

R. Porritt (Referee)

In this paper, the authors expand on the discussion presented in Kosarev et al., 2018 by focusing on the depressed 410km discontinuity under the Tarim Basin. Correlating this depression with the location of ~300Myr old basalts, they argue for a tectosphere style interpretation in which the upper ~400km translate coherently over ~300Myr and 2000km. This represents a controversial view as typical thought is that the mechanical lithosphere is limited to ~100 – 250 km.

The additional evidence, beyond the seismic data of Kosarev et al., 2018, they provide is a pair of simple models for 1D and 2D heat diffusion from a plume, suggesting the interpreted temperature perturbations are consistent with 300Myr of cooling from a 300Ma plume.

We appreciate comments from the reviewer. In response to the critical comments we have made numerous changes in the manuscript.

The primary weakness of the paper is the reliance on a spatial correlation between basalts and seismic observations of a warm upper mantle and I don't feel they've done a rigorous enough job of evaluating and eliminating alternative hypotheses.

We propose a causal relation between the Permian basalts and the anomalous transition zone. Alternatively the anomaly of the MTZ may be caused by another, relatively young thermal event. This is less likely because only one significant thermal event in Tarim is known since the Permian (lines 133 - 139).

A secondary weakness in the paper is the frequent use of approximate phrases where a more specific quantification is warranted. For example, line 68 they state that about 100 broadband stations were used rather than listing the actual number of stations. I assume these shortcuts were taken as the interested reader can see the Kosarev et al., 2018 reference, but much of the method section uses the same loose language in Kosarev et al., 2018.

In response to this comment we made many changes. For example for the number of stations we have given precise number (64), see line 69.

A few additional citations are required.

We have added 7 additional citations.

“Siberian LIP drops by a few percent”: quantify “a few”

We have changed it to 4-5% (line 38).

Line 37-39: Expand on evidence used for “partial melt” and alternatives. Not all low velocity mantle anomalies are partial melt.

To our knowledge, melting is the only explanation for the low velocity atop the 410-km discontinuity that was discussed in the literature.

Line 68: “about 100 stations”: how many were actually used?

Precise number is 64 (see line 69).

“corner at around 6 s: what were the actual period limits?

We have removed “around” (line 70).

Line 83-86: Why was this stacking method used rather than the more traditional CCP? Kosarev et al., 2018 does briefly discuss it, but rephrasing it here would be useful for analysis of the data presented here.

We have added lines 84-96. This should minimize the effect of lateral heterogeneity of the earth's medium above the 410-km discontinuity.

Line 87-88: What is the event coverage? Perhaps reproduce Kosarev et al., 2018 figure2 with figure 1 or 2 here.

We have added lines 97-99 and Table 1.

Line 89-90: How is a confidence interval of 66% determined?

It was determined by Bootstrap resampling (see lines 106, 107).

Line 91: Citation for IASP91 model? Also I assume that the thickness perturbations are based on that same model.

We have added the reference (Kennett and Engdahl, 1991) at the first IASP91 model in Line 38.

Of course, the thickness perturbations are based on that same model. For details see Kosarev et al., 2018.

Line 93-97: Somewhere in here, it would be useful to label the anomalous boxes (a,b,c) for referencing.

Done, see line 111 and new fig. 3.

Citation needed for high heat flow and uplift during the Permian.

Done, see references in line 132 (Zhang et al., 2008, 2010).

“Coherence” should be “correlation”.

Corrected everywhere.

Citation is needed for heat diffusion equation and choice of parameters.

Done, see lines 147 and 150 (Zharkov et al., 1969; Morgan and Sass, 1984).

Line 137-138: What is the relation between increased Mg content and partial melting (citation).

Done, see line 159-161. The depleted composition and increased Mg# are commonly interpreted as effects of melting (e.g., Boyd, 1989).

Anonymous Referee

Reviewer #2.

In this paper Vinnik et al. discuss the results of Kosarev et al. 2018 that show there is a relatively thin mantle transition zone (MTZ) beneath part of the Tarim Basin that is coincident with the presence of 290-260Ma basalts, thought to be plume related. They calculate that a plume present ~300Ma could still leave a thermal signature on the MTZ. They argue that these results support a tectosphere model: that the layer that translates coherently with the continental plate extends to the top of the MTZ at around ~410km depth, although they do mention that if the rate of plate motion is an order of magnitude less than predicted by plate reconstruction models this may not necessarily be the case. It is an interesting possibility, however I feel that the manuscript would benefit from the authors addressing several weaknesses prior to publication.

Thanks for the constructive comments, which have greatly improved the manuscript.

A major weakness I found with this manuscript was that in order to understand much of the detail of the data and results it was necessary to also read (and thus have access to) Kosarev et al. 2018. One such example is the choice of 2 degree boxes for stacking

the receiver functions, which is explained in the earlier paper, but not in this manuscript. I appreciate that the authors may want to avoid republishing the same information multiple times, however including details such as a figure of piercing points and/or a table showing the number of receiver functions stacked in each box would be very valuable. Some of this could go in supplementary material, but I do think it is needed somewhere.

We have explained the choice of the degree 2 boxes in lines 99-106 and present Table 1. Other problems of data processing are discussed in lines 84-96.

The manuscript would benefit from the authors discussing alternative possibilities as to the cause of the relatively thin MTZ in their results in this part of the Tarim Basin. It would be good for them to try and find stronger evidence for them being both being caused by the same plume, and to discuss possibilities for them being unrelated.

We have addressed this problem in lines 133-138.

It concerns me that, according to the figure in Kosarev et al. 2018, the number of piercing points, and so presumably seismograms in the stacks, is lowest in this region.

We have addressed this question in lines 113-115.

Further, it would be useful for the authors to try and find other evidence that may indicate whether the tectosphere extends to over 400km depth. While it may not be conclusive, and I'm not sure if appropriate data exists in this instance, it would be interesting for them to look at the strength and direction of azimuthal anisotropy in the 100-400km depth range to investigate if there is evidence for flow related to absolute plate motion shallower than the MTZ.

It is difficult to address these questions with the available seismic data. The Tarim basin is the largest desert area in China, practically devoid of seismograph stations, but our group already deployed several stations. We will use these data to discuss the issues as you're mentioned.

The manuscript is generally well written and the figures are mostly clear, however there are a few issues that need to be resolved:

Line 37: How much is a few percent?

We have changed it to 4-5% (line 38).

Line 68: "around 100 broad-band stations" - how many was it exactly?

Precise number is 64 (see line 69).

"around 6 s" What exactly was the corner frequency?

We have removed "around".

"their depths are sensitive to the temperature" - it would be good to also mention that they are sensitive to composition here.

We added "composition". See also the lines 157-162.

"on the order of several hundreds" - how many was it exactly - include a table of the numbers.

We have added Table 1 with the numbers.

Lines 109-111: citations needed for the discussion about the Permian basalts.

We have added reference to Wei et al., 2014 (line 129).

Lines 122-133: This section needs rewriting to make it clearer. Why/how did you choose a diffusivity value of $32 \text{ km}^2/\text{m.y}$? By reduced twice do you mean halved?

We used the standard value of diffusivity with reference to Morgan and Sass (lines 150-152).

We have changed “reduced twice” to “halved”.

Figure 5: Given the discussion is of something that occurred 300ma, I think this figure would benefit from showing the curve for 300 m.y. Is R in the figure the same as described in lines 122-133?

In this figure, to avoid any confusion, we replaced R by r. We tried to replace 400 m.y. by 300 m.y. but this change failed to produce positive effect.

Is there any paleomagnetic data that the authors can find for Tarim that describes how far it may have moved?

We have provided reference to Zhao et al., 1996, which contains other useful references (line 166-169).

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
10 ~~coherence~~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,
15 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.

20 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 Permian-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 ~~in the region~~ beneath the Siberian LIP ~~drops~~ is reduced by ~~a few percent~~ 4 – 5% (Vinnik and Farra, 2007) relative to IASP91 model (Kennett and Engdahl, 1991). This ~~effect~~ is a likely ~~result~~ effect of ~~partial melting~~ 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 ~~and may also be the result of partial melting. Similar anomalies were previously. Previously this layer was~~ found in the vicinities of several ~~presently active hot spots (e.g., Vinnik and Farra, 2006). 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.

50 | ~~————~~ 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
55 | 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.

60 | ~~————~~ Here we ~~use P receiver functions (PRFs) to do the~~ describe a similar analysis for the central Tien Shan and Tarim in central Asia. ~~And then we~~ and discuss ~~the~~ possible implications ~~for the origin of the seismic features. these observations.~~

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

65 | ~~————~~ 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
70 | 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).

75 ———Teleseismic recordings of ~~about 10064~~ broad-band stations in Fig. 1 were low-pass filtered with a corner at ~~around 6 s~~ and transformed into ~~PRFPRFs~~. 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 80 410-km and 660-km discontinuities mark the top and bottom of the MTZ and their depths are sensitive to the temperature- and composition.

85 ———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 ~~different~~ effects is the main problem of interpreting the observations of ~~these~~ 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 ~~the~~ P660s and P410s phases in the crust and upper mantle are close to each other for the same seismic recording ~~are very close to each other at depths less than 410 km and, therefore, the time difference between them (differential time) depends mainly on the width of the MTZ.~~ The study 90 area was divided into rectangular boxes 2° in, and, as a result, the differential time is insensitive to the SN and EW directions (220 and 160 km, respectively). The ~~theoretical conversion points in the middle~~ properties of the MTZ (535 km) for the ~~standard reference model IASP91 were projected on the Earth's surface for all available recordings. Those PRFs, the projections of the conversion points of which fall in the same box, were stacked with move out time~~ corrections medium above the MTZ. 95

———The ~~number of the stacked PRFs in most of the boxes is on the order of several hundreds. These numbers are sufficient for a robust detection of P660s and P410s seismic~~ 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)

100 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
105 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
110 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
115 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
120 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, -
125 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, ~~respectively.~~ 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 ~~beneath the south-central Tien Shan~~ 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 ~~beneath the Fergana~~ in b and ~~Tarim basins~~ c is the effect of a depressed 410-km discontinuity and a stable 660-km discontinuity. The depressed 410-km discontinuity beneath ~~Fergana~~ b and ~~Tarim~~ c is likely a result of a temperature anomaly of about +100-°C. The elevated temperature ~~beneath Fergana~~ 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 ~~beneath 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 basalt reaches ~~700~~ 800 m. The age span of the magmatism extends from about ~~290~~ 292 Ma to ~~260~~ 272 Ma, with ~~a peak between 270~~ two peaks at 279 Ma and ~~280~~ 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 ~~high heat flow and uplift during~~ 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 ~~in Tarim~~ is known ~~inafter~~ the ~~Cretaceous and Cenozoic~~ (Permian) (Zhang et al., 2013; Deng et al., 2017).

— Fig. 4 demonstrates a striking spatial ~~coherence~~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 ~~m.y~~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 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 ~~reduced~~ twice 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 ~~anomaly at an anomalous~~ depth of ~~~400~~the 410-km discontinuity is an effect of ~~chemical anomalous~~ composition. — The pressure of the phase transition in (Mg,Fe)₂SiO₄ depends on the Mg content (Mg#) relative to Fe (Fei and Bertka,

1999). Increasing ~~the Mg-content#~~ from 89% to 92% results in up to 10-km deepening of the 410-km discontinuity (Schmerr and Garnero, 2007). ~~TheThe depleted composition and~~
180 increased ~~contentMg# are commonly interpreted as effects~~ of Mg in the plume may be a result of ~~partial~~ 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. ~~Reconstructions~~ Reconstruction of positions of old continents is difficult for the time exceeding the age of the oldest hot-spot trails
185 (130 Ma). There are abundant paleomagnetic data for the earlier times, but they do not constrain paleo-longitudes. ~~The uncertainty can be minimized~~ 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
190 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, ~~and~~ 2000 km can be used as a rough
195 estimate of the shift of Tarim. ~~Additionally, Tarim moved to the northeast as a result of the collision of India with Eurasia (Molnar and Tapponnear, 1975).~~

—The spatial ~~coherence~~ 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
200 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

205 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
210 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.

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220 reviewer.

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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
320 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. Superimposed 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.

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