Thanks for the constructive comments from the two reviewers, which do improve the manuscript greatly. Here followed the detailed response to all comments.

Reviewer: Dr. R. Porritt
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.

We don't quite agree on this comment if we understand it correctly. This concern has no serious grounds because the move-out artifacts are controlled in our analysis. The move-outs are calculated for the assumed depths of conversions from 0 to 800 km (see Fig. 3). If the move-outs are free from significant artifacts, the maximum amplitudes of either P410s or P660s are observed at the depths which are close to 410 km or 660 km. This is seen very clearly in Fig. 3 and is stated in the text (Lines 144-148). We have used this method of control for 40 years (since Vinnik, 1977). The reviewer does not explain what is wrong in this method. The recommends his own method which, unfortunately, has no adequate explanation. For example: "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". We cannot understand this as well as the rest of this paragraph of the review, so we don't make further work.

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

We agree and have added one paragraph to discuss this alternative. Details are shown in Lines 208-217.
In this manuscript, first of all, we testify the observation is robust. Second, we state why it was caused by a plume, not others (subduction, heterogeneity). Third, we state why it was an ancient plume.

Line 10: The term "most likely" is unnecessary
Agree, we have deleted it.
Line 21-22: "tens kilometers" should be "tens of kilometers"
Corrected.
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)."
Agree and corrected.
Line 38: "to IASP91" should be "to the IASP91" (see also line 51)
Corrected.
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".
Corrected.
Line 62: "Asia is a likely far-field" should be "Asia is likely a far-field"
Corrected.
Line 73-74: "components in time domain" should be "components in the time domain"
Corrected.
Line 85-86: "CCP (Common Conversion Point)" should be "Common Conversion Point (CCP)"

Corrected.

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."

We have changed the sentence according to the suggestion.

Line 102: What metric was used to define "best quality"?

We have deleted the description of "best quality". Instead, we give more details on the quality process in Lines 92-94 "The individual PRFs were visually inspected and those with a relatively low noise were stacked. The low-noise PRFs present on the average about 50% of all inspected PRFs."

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.

We have changed them according to the suggestion.

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).

We have rewritten this sentence.

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.

We have changed two "likely" to "may be".

Line 123: "Possible…" should be "A possible…"

Corrected.

Line 126: "basalts with the areal" should be "basalts with an areal"

Corrected.

Line 132: "and the high zircon" should be "and high zircon"

Corrected.

Line 135: "with implication of" should be "and we infer"

Corrected.

Line 146: "for 1D" should be "for a 1D"

Corrected.

Line 146: "the well known" I think should be "a simple heat diffusion"

Corrected.

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.

The estimates of temperature are obtained by Kosarev et al. (2018). Here we just want to show the temperature modeling is comparable to that from our seismic data, we don't make further discussion here.

Line 154: "for 2D" should be "for a 2D"

Corrected.

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

You are right. It should be 600-700 km.

Reviewer: Dr. Jennifer Jenkins
Permian plume beneath Tarim from receiver functions

This paper uses receiver function analysis to image the mantle transition zone (MTZ) discontinuities beneath the Tarim basin. While most of the area shows average MTZ thicknesses, several regions show anomalously thin or thick MTZ. The authors focus on one of these regions in their interpretation which shows a thinned mantle transition zone which they suggest is due to a depressed 410 caused by a hot temperature anomaly. They note that this region it is co-located with Permian basalt deposits at the surface and suggest that these formed as a result of the underlying temperature anomaly – which is interpreted as a remnant of a mantle plume. Simple temperature modeling suggests that a cooling remnant plume would have sufficient temperatures to cause the currently observed depression on the 410. The key claim of this paper is that since the eruption of these basalts, the Tarim region has been tectonically displaced by 2000 km as based on palaeomagnetic reconstructions. The authors argue that since the underlying temperature anomaly is still located beneath the erupted basalts, this suggests that the upper mantle down to 430km has translated with the overlying plate, following the tectosphere model of Jorden, (1978).

I would recommend this paper for publication after some minor corrections/comments are addressed. I have outlined my major suggestions/questions below and also made a list of minor spelling/rewordings.

General comments

Overall I find the paper provides a reasonably convincing observation with a very interesting interpretation. Many of my comments relate to what tomographic models of the region would add to this study, whether they can improve methodology and/or support the interpretation. My other main comment is that the authors present two options:

☐☐The whole of the upper mantle has been translated beneath Tarim, OR Palaeomagnetic reconstructions are wrong in this area by an order of magnitude I feel I would like to see more details on the practicalities of how the first option would work if it were the case, and an indication of how reliable palaeomagnetic reconstructions are. I would like to get a sense of which of these interpretations the authors support, because both are big claims.

Thanks for your comments. We have given the discussion of tomographic model in Lines 131-134, 205-207. The resolution of tomographic model is too low to discuss the thickness of MTZ.

We give two alternatives for the observation. We are not experts in paleomagnetics. We take paleomagnetic data from published papers and give proper references. We trust these data so far as they are not discredited by other publications. But we admit that these models may be replaced in the future by other models.

Question about Tectonosphere model

In the introduction (lines 28-46) the authors suggest that the Siberian LIP may show evidence for a coupled tectonosphere based on observations of:

☐☐depressed 410 discontinuity
☐☐Slow velocities 350-410km
☐☐Low vel. layer 460-500km

This would suggest a tectosphere extending to depths >500 km to explain the low velocity layer, but in the conclusion, based on the observations of the current study, the authors cite a translation down to depths of 430km (line 187)? So how deep would this tectonosphere extend? Do the authors suggest it could be different depths in different locations? And is there any more background to this theory of a coupled tectosphere? By what mechanism would this large scale deformation take place?

Would we expect to see an observable feature at the base of the coupled section? Is there other ways we should be trying to test this hypothesis?

We conclude that the tectosphere of Tarim may reach the top of the MTZ, but we do not know where the base is. Similarly we do not know where is the base of the tectosphere in Siberia. However, it is important that it is much deeper than the LAB (~200 km).

About the coupled tectosphere, in addition to Jordan we refer to Conrad and Lithgow-Bertelloni (2006). See the discussion in Lines 261 – 269.

Line lines 77-83

The authors discuss using differential arrival times because P410s and P660s are equally affected by velocity heterogeneities above 410 km. What about velocity heterogeneities extending through the MTZ? I realize these are likely to be smaller magnitude at depth, but if you are looking at a region where you are arguing for the possible presence of a plume, you might expect velocity anomalies extending deeper than 410 km. Using your methodology such anomalies would effect only P660s phases and would not be accounted for, effecting estimates of differential time. Can the authors justify why this would not be problematic in their specific region, or why they deem it not necessary to consider? What do tomography models of the region look like? Do they suggest strong heterogeneities are restricted to < 410km? More generally do tomographic models agree with their observations of a depressed 410 in this region (e.g. a slow velocity anomaly)?

We have given more discussion on this issue. See Lines 124-128: "We neglect velocity heterogeneities extending through the MTZ because for a realistic temperature anomaly of 100 K the related time residual of P660s in the MTZ is around 0.2 s (e.g., Shen et al., 2002), The residuals that are accumulated in the crust and upper mantle above the 410-km discontinuity are usually much larger. The average residual for the crust and upper mantle of the Tien Shan is 0.6 s (see the rest of this Section)."

Even the best models based on travel-time tomography have no resolution to detect a depression of the 410-km discontinuity of 10-15 km. That is one of the reasons why people use receiver functions. Moreover, resolution of tomographic models for most of Tarim is low because of a poor or missing seismograph network.

Lines 84-96

This section describes stacking based on pierce points – how are these calculated? Are they just based on the IASP91 model? Again what do tomography models of this region look like? Is it reasonable to use pierce points from a simple 1D model? Or would tracing through a 3D model, offset the pierce locations significantly? Stacks are based on 535km pierce points, which justifies the use of differential time measurements as corrections for upper mantle velocity heterogeneity. But as the authors themselves point out, the pierce points

between P410s and P660s for the same recording are 1-2 degrees offset, on the order of a few 100km. So the differential time measurements relates to an offset thickness of the TZ. This would prove problematic if a velocity anomaly effecting both discontinuities was observed by at 410 pierce point location, but the 200km offset 660 was not effected by it. Do this authors think this could cause a problem for their results?

We give more details on the stacking in Lines 130-134. Yes, it is based on IASP91 model. We think the IASP91 model is simple, robust and sufficiently accurate for our task.

The effect of the offset thickness is reduced by stacking the receiver functions in many azimuths. The effect is also reduced because the signal is formed not in a piercing point but in the Fresnel zone with a diameter of ~100 km at a depth of 410-660 km. In our case the offset can be neglected because the topography beneath Tarim is found only on the 410-km boundary (the 660-km boundary is flat). See Lines 119-123.

Line 103 – "*optimum size of stacking boxes was found through trail and error*" – could the authors by more specific what they mean by this? What made them use these specific dimensions?

We have given more details in Lines 135 – 141. "The cells were chosen in the form of a rectangular box. The optimum size of the box was found through trial and error. If the box is too small, we cannot find a sufficient number of receiver functions with piercing points within the box. If the box is too large, the anomalies of travel time of P410s and P660s may be lost because of smoothing. The optimum size (2° for NS and EW or 220 km and 160 km, respectively) provides a reasonable compromise. "

Line 105 – "*sufficient for a robust detection*" - what quantative criteria are used to define a robust detection?

Robust detection implies: (1) a large amplitude of the signal relative to noise (the signal/noise ratio is at least 3); the largest amplitude is observed at the appropriate depth. Fig. 3 gives a good example of a robust detection of P410s and P660s.

Line 111 - "*The resulting anomalies of thickness of the MTZ for a, b and c are +15 km, -11 km, and -15 km, respectively*" – based on what velocity model? IASP91? Is a 1D model sufficiently accurate in this area?

The estimates of thickness are based on the IASP91 model. See Lines 130-134.

We think the IASP91 model is simple, robust and sufficiently accurate for our task.

Line 116 – "*The further analysis (Kosarev et al., 2018) demonstrates*" – what further analysis was conducted? How did Kosarev et al. determine that the thickening or thinning of the TZ was caused by one discontinuity or another? Since the interpretations of this paper hinges on some of the conclusions of the Kosarev paper (e.g. that in b and c thinning is due to a depressed 410 but stable 660), I think it is important to state how this was determined.

We give the details in Lines 162-175 "Beyond the differential time, the analysis involves evaluation of topography of the 410-km and 660-km discontinuities. The P410s and P660s phases propagate within the crust and upper mantle only in the nearest vicinities of the seismograph stations. These stations are usually located outside the related box (see Kosarev et al., 2018) and spread in the region which is comparable in dimension with the station network. Therefore the residuals that are accumulated at shallow depths and observed in a certain box may be close to the average residual for the station network. In the estimates of the average residuals the data from the three anomalous boxes A, B and C are excluded. The average residuals thus obtained are +0.5±0.3 s for P410s and +0.7 ±0.4 s for P660s. Both estimates are close and the value which is adopted for the further calculations is +0.6±0.3 s. After the removal of this residual from the observed travel times, for the anomalous box C the anomalies are +1.3±0.3 s and -0.2±0.3 s, for P410s and P660s, respectively. The related anomalies of depth are +13±3 km and -2±3 km for the 410-km and 660-km boundaries. In other words, the 410-km boundary is depressed by ~13 km, whereas the 660-km boundary is flat. "

Lines 114-124 – I am interested here why of the 3 anomalous regions that the authors identify only one seems to justify a full discussion and interpretation. Areas a and b are given only a single sentence of interpretation here.

This paper is written on the anomaly of Tarim (c). Two other anomalies were discussed at length in the paper by Kosarev et al. (2018).

Lines 120-121 – "*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.*" – I feel like this statement could do with a reference? What is this interpretation based on?

This subject was discussed by Kosarev et al. (2018). The necessary reference is now given (Sobel and Arnaud, 2000)

Line 134 – " *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*" – I take your point but as all good scientists know correlation does not equal causation! Maybe rephrase somehow? I also note that while stacking

region c sits in the centre of the magmatic province, from what I can tell it also seems to extend to the areas covered by the stacking regions to both the north and the west, neither of which appear to be significantly effected. Maybe the distribution of pierce points in these regions do not densely sample this effected area?

We rephrased it as "and we infer a relation between them".

No, distribution of pierce points in these regions is sufficiently dense (see new Figure 2).

Lines 139-140 – *"The depressed 410-km discontinuity and the stable 660-km discontinuity are typical for hotspots and plumes (e.g. Du et al., 2006)"* – I don't know that I would agree that the conclusion of the Deuss paper is that hotspots "typically" show a depressed 410 and an unaffected 660. Certainly it is not unusual, but neither would it appear to be typical.

To avoid contradiction, we removed the statement that the 660-km is typically not depressed in the hotspots.

Lines 141-143 –*"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)."* - I don't know that the Hirose paper suggests that the presence of 2 different transitions would cancel each other out to produce a null average observation. The recent paper of Liu et al. (2018), also seems to suggest we might expect to see double discontinuities in the very hot plume centre or one phase transition dominating another, such that the one peak observed is biased towards one transition or another if it is too low freq to capture both peaks, but – anomalous in either case. In any case the appearance of a garnet transition is thought to become significant only at the higher end of plume temperature estimates, so may not be relevant in this cooling remnant plume scenario.

I also note that for the authors interpretation of a translating tectonosphere a flat 660 would be expected anyway, so there is no need to invoke complex phase transitions in this case.

Ref: Liu, H., Wang, W., Jia, X., Leng, W., Wu, Z., & Sun, D. (2018). The combined effects of post-spinel and postgarnet phase transitions on mantle plume dynamics. Earth and Planetary Science Letters, 496, 80-88.

We propose another explanation: the 660-km discontinuity may be outside the tectosphere (lines 238 – 239).

Line 173 – *"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."* – Is this a common and justifiable assumption? What if you don't make that assumption, how would that effect the relative motion of Tarim?

The assumption that Tarim and the Siberian craton were parts of the same continental plate was made in the previous version of the paper. In the present version it does not play any significant role.

Line 175-178 – *"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"* – If this is the case then presumably offset 2000 km to the west is the remnants of the deeper section of this hypothesized plume. Is there any evidence for this in tomographic images? As mentioned in my previous comments – this may be a good point to explicitly say this interpretation would suggest no temperature anomaly at 660, which fits with your observed average depth 660 discontinuity.

In the global tomographic models there is something in the lowermost mantle that may be interpreted as a remnant of the Siberian plume (e.g. Torsvik et al., 2008). The plume of Tarim is relatively small and its origin near the core/mantle boundary is not proved.

Line 179 – *"Alternatively this is possible without the recourse to the deep tectosphere, if the available palaeo-reconstructions for Asia are too rough and the actual shift of Tarim is by an order of magnitude less than predicted."* – as before estimates of error, or the reliability of reconstructions would help here. Is it likely that reconstructions could be off by such a large amount? Or is it relatively robust, and this really is not a viable alternative explanation, providing strong evidence for your tectosphere interpretation?

Paleoreconstructions for old continents contain hypothetic elements and their accuracy is a subject of dispute.

Figure 1 – Maybe include a large scale inset map of regional location – so readers can relate its relative location to other major tectonic refions discussed (e.g. Siberian LIP etc.)

A relation between Siberia and Tarim plays no role in the present version.

Figure 2 – The string of numbers at the top of the figure seems to relate to stack location, no. of RF, times of 410 and 660? In sec? etc. etc. – While it is possible for the reader to try and work this out themselves, why not make it clearer by reformatting the figure with this information more clearly presented? The caption of this figure and axis describe "trial depths". I assume this relates to some kind of move out correction given an assumed depth? This is not mentioned anywhere in the methodology or main text. Maybe add in some where or add a reference it for the reader can find what you mean by this.

The string of numbers is removed, the figure caption is modified and the discussion is extended.

Figures 3 and 4 – I feel that these figures could easily be combined into one. Just transfer the outline of the Permian basalts onto figure 3. I also feel that plotting on pierce points used to determine stack would help give an understanding of the data distribution – I know this information is given in Table 1 but it is much easier to

have it visualized.
We have changed according to the suggestion.

Minor corrections/questions

Line 69 - The 64 stations used – were these part of a net work? Should a paper or data doi be referenced acknowledging it? How long were the stations operational for? How many RF were produced from this data set, and after quality control how many were used? Is the data open source? Will the data products be made open source? If at all possible this is something that should be aimed for by all authors where possible, for future studies and reproducibility checks. I believe this may also be in the journal requirements

We have given the detailed information of data network in Lines 81-84. And we also acknowledge the data source (IRIS).

Line 70 – "*PRFs*" – make sure to define this somewhere before using the acronym

This acronym is explained in the first description.

Line 148 – "*Q is constant*" – Maybe Q is **a** constant? What is this constant?

This constant is close to unity and is now removed from the expression.

Line 167 – "*Tarim might be attached to Eurasia since the Late Paleozoic time*" –Tarim **may have been** …

Corrected

Line 174 – "*2000 km can be used as a rough estimate of the shift of Tarim.*" - direction of shift? Relative to..? Are there any error estimates on this distance? How rough is a rough estimate?

The direction is in north-east relative to Eurasia. The order of magnitude should be accurate. As mentioned before, Paleoreconstructions for old continents contain hypothetic elements and their accuracy is a subject of dispute.

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~~<u>the possible motion</u> of ~~paleo-continents since~~<u>Tarim on</u> the ~~Permian~~<u>order of 1000 km</u> by assuming that the mantle layer~~,~~ which ~~translated~~<u>moves</u> coherently with the ~~Tarim~~ plate ~~extended~~<u>since the Permian, extends</u> 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~~<u>motion</u> since the Permian is <u>less</u> 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~~<u>The</u> rigid lithosphere and the underlying ductile upper mantle (asthenosphere)<u> should be decoupled</u> at the lithosphere-asthenosphere boundary (Eaton et al., 2009). The depth to the lithosphere-asthenosphere boundary (LAB) ranges from a few tens <u>of</u> 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

25   translates coherently with the continental plate (tectosphere) may extend to a depth of at least

400 km (Jordan, 1978). The tectosphere is stabilized against convective disruption by depletion

in the basalt-like component. Examples of successful application of the concept of deep

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

30   outcrops at the Earth's surface.

Recently this test was applied to the mantle beneath the Siberian ~~Large Igneous Province~~

~~(LIP). The Siberian~~traps (Vinnik et al., 2017). These 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

35   aid of receiver function techniques that were applied to the recordings of seismograph station

Norilsk (NRIL) ~~within the Siberian LIP (Vinnik et al., 2017).~~in the north of the Siberian Large

Igneous Province (LIP). In the vicinity of NRIL, thickness of the traps is maximal (in a range of

a few kilometers). 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

40   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~~traps is

reduced by 4 – 5% (Vinnik and Farra, 2007) relative to the IASP91 model (Kennett and Engdahl,

1991). This is a likely effect of about 1 vol % or more melt (Hier-Majumder and Courtier, 2011)

45   which is unusual for 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~~A similar anomaly 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

2

50   abrupt decrease of the solidus temperature of carbonated mantle (Keshav et al., 2011) and may

also be related to melting.

    The present day coordinates for the center of the Siberian traps are 65.0 N, 97.0 E. The estimated coordinates for the reconstructed eruption center are 57.7 N, 54.7 E (Torsvik et al., 2008). Craton shiftedThis means the lithosphere underlying the Siberian traps moved in the last

55   250 Myr by about 2000 km to the northeast east (Torsvik et al., 2008). The anomalies of the MTZ might preserve their position beneath the Siberian LIPtraps in spite of the plate motion if they translatedmoved 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

60   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 the IASP91 reference model. The 410-km discontinuity in these regions is depressed by more than 20 km. The depression can be explained byKraft et al.(2018) interpret this as due to elevated temperature. The basaltic outcrops and the related

65   temperature anomalies are likelymay be related to the passage of Greenland over the Iceland hot-spot. This explanation is consistent with the concept of deep tectosphere and implies that the upper mantle beneath Greenland to a depth of at least 430400 km translatedtranslates coherently with the Greenland plate.

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

70   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 a 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~~at least 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~~The seismograph network in Fig. 1 is composed of several networks. The largest networks are CHENGIZ, MANAS, KNET, KRNRT and KZ. CHEGIS and MANAS were deployed for 1.5-2 years. KNET, KZ and KRNET are practically permanent. As the MANAS network is very dense relative to the others, the MANAS stations were divided into clusters of 4 neighboring stations and each cluster was replaced by one station with a reduced number of recordings. Seismic events of sufficient magnitude (5.5 and more) in a distance range from 35° to 90° are abundant in a broad azimuth range (Fig.2a).

The recordings of 64 broad-band stations in Fig. 1 were low-pass filtered with a corner at ~~6s~~6 s 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 the time domain. The individual PRFs were visually inspected and those with a relatively low noise were stacked ~~to reduce noise.~~. The low-noise PRFs present on the average about 50% of all inspected PRFs.

In the context of our study the most important elements of the stacked 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 One possibility 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 (CCP) stacking: to divide. This process divides the Earth's surface into cells and to stack withstacks, after an appropriate move-out time corrections the PRFs, the projections of the conversion points ofcorrection, the PRF amplitudes which fallproject 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. The offset of 1° of the projections of P660s and P410s piercing points may distort the stack, but this effect is strongly reduced by stacking PRFs in opposite back azimuths. The effect of the offset disappears completely if one discontinuity (660-km or 410-km) is flat. This is characteristic of sub-regions B and C (see the rest of this Section).

We neglect velocity heterogeneities extending through the MTZ because for a realistic temperature anomaly of 100 K the related time residual of P660s in the MTZ is around 0.2 s (e.g., Shen et al., 2002), The residuals that are accumulated in the crust and upper mantle above the

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410-km discontinuity are usually much larger. The average residual for the crust and upper mantle of the Tien Shan is 0.6 s (see the rest of this Section).

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~~.~~ (Fig. 2b). The conversion points were calculated by using the IASP91 model. 3D tomographic models (Lei and Zhao, 2007; Li et al., 2009; Zabelina et al., 2013) were not used for ray tracing because they represent only central part of the study region and differ in details. On the other hand, the IASP91 model is simple, robust and sufficiently accurate for our task. The cells were chosen in the form of a rectangular box. The optimum size of the box ~~affects lateral resolution and,~~was found through ~~the~~ trial and error. If the box is too small, we cannot find a sufficient number of ~~stacked PRFs, accuracy of the estimates~~receiver functions with piercing points within the box. If the box is too large, the anomalies of ~~the differential~~travel time~~. The individual PRFs were visually inspected and only those~~ of ~~the best quality were stacked.~~P410s and P660s may be lost because of smoothing. The optimum size ~~of the box~~ (2° for NS and EW or 220 km and 160 km, respectively) ~~was found by trial and error.~~provides a reasonable compromise.

The largest number of the stacked PRFs exceeds 1750, the smallest is 48 ~~(See Fig. 3).~~. These numbers are sufficient for a robust detection of P660s and P410s phases (see example in Fig. ~~2).~~3, where the number of stacked PRFs is 48). The move-out corrections for stacking are calculated for different assumed depths of conversion in a range from 0 km to 800 km. If the move-outs are free from significant artifacts, the maximum amplitudes of either P410s or P660s phases are observed in the traces corresponding to the depths that are close to 410 km or 660 km. This is evident in Fig. 3. The accuracy of the estimates of the differential time (confidence interval of 66%) which was determined by bootstrap resampling (Efron~~,~~ and 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).~~4). 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. For the IASP91 velocities the resulting anomalies of thickness of the MTZ in 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. 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 stack (Fig. 3) is comparable in quality with those in the other boxes.

Beyond the differential time, the analysis involves evaluation of topography of the 410-km and 660-km discontinuities. The P410s and P660s phases propagate within the crust and upper mantle only in the nearest vicinities of the seismograph stations. These stations are usually located outside the related box (see Kosarev et al., 2018) and spread in the region which is comparable in dimension with the station network. Therefore the residuals that are accumulated at shallow depths and observed in a certain box may be close to the average residual for the station network. In the estimates of the average residuals the data from the three anomalous boxes A, B and C are excluded. The average residuals thus obtained are +0.5±0.3 s for P410s and +0.7 ±0.4 s for P660s. Both estimates are close and the value which is adopted for the further calculations is +0.6±0.3 s. After the removal of this residual from the observed travel times, for the anomalous box C the anomalies are +1.3±0.3 s and -0.2±0.3 s, for P410s and P660s, respectively. The related anomalies of depth are +13±3 km and -2±3 km for the 410-km and 660-km boundaries. In other words, the 410-km boundary is depressed by ~13 km, whereas the 660-km boundary is flat.

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. This is indicative of a low temperature. The MTZ in A may be cooled by a detached and sinking mantle lithosphere.

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(Kosarev et al., 2018). The thinned MTZ in ~~b and c~~B is the effect of a depressed 410-km

discontinuity and a stable 660-km discontinuity. The ~~depressed~~depression of the 410-km

discontinuity ~~beneath b and c is likely a result~~in B, like in C, may be an effect of a temperature

anomaly of about +100~~°C~~ K. The elevated temperature in ~~b~~B may be related to a small plume

which is responsible for small-scale basaltic volcanism in the Tien Shan from 72 Ma to 60 Ma~~.

Possible~~ (e.g. Sobel and Arnaud, 2000). A possible origin of the anomaly in ~~c~~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 evolutional

history (Zhang et al., 2013; Deng et al., 2017). In the Permian, basalts with ~~the~~an 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 in

this region 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~~and we infer 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).~~ this region. Tomographic mantle models for the Tien Shan (Lei and Zhao, 2007; Li et al., 2009; Zabelina et al., 2013) still are not detailed enough to resolve this issue.

Mantle upwelling and the related magmatism can be associated with subduction. For instance, Tang et al. (2014) proposed that Changbaishan volcanism in northeast China is linked to subduction-induced mantle upwelling which may result in thinned MTZ. In the Tien Shan there are indications of two subduction zones in the Paleozoic time (Windley et al., 1990). The older, Devonian suture in the south marks accretion of the southern passive margin and subduction to the north. The younger, late Carboniferous accretion in the northern Tien Shan took place by southward subduction. The time and location of these episodes of subduction are hardly suitable for explaining the Permian magmatism in Tarim. Moreover, even if the Permian basalts in Tarim were somehow subduction-related, this would not invalidate the idea of a relation between the Permian basalts and the presently observed thinned transition zone.

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 a 1D conductive medium by using ~~the well known~~a simple heat diffusion 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 thermal 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 thermal 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. (Kosarev et al., 2018). A comparable result is obtained for

~~a~~ 2D conductive medium (Fig. 5b). These calculations suggest that the thermal anomaly at a

230   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

235   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~~

240   ~~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~~have been attached to Eurasia since the Late Paleozoic time, ~~and there are paleomagnetic indications of displacements of~~ but relative motions between Eurasia/Siberia and Tarim continued in the Mesozoic. A 30° counterclockwise rotation of Tarim with respect to

245   Eurasia can account for the difference between their Permian and Triassic Euler rotation poles. This implies a left lateral strike-slip displacement of 1400 km for Tarim relative to Eurasia along the southern margin of Kazakhstan. Tarim moved northeast even after the Cretaceous, ~~apparently owing to the India-Eurasia collision (Zhao et al., 1996). The uncertainty of the paleoreconstructions~~ but the estimates of length of this path are uncertain, and we take 1400 km

250   for the ~~Mesozoic can be minimized by selecting Africa as a reference continent that was most stable longitudinally~~minimum estimate of motion since the Permian time. As the motion of Eurasia is very slow (Torsvik et al~~.,~~., 2008~~). In~~) this ~~reference frame~~can be taken for the ~~Siberian traps shifted to the east by nearly 2000 km since they were erupted at 250 Ma~~absolute ~~(Torsvik et al., 2008). On the assumption that Tarim and the Siberian craton were parts of the same~~

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255 ~~continental~~ plate ~~in the past 300 Myr, 2000 km can be used as a rough estimate of the shift of Tarim~~motion.

The spatial correlation between the anomaly ~~in the MTZ~~at a depth of ~400 km and the basalt eruptions in Tarim (Fig. 4) in spite of the ~~shift~~motion of the Tarim craton to the ~~east and~~ north-east by ~~a few thousand kilometers~~ 1000 -2000 km is possible if the ~~layer~~tectosphere which

260 translates coherently with the plate ~~includes~~reaches the top of the MTZ.

The difference in viscosity between the lithosphere and asthenosphere suggests that the lithosphere and the underlying mantle are decoupled at the LAB at a depth of ~200 km (Eaton et al., 2009). This is hard to reconcile with the presence of deep tectosphere. However, the calculations (Conrad and Lithgou-Bertelloni, 2006) indicate that the low-viscosity asthenosphere

265 is important only if > 100 km thick. Moreover, lateral viscosity variations or topography on the LAB may increase plate-mantle coupling by a factor of 5. In fact, coupling between the lithosphere and the underlying mantle is necessary if, as is often accepted, the plates are driven by mantle flow. Qualitatively this is consistent with our observations. The 660-km discontinuity may be flat in C, because the depth range of this discontinuity is outside the tectosphere.

270 Alternatively ~~this~~the correlation between the Permian basalts in Tarim and the anomaly of the 410-km discontinuity 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~~may also be true for the Siberian traps.

275 **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~~Some reconstructions ~~(Torsvik et al., 2008)~~ ~~demonstrate~~suggest a shift of Tarim of ~~about 2000~~more than 1400 km with respect to Eurasia in

280 the past 300 Myr. This can be taken for the absolute plate motion. Then the observed relation

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between the deep and shallow features can be explained by a coherent translation of the crust and mantle to a depth of ~~430~~>400 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~~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~~This will require further detailed studies of the MTZ. 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.~~. At present the lack of seismograph stations in Tarim makes this impossible.

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Figure captions

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

Figure 2. Epicenters of seismic events (a) and projections of piercing points at a depth of 535 km (b).

Figure 3. Stacked PRFs for the box with the ~~coordinates:~~corners at 38~~°~~ - 40°N~~, 40N,~~ and 80~~E and° -~~ 82~~ E. Trial conversion depths in kilometers~~°E. Moveout corrections for ~~each trace~~stacking

425   are ~~shown~~calculated for depth (in km) attached to the traces 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~~4. Residuals of the differential time between P660s and P410s phases in seconds relative to <u>the</u> IASP91. Strongly anomalous boxes <u>(A,B,C)</u> 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. The number of stacked receiver functions in each box is shown by italics. <u>Permian basalts in Tarim are orange.</u>

~~**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.