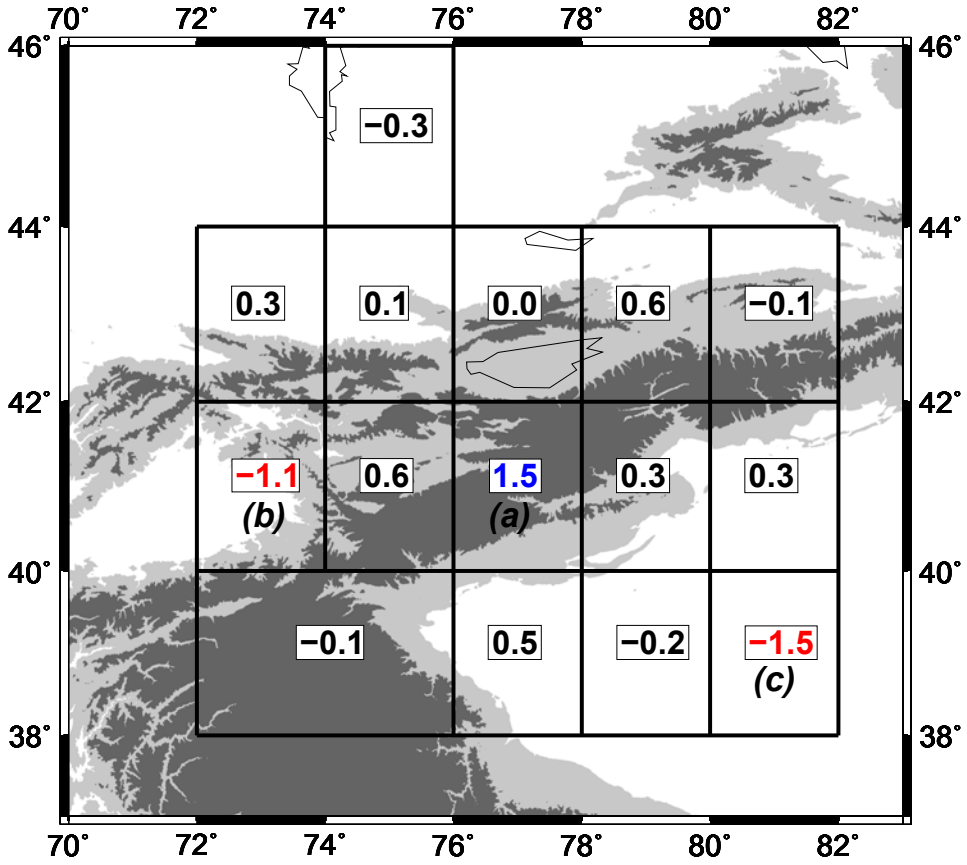

70°
72°
74°
76°
78°
80°
82°
46°
44°
42°
40°
38°
−0.3
0.3
0.1
0.0
0.6
−0.1
−1.1
(b)
0.6
1.5
(a)
0.3
0.3
−0.1
0.5
−0.2
−1.5
(c)

Figure 4

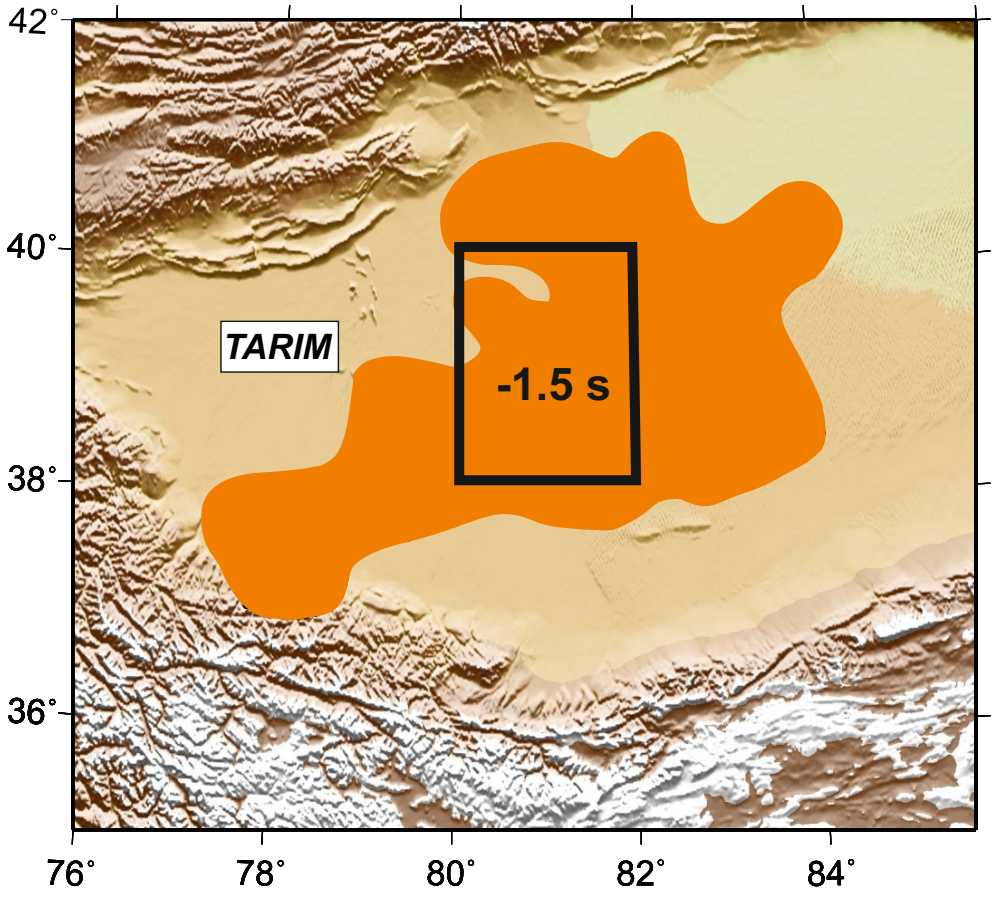
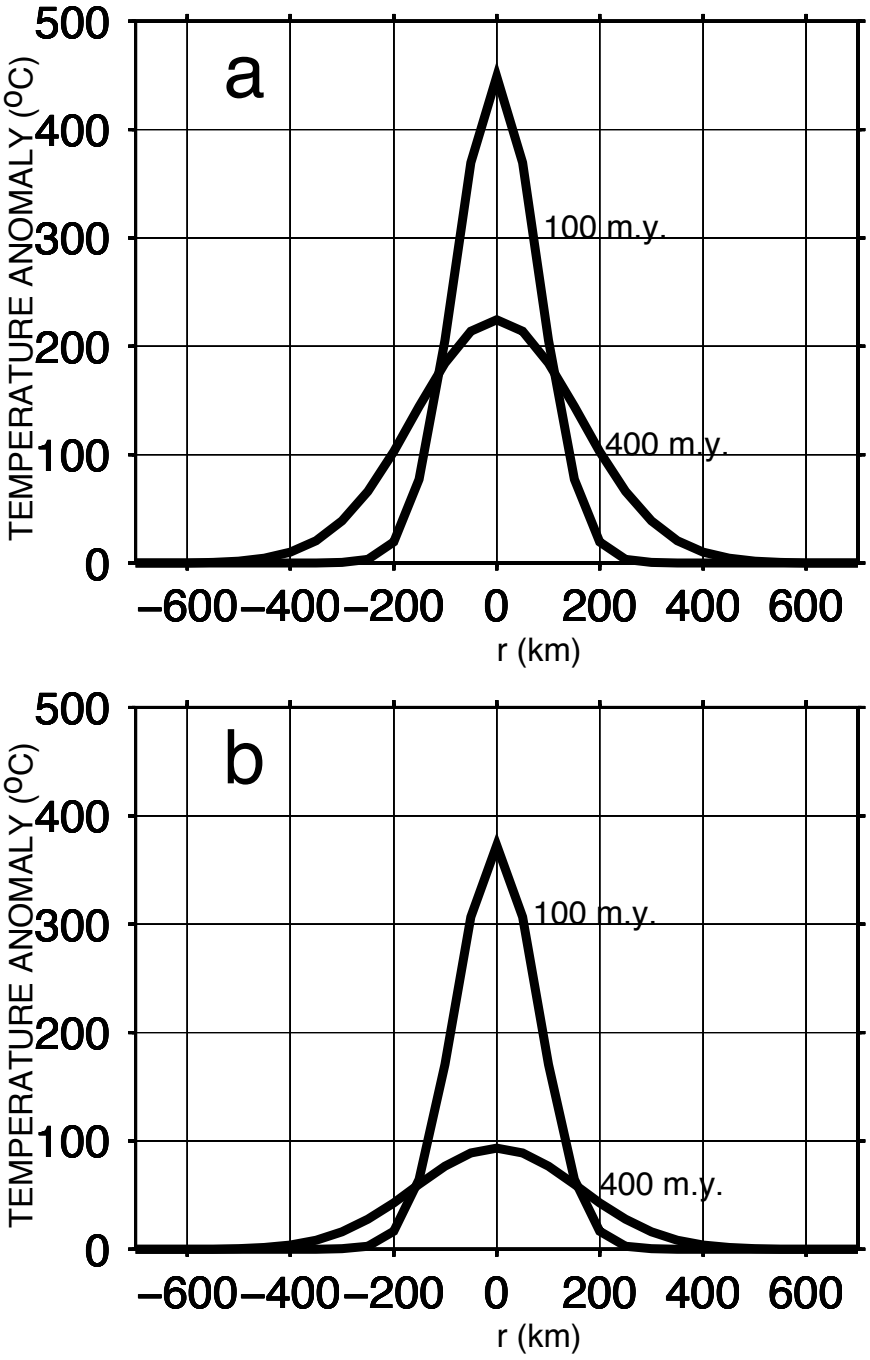


Figure 5


a
b
TEMPERATURE ANOMALY (°C)
500
400
300
200
100
0
100 m.y.
400 m.y.
–600 –400 –200 0 200 400 600
r (km)