Mantle and crustal sources of magmatic activity of Klyuchevskoy and surrounding volcanoes in Kamchatka inferred from earthquake tomography

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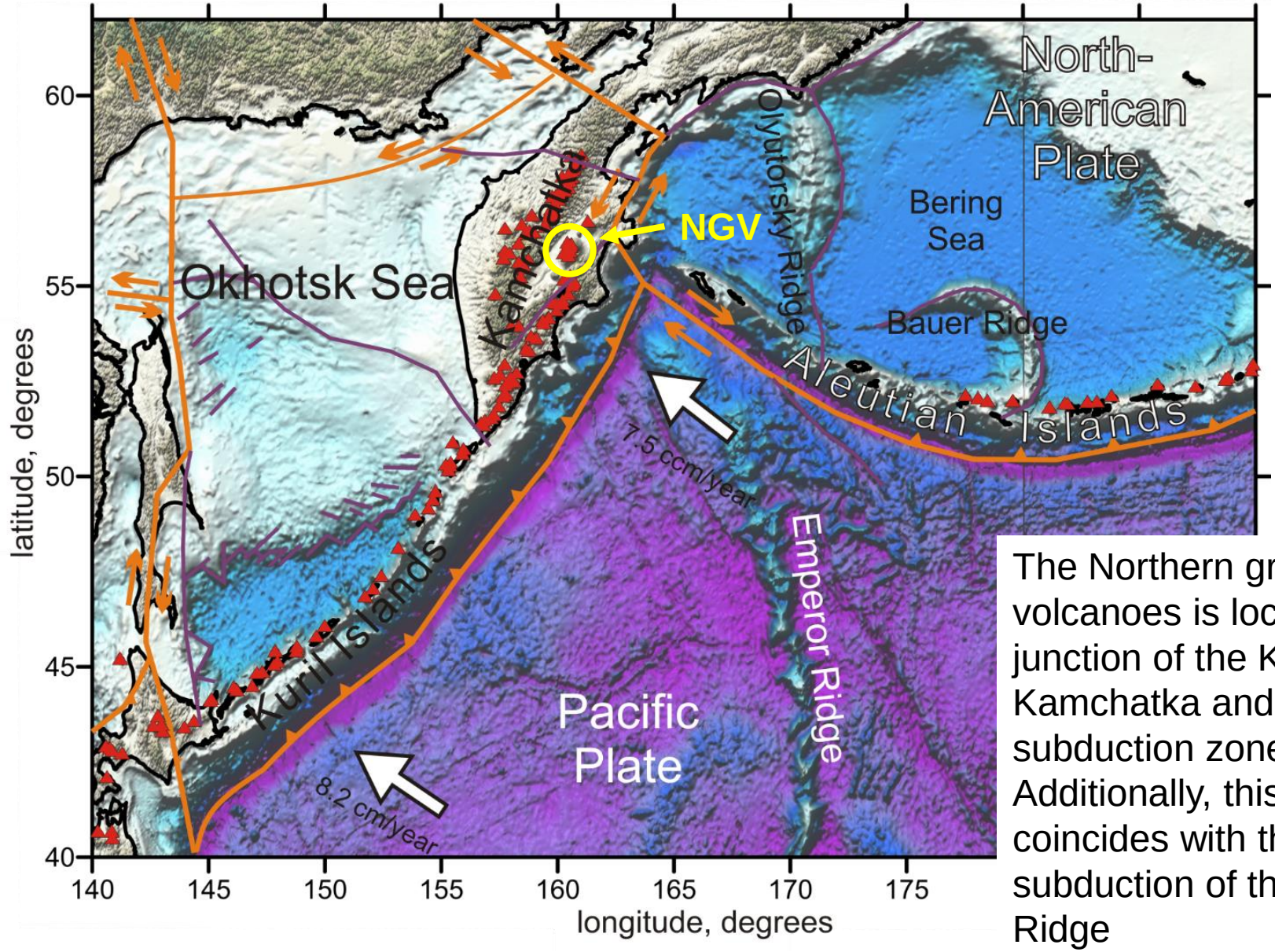
Study area at Kuril-Kamchatka and Aleutian Arcs junction

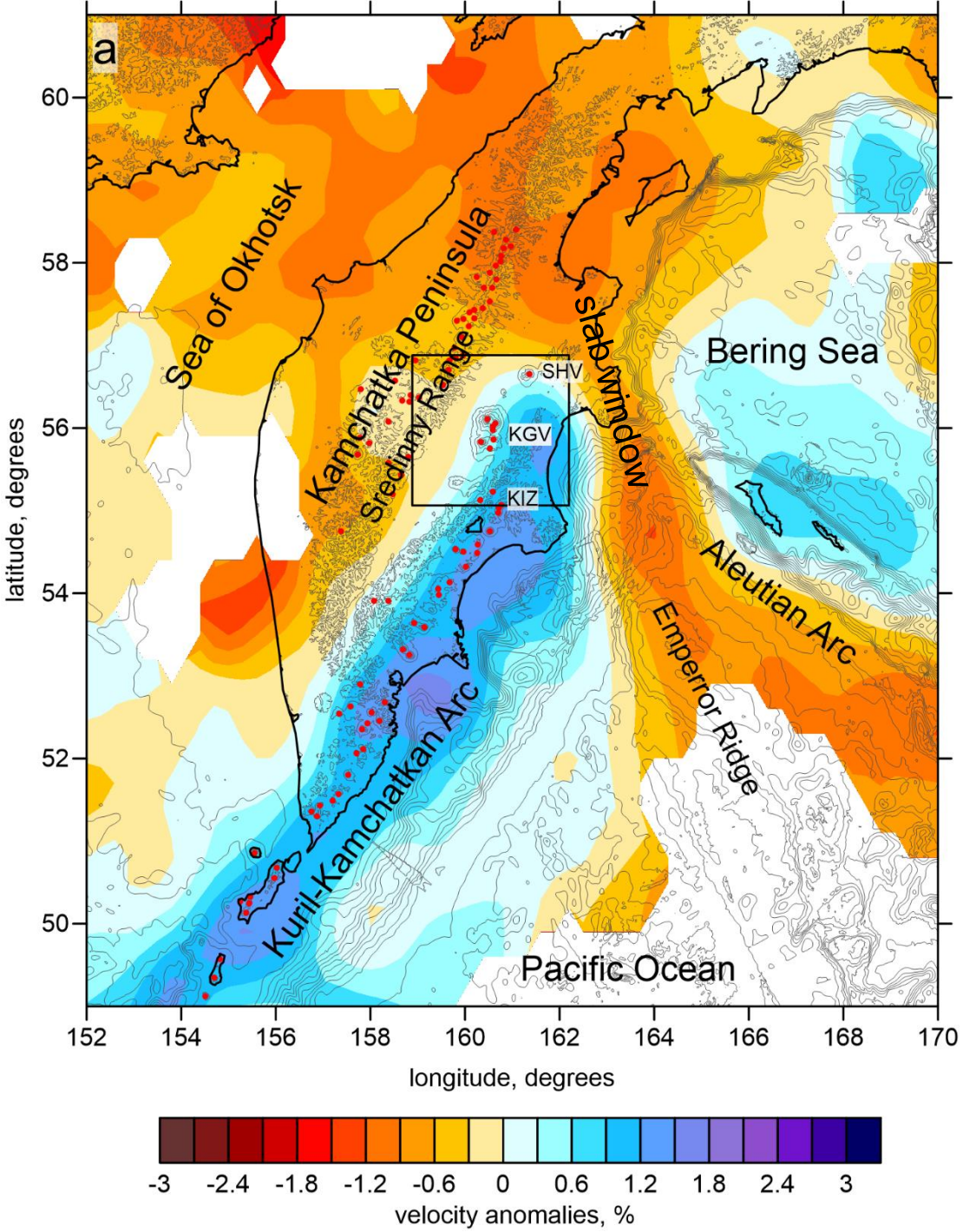


The Northern group of volcanoes is located at the junction of the Kuril-Kamchatka and Aleutian subduction zone. Additionally, this area coincides with the subduction of the Emperor Ridge

Red triangles depict volcanoes

Study area:

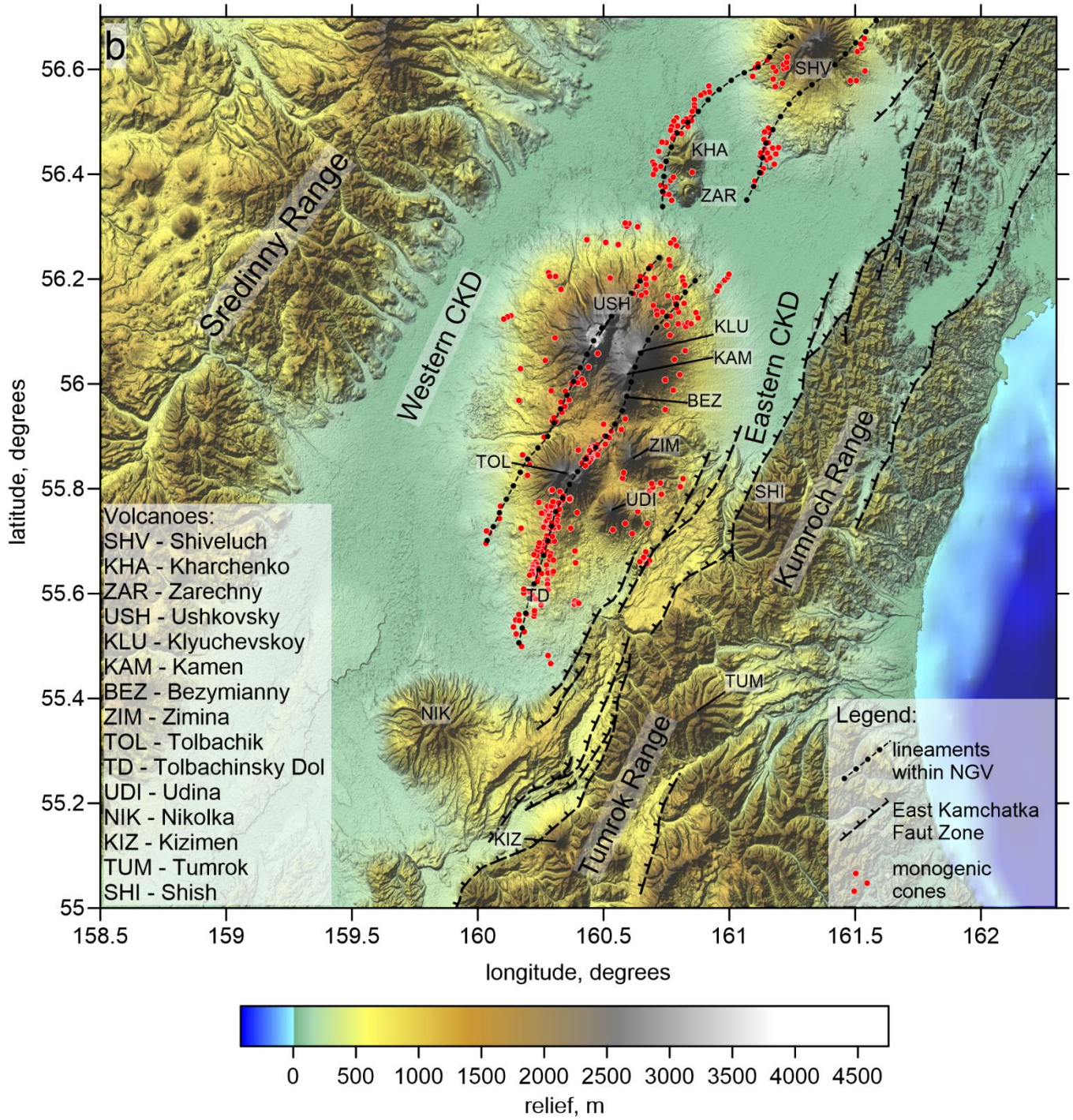
The Northern group of volcanoes is located at the edge of the Pacific slab, close to the slab window between the Kamchatkan and Aleutian slabs. Additionally, this area coincides with the subduction of the Emperor Ridge
All these factors explain exceptional variety and intensity of volcanism in the area.



Horizontal section at 150 km depth of the P-wave velocity anomalies from the regional tomography model by Koulakov et al. (2011).

Klyuchevskoy volcano group (Kamchatka)

Northern Group of Volcanoes:



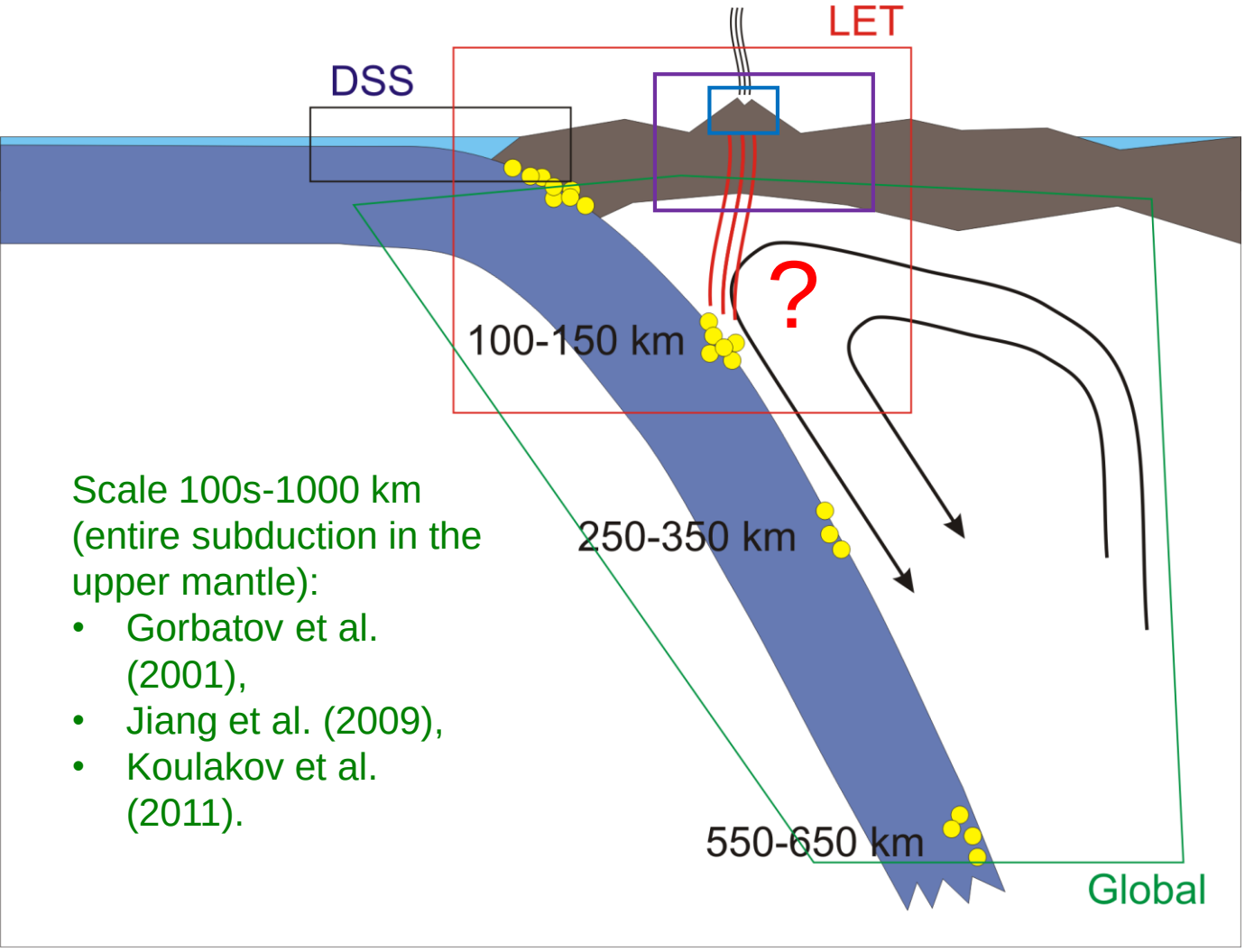
Major structural elements and volcanoes within the study area:

Red dots are the monogenic cones from [Volynets et al., 1998; Churikova et al. 2015] and authors' interpretation.

East Kamchatka Fault Zone is drawn based on (Kozhurin and Zelenin, 2017).

Lineaments along the NGV are according to (Ermakov et al., 1973; Melekesetsev et al., 1991) and the author's own interpretation.

Multiscale tomography studies in subduction zones: case studies of Kamchatka and KGV



Scale 100s-1000 km (entire subduction in the upper mantle):

- Gorbatov et al. (2001),
- Jiang et al. (2009),
- Koulakov et al. (2011).

Scale 1s-10 km (shallow magma structure):

- Udina (Koulakov et al., 2019),
- Bezymianny (Ivanov et al., 2015)

Scale 10s km (whole crust of KGV):

- Slavina et al. (2001),
- Khubunaya et al. (2007),
- Lees et al. (2007),
- Koulakov et al., (2011, 2013, 2017).

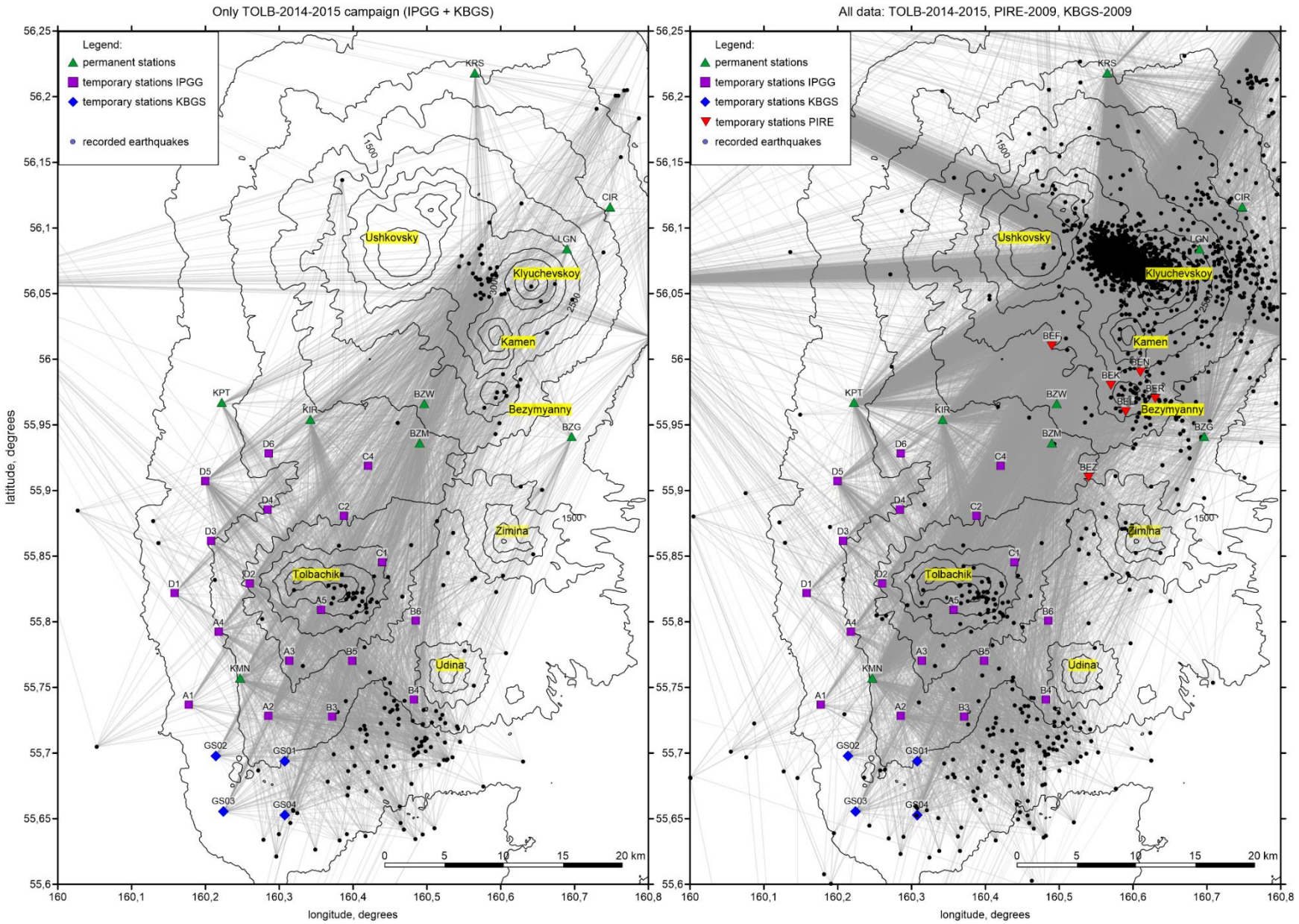
Scale 10s-100 km (mantle wedge):

- Gorbatov et al. (1997, 1999),
- Nizkous et al., (2006),
- Koulakov et al. (2016).

Very sparse and uneven distributions of stations. The resolution is not good.

Data available prior to the KISS experiment

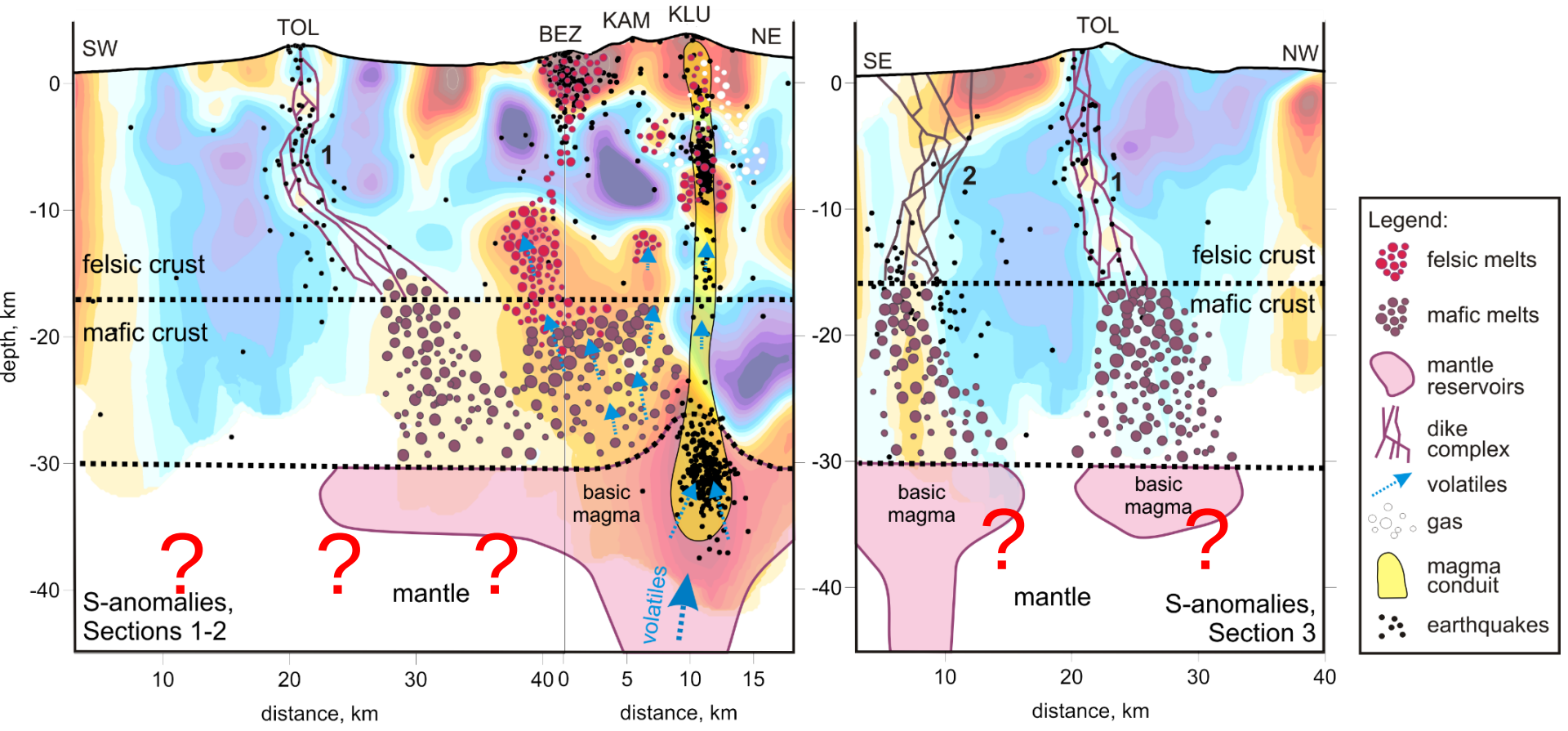
Permanent stations, TOLB-2014-2015 experiment and other networks

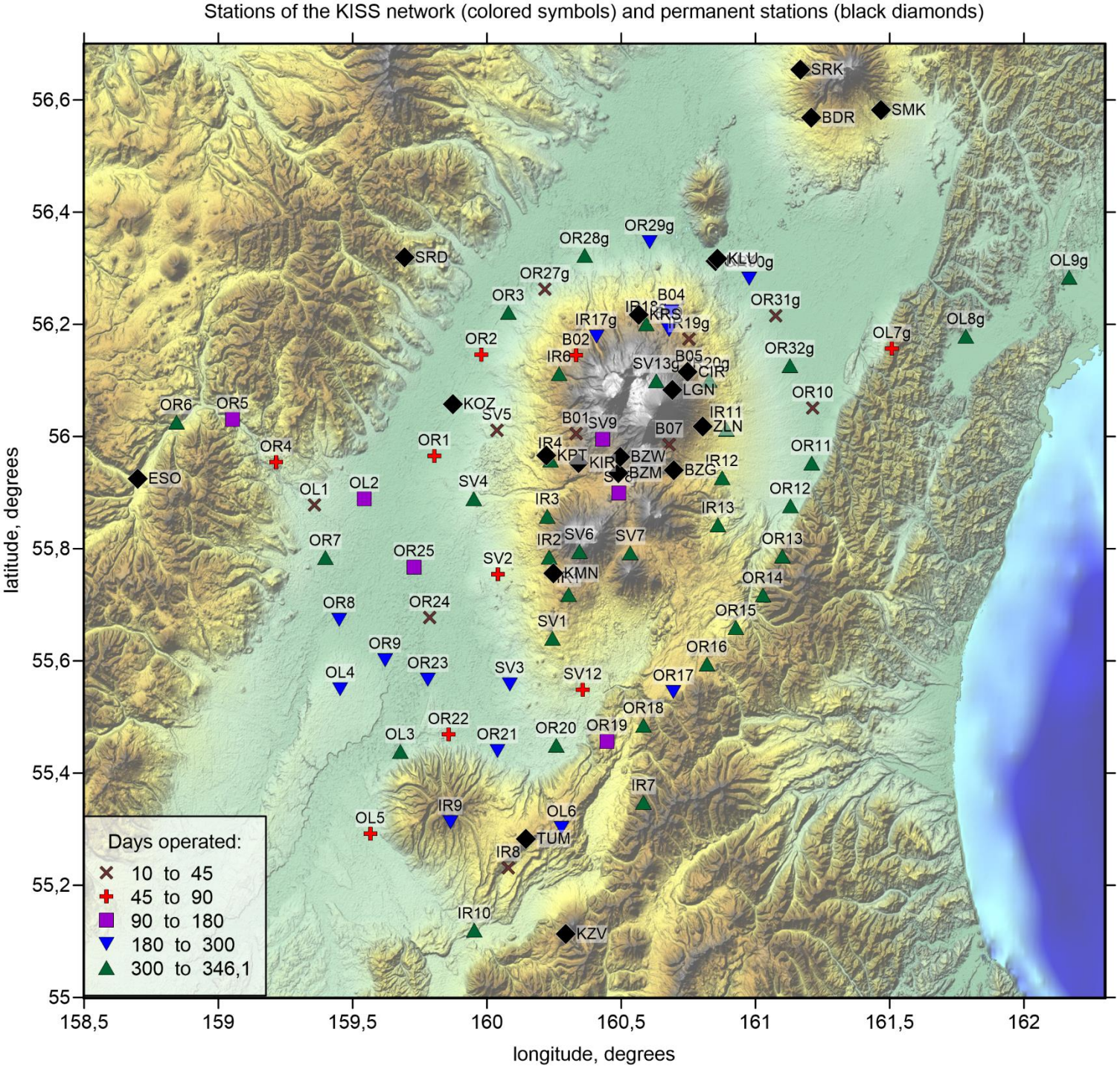


Previous studies: good coverage for the crust; no information on the mantle

Three types of feeding systems beneath Klyuchevskoy, Bezymyanny and Tolbachik:

1. Straight “pipe” beneath KLU.
2. Beneath BEZ, slow magma separation in the middle crust.
3. TOL: basalts ascend through a system of dykes, probably associated with fault zones.





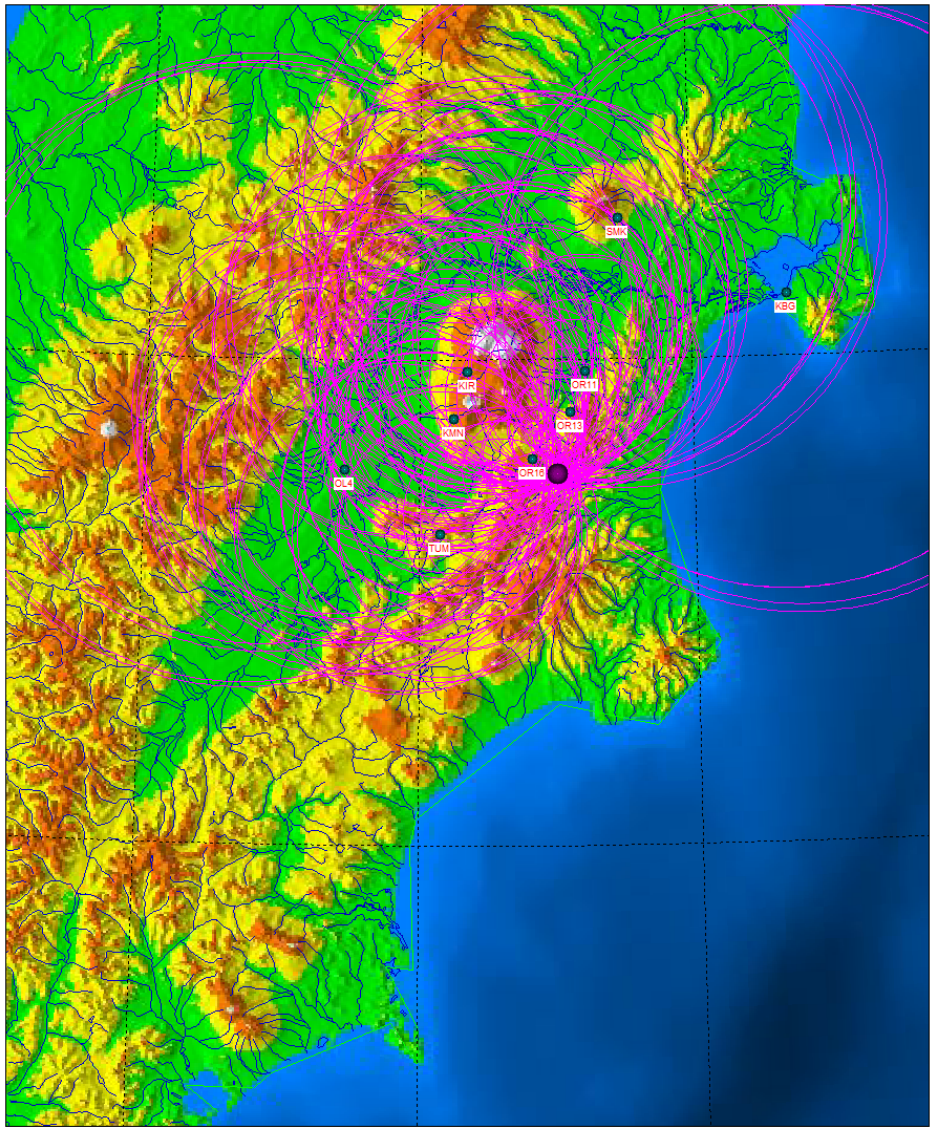
To study details of the mantle structures beneath KGV:

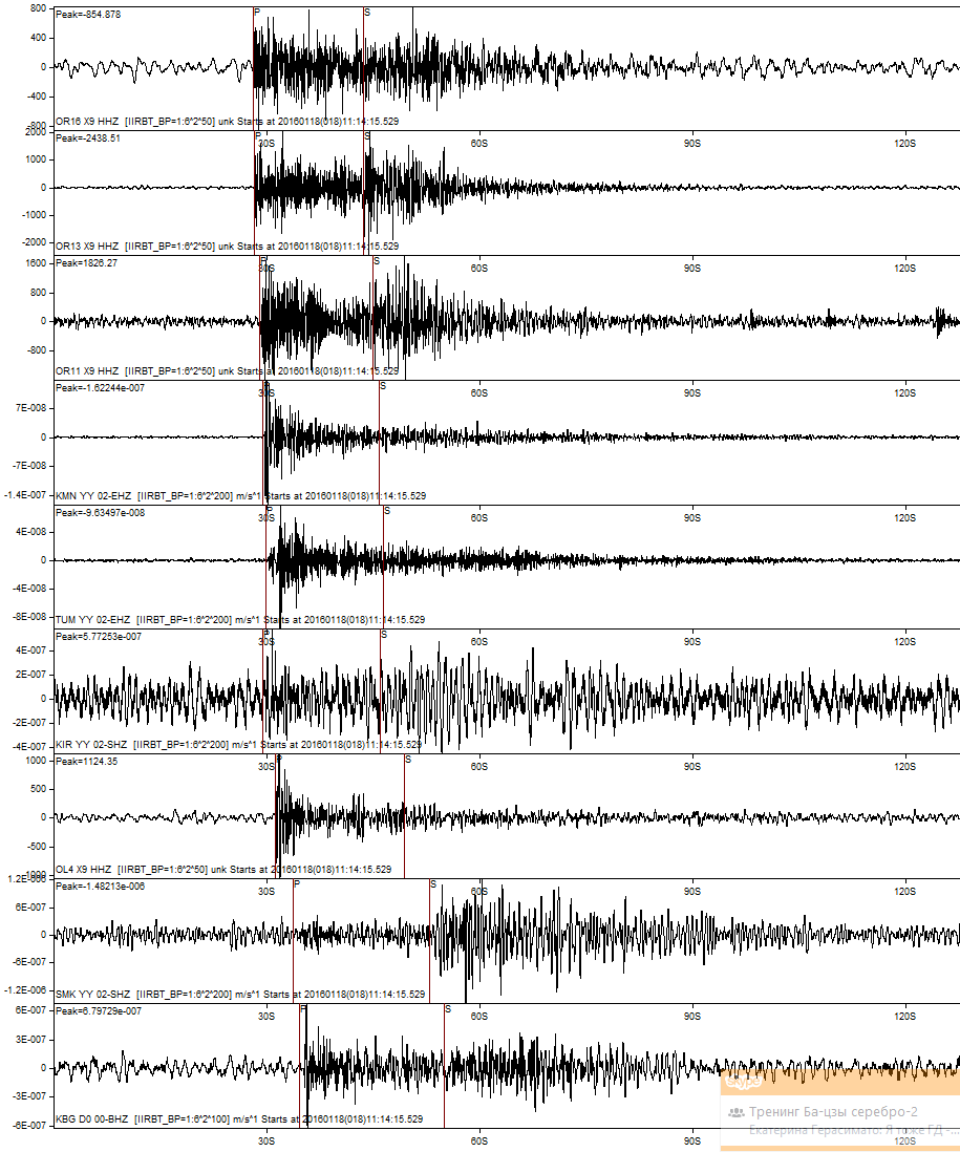
KISS

Klychevskoy Investigation - Seismic Structure of an Extraordinary Volcanic System

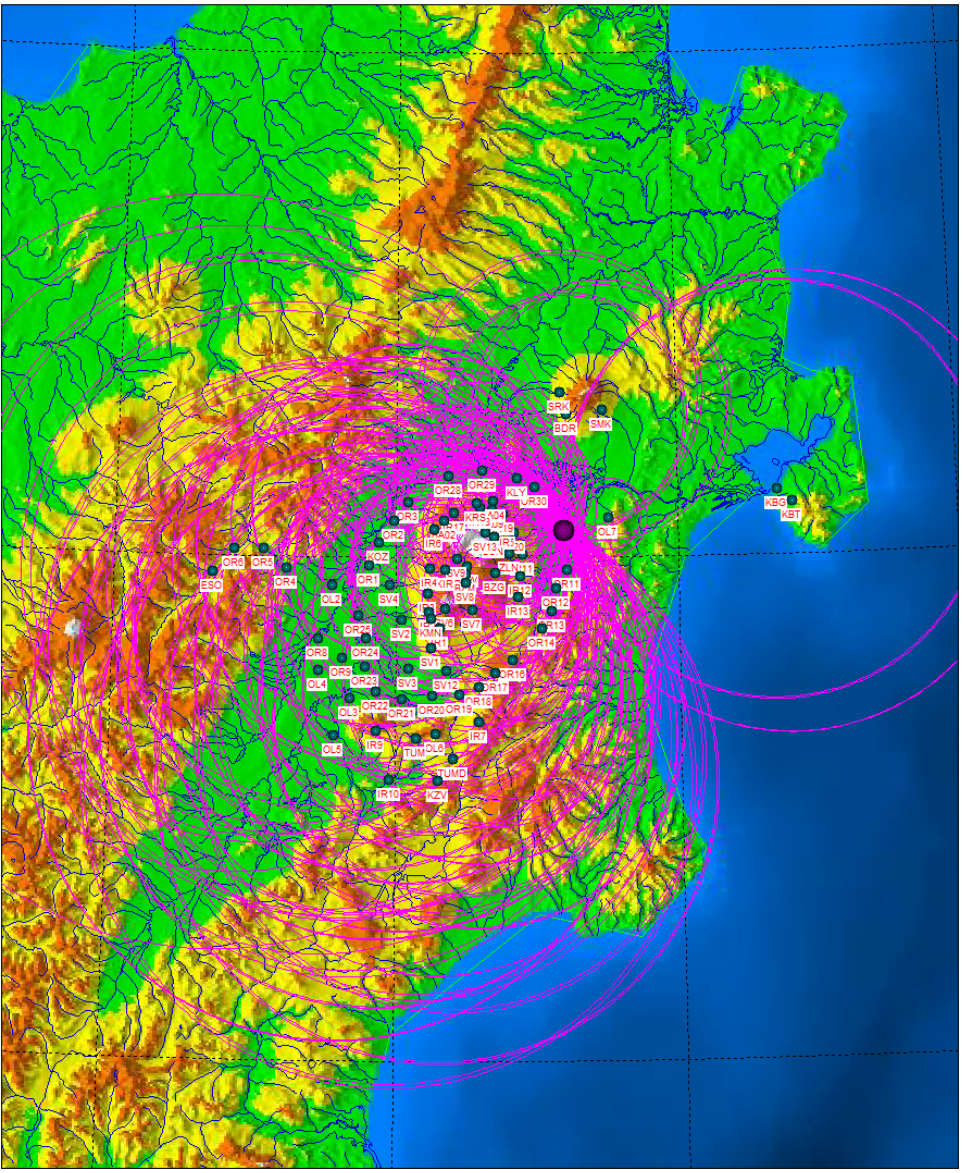
More than 100 temporary and permanent stations recording simultaneously from August 2015 to July 2016

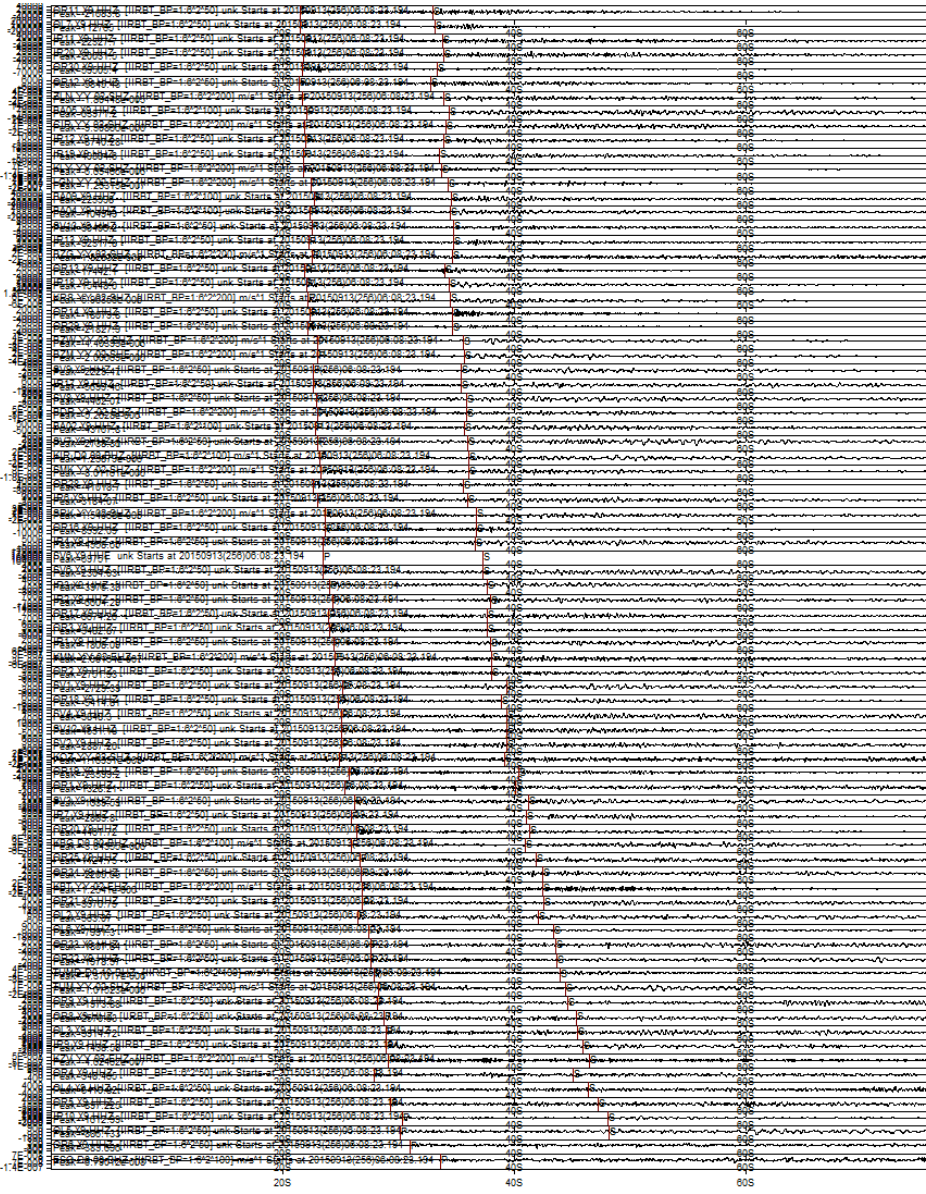
Example of manual time picking of an event at 150 km depth (18.01.2016):

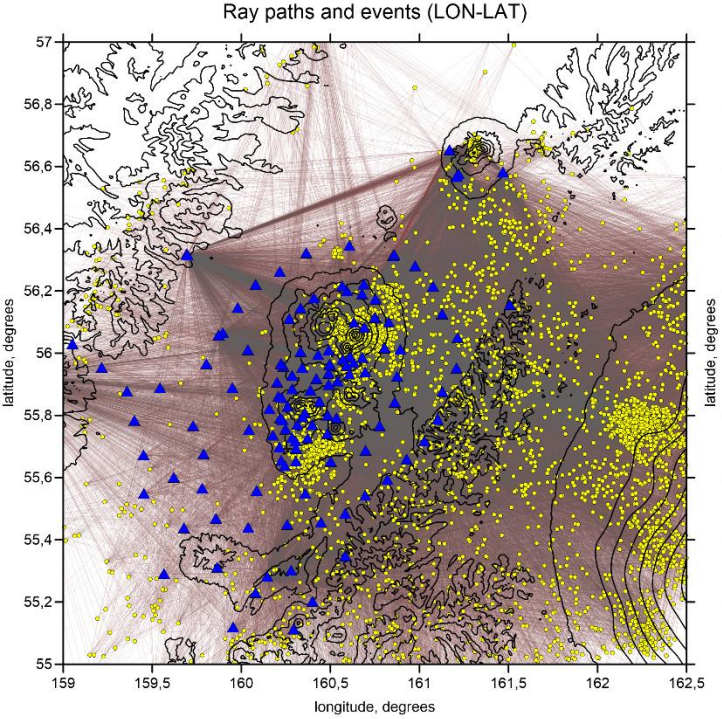


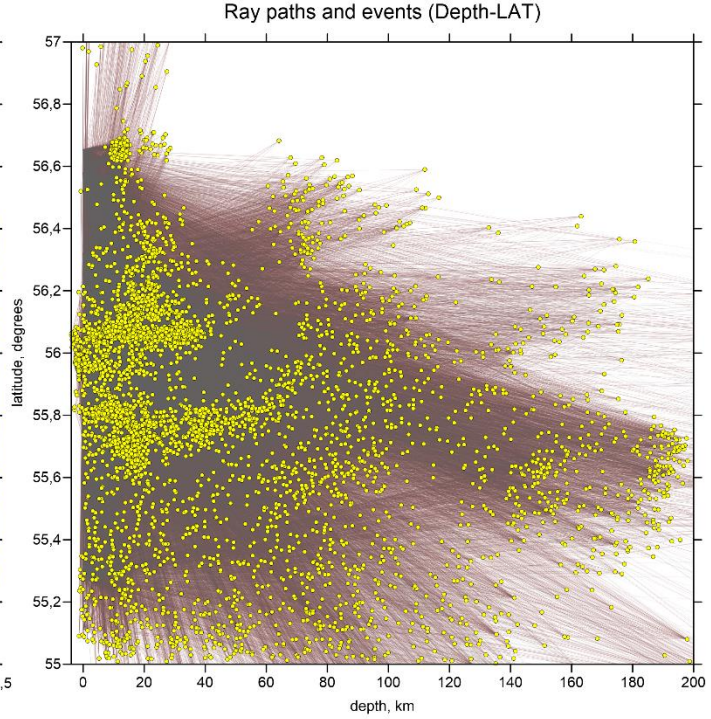


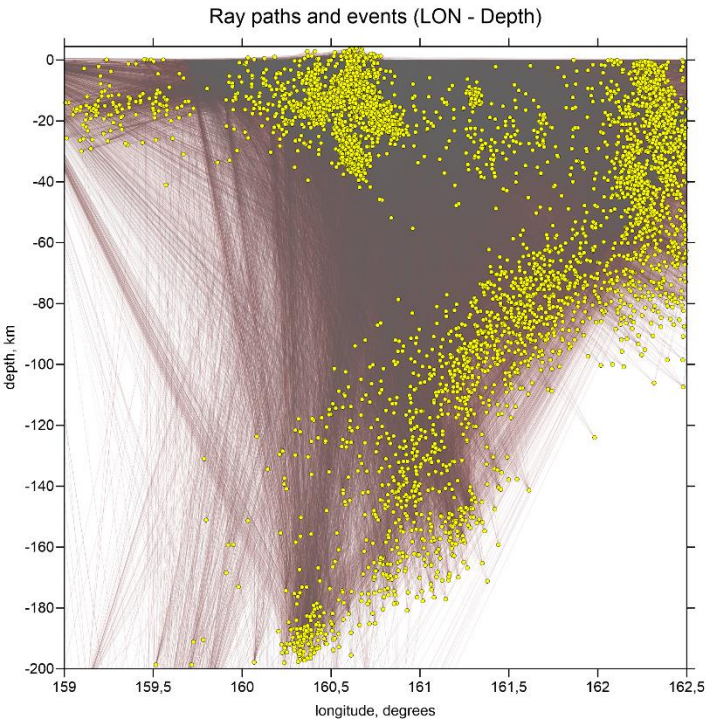
Example of manual time picking of an event at 108 km depth (13.09.2015):











Data used in the tomography inversion:

The merged dataset included the data of:

1. KISS-2015-2016 experiment +
2. TOLB-2014-2015 temporary network +
3. Permanent network (slab and local seismicity)

<u>Combined dataset used for tomography:</u>

Number of events: 7,464

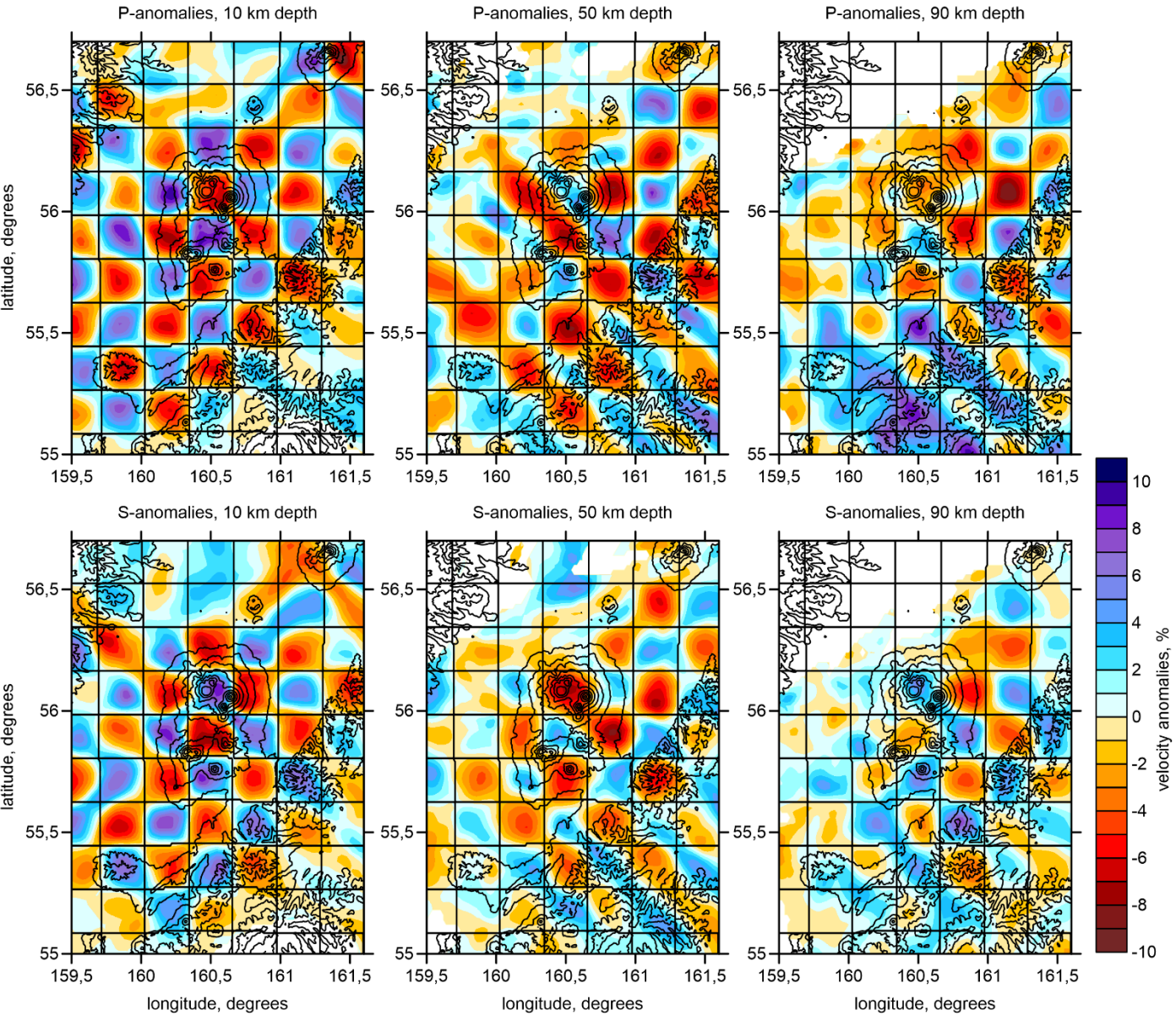
Number of picks 191,656 (95,132 P and 96,524 S)

Picks per event: 25.6

Checkerboard test: horizontal resolution

Anomaly size: 20x20 km; Sign changes at 30 km, 70km, 110km depth etc

Noise: 0.1 s and 0.15 s for the P and S wave data

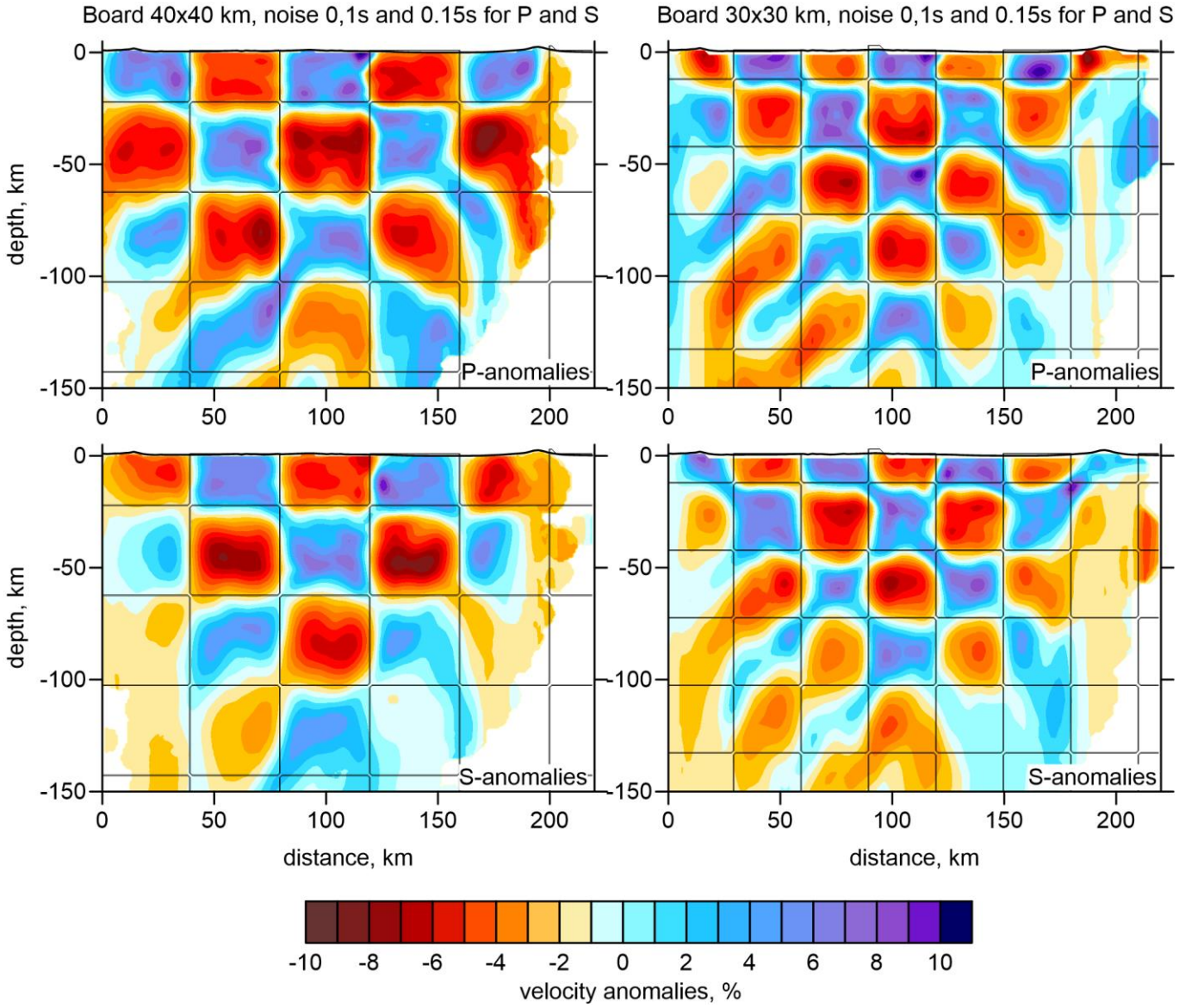


Fair reconstruction of anomalies in the crust and uppermost mantle.

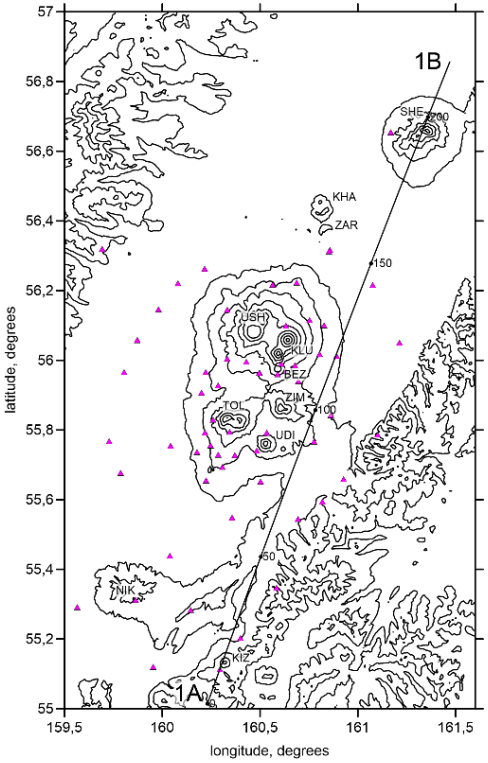
Fair recovery of sign change at 30 km and 70 km depth.

This resolution is much better than in all previous studies of this area

Checkerboard tests, vertical resolution

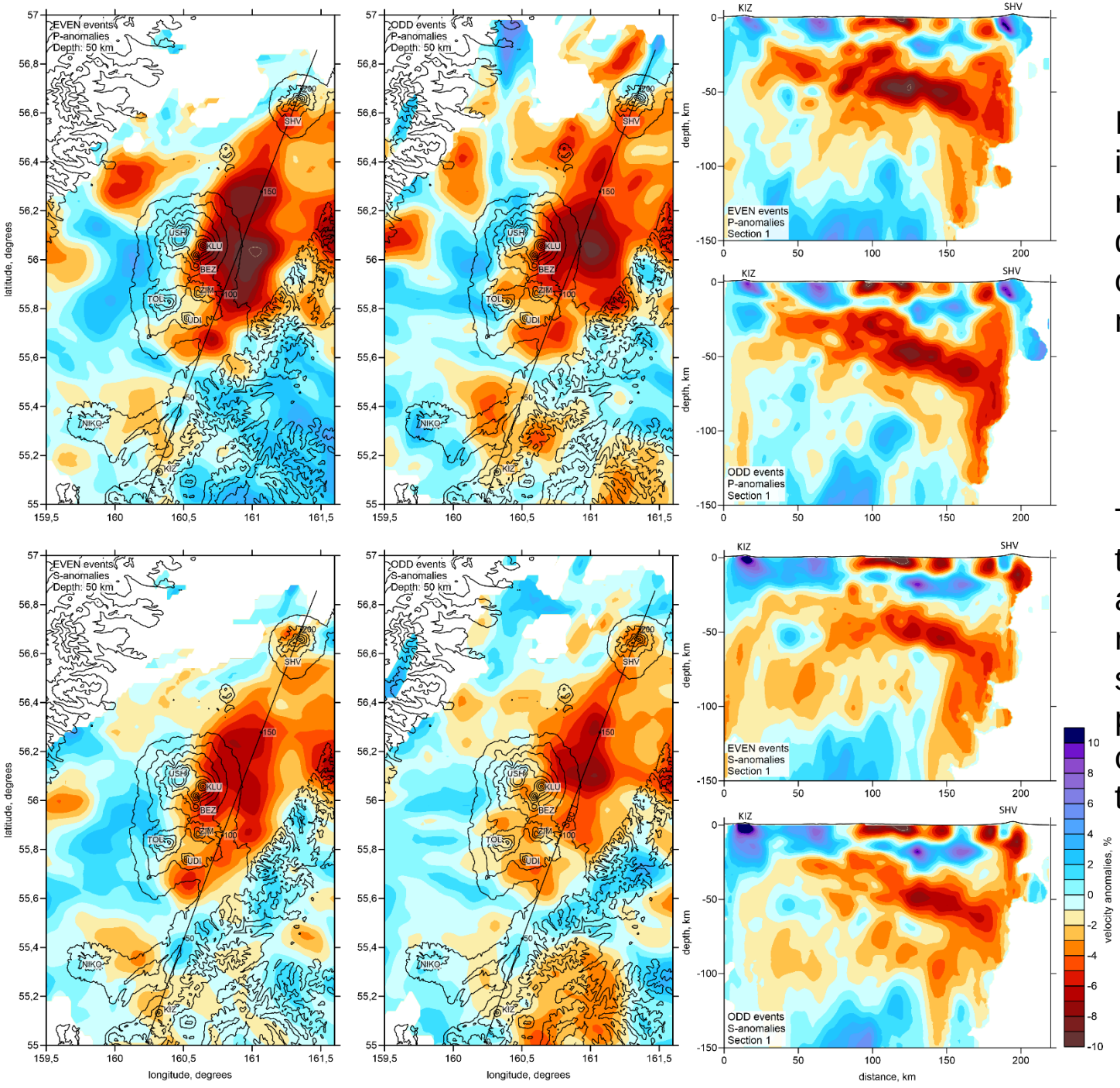


Compared to the previous studies, the present dataset enables very good vertical resolution.



The resolution is compatible to that existing in well-covered areas, such as Japan and Etna. For wild and inaccessible Kamchatka, it is almost a miracle!

Odd/even test

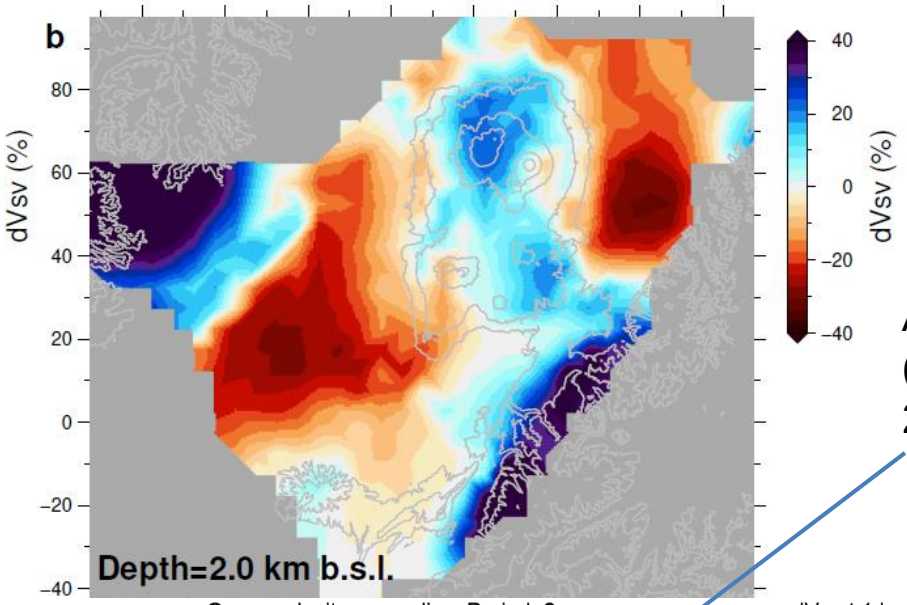


Independent inversions with randomly separated data subsets (with odd and even numbers of events)

This test shows that the major large anomalies are robust, whereas some smaller patterns might be caused by noise in the data.

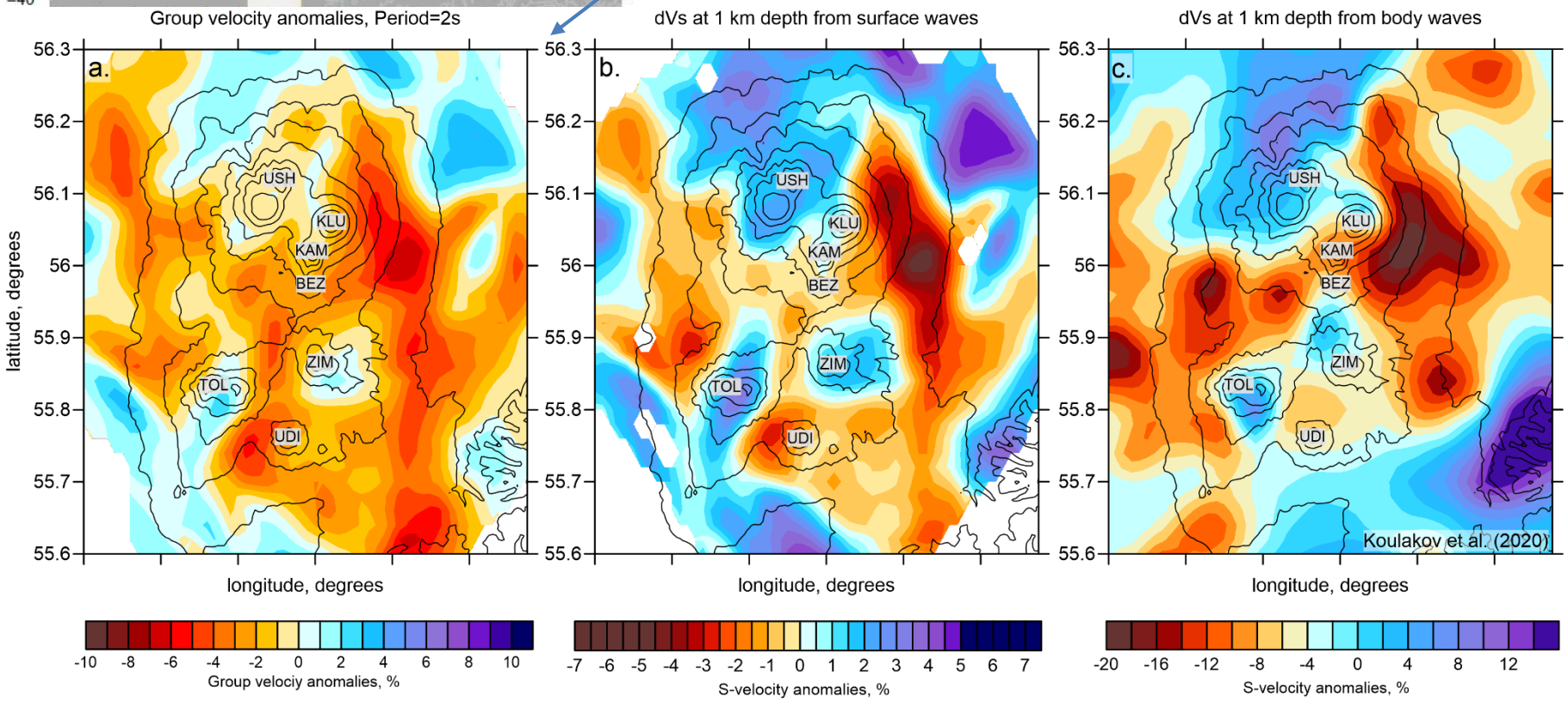
Comparison with the results of ambient noise tomography

ANT tomography (Green et al., 2020)

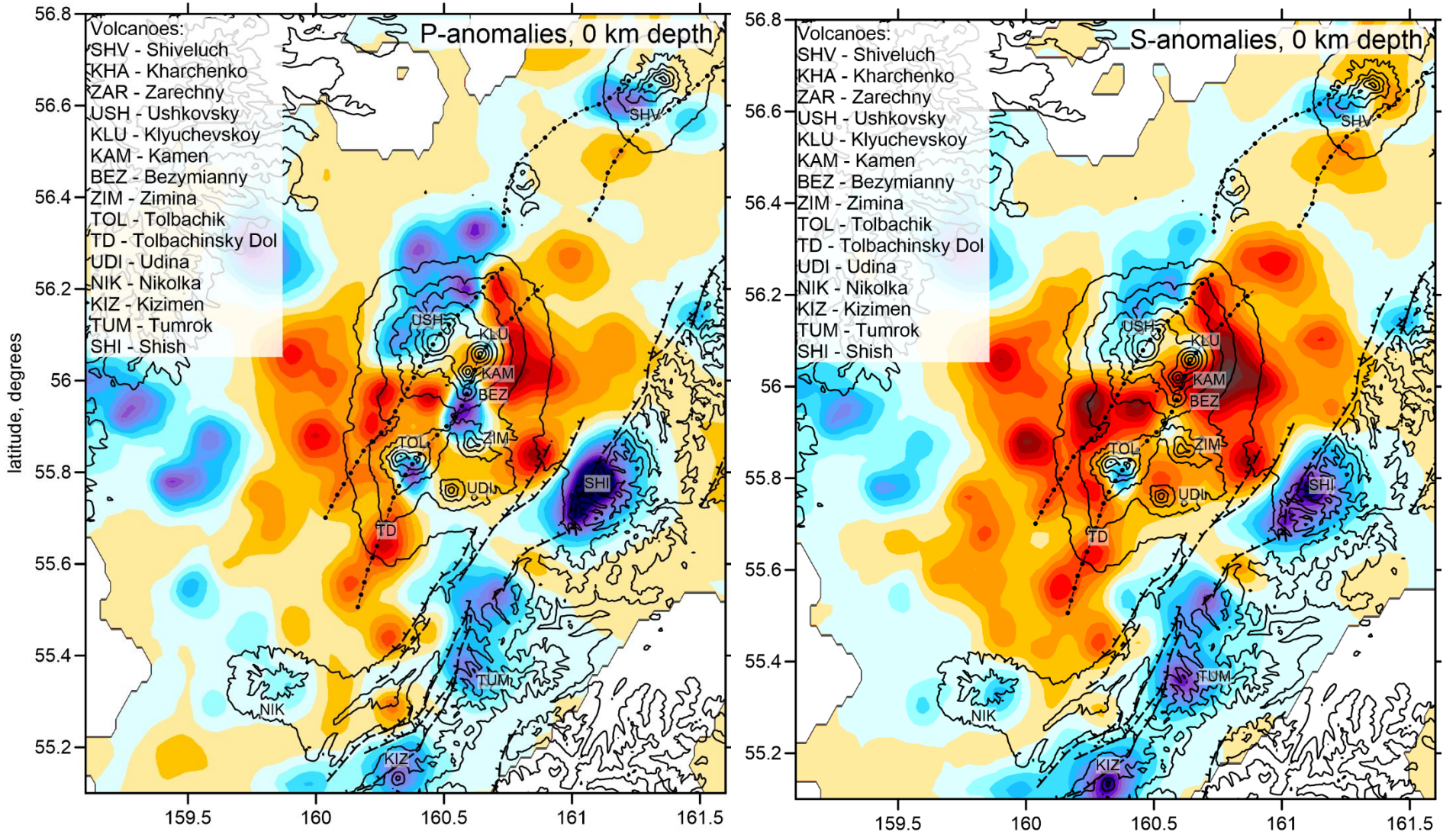


ANT tomography (Egorushkin et al., 2020)

Body wave tomography (this study)

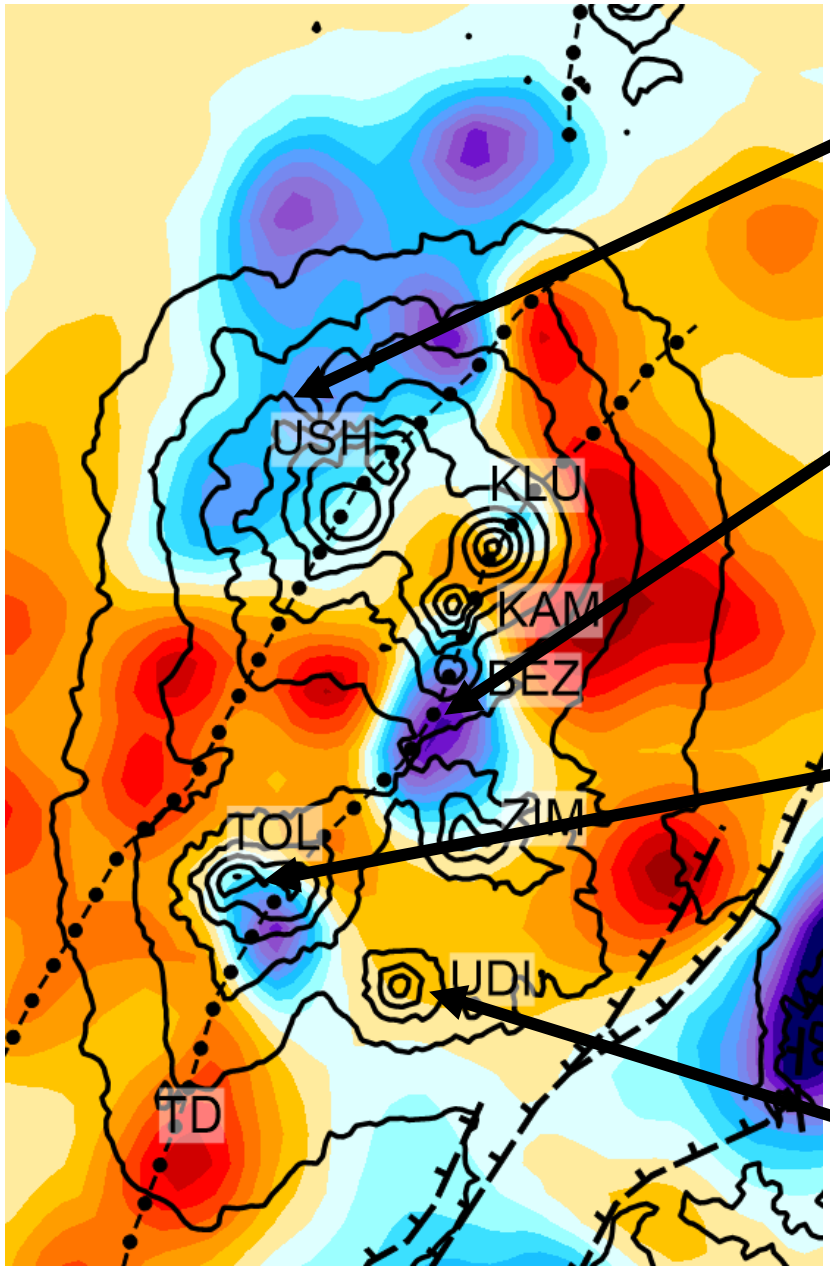


P and S wave anomalies at shallow depths



dVp and dVs consistently reveal the main structures associated with most of volcanoes in the Northern Group of Volcanoes

Links of the crustal P and S wave anomalies with volcanoes



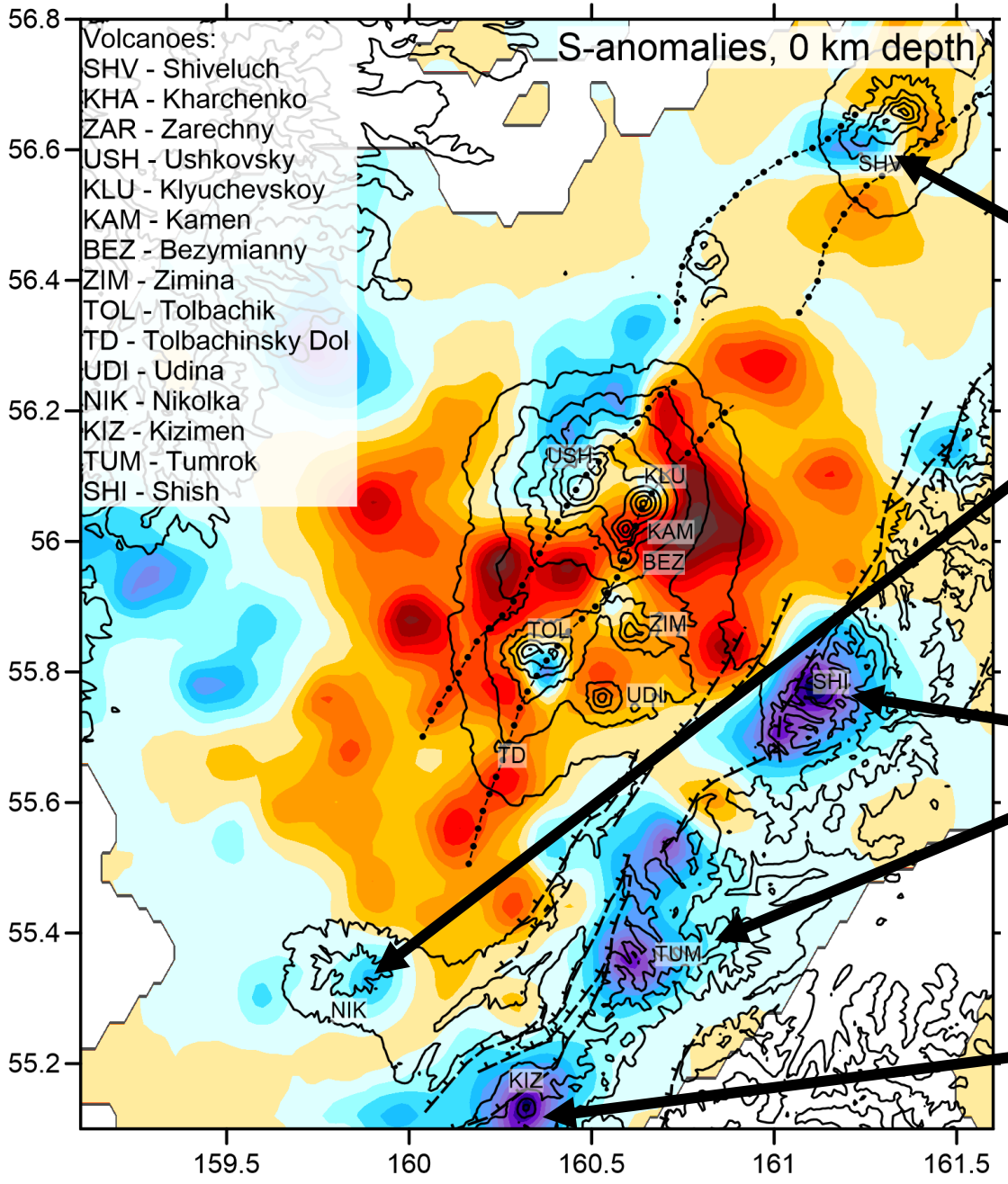
A giant volcano **Ushkovsky** is associated with high-velocity roots in the crust. At shallow depth, high-V marks the location of the Pra-Ushkovsky shield volcano

Zimina is mainly composed of andesites and dacites. However, at the initial stage, it was basaltic. At shallow depth, high-V marks the location of the Pra-Zimina shield volcano

Beneath **Tolbachik**, shallow high-V anomaly marks the location of the basaltic basement. Low V at greater depths indicate active state of the plumbing system. Actively erupting **Tolbachinsky Dol** is low-V.

Udina is associated with low-V in the crust. Similarly as Zimina, it was considered as extinct andesit-dacitic volcano. However, after 2017 it demonstrates high seismic activity (active magma system?)

Links of the crustal P and S wave anomalies with volcanoes



Volcanoes beyond KGV:

Shiveluch – highly explosive andesitic volcano is associated with high-V beneath the SW part indicating the solidified feeding system

Nikolka – strongly eroded large extinct shield volcano is associated with high-V in the crust

Shish and Tumrok –two large extinct volcanoes in the East Volcanic Front are associated with high-V

Kizimen – active explosive andesitic volcano is associated with high-V. No structures associated with active magma system are revealed.

Revealing slab-related fluids as a major factor for volcano feeding in KGV:

Beneath Klyuchevskoy:

The “famous” anomaly of high Vp/Vs ratio coinciding with the dense cluster of long-period seismicity at ~30 km depth is clearly seen in this model.

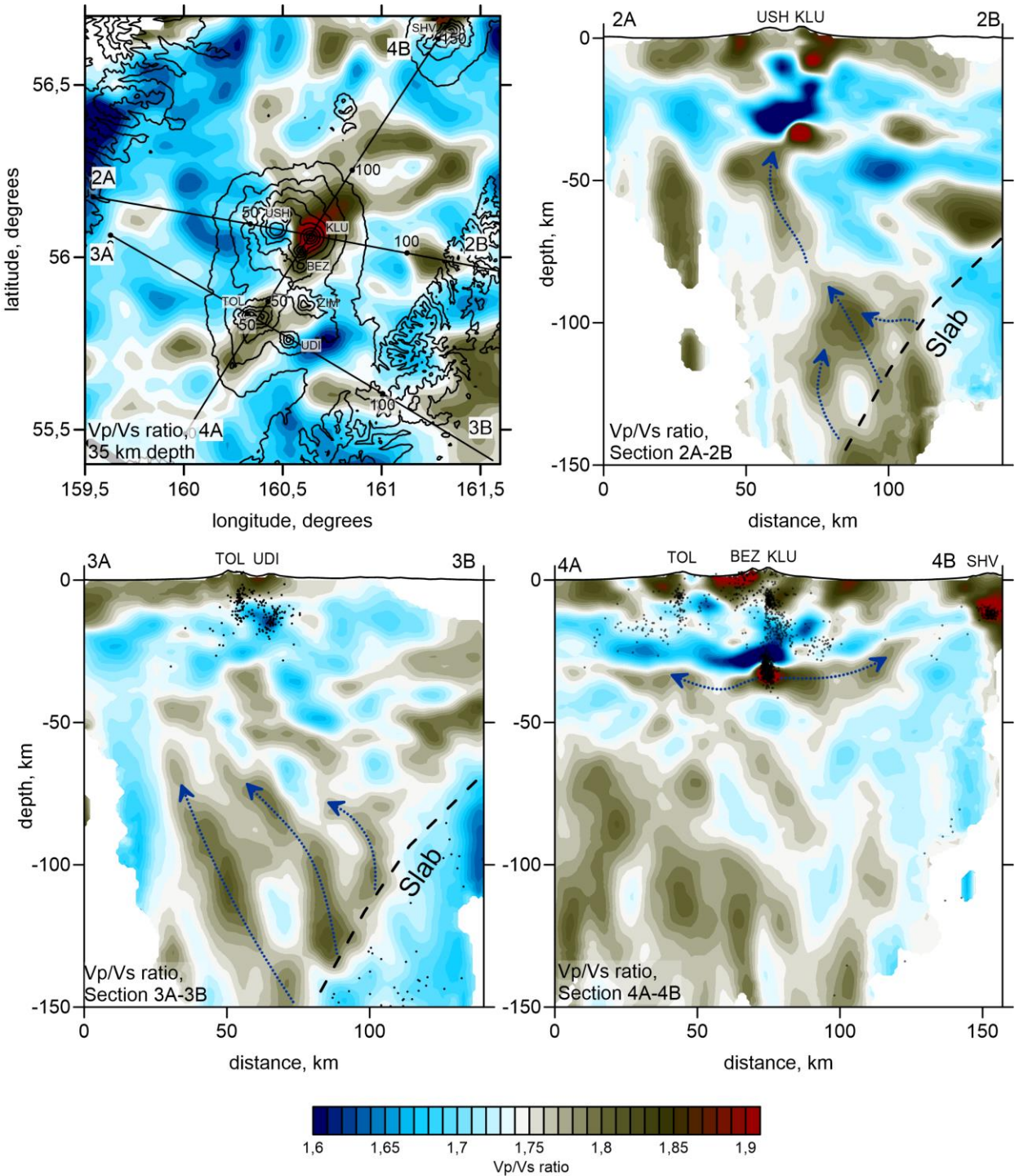
In a section with the Vp/Vs ratio, it seems to be connected with the slab dehydrating zone at depths from 100 to 150 km.

This might represent the path of ascending fluids.

Beneath Tolbachik:

Three paths of fluids escaping from the slab do not form a single reservoir.

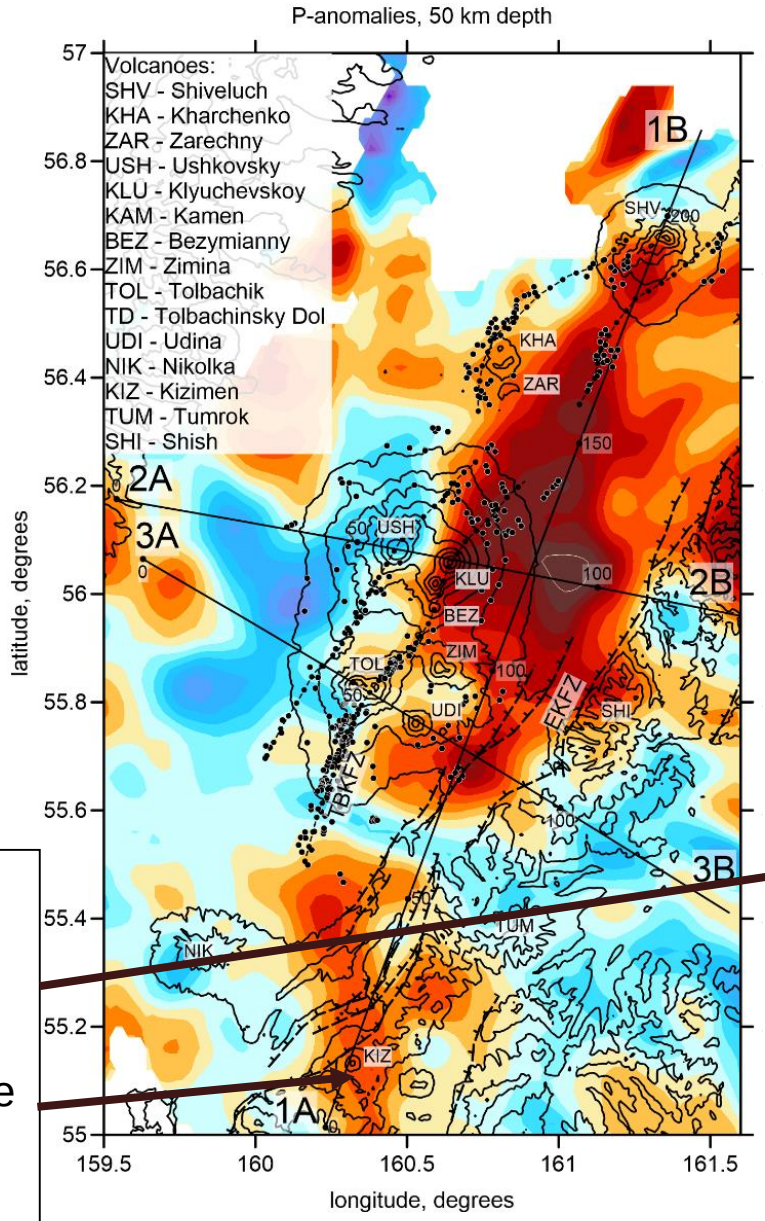
The material migrates laterally from the Klyuchevskoy reservoir along the Moho.

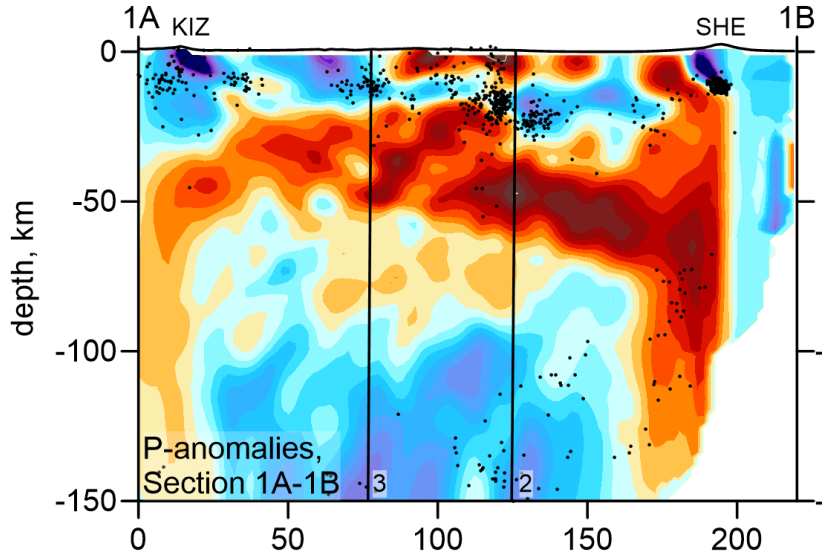


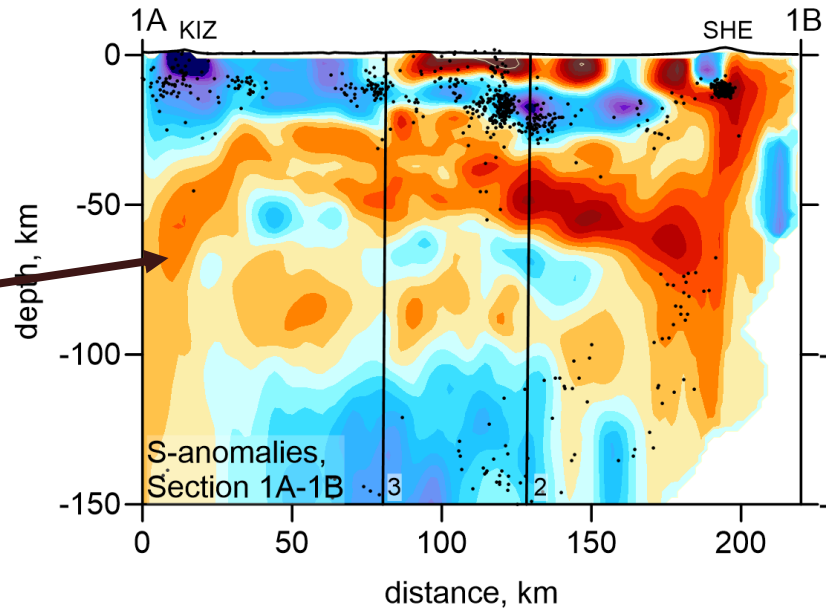
P- and S wave anomalies in the profile from Kizimen to Shiveluch

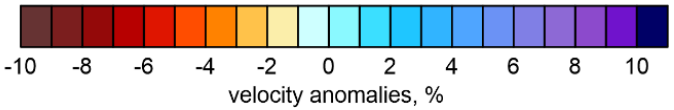
The area of feeding the KGV in the mantle wedge appears to have a single source located above the slab window beneath Shiveluch

Possibly, Kizimen is fed from another source, which agrees with the concept of discrete “hot fingers”.

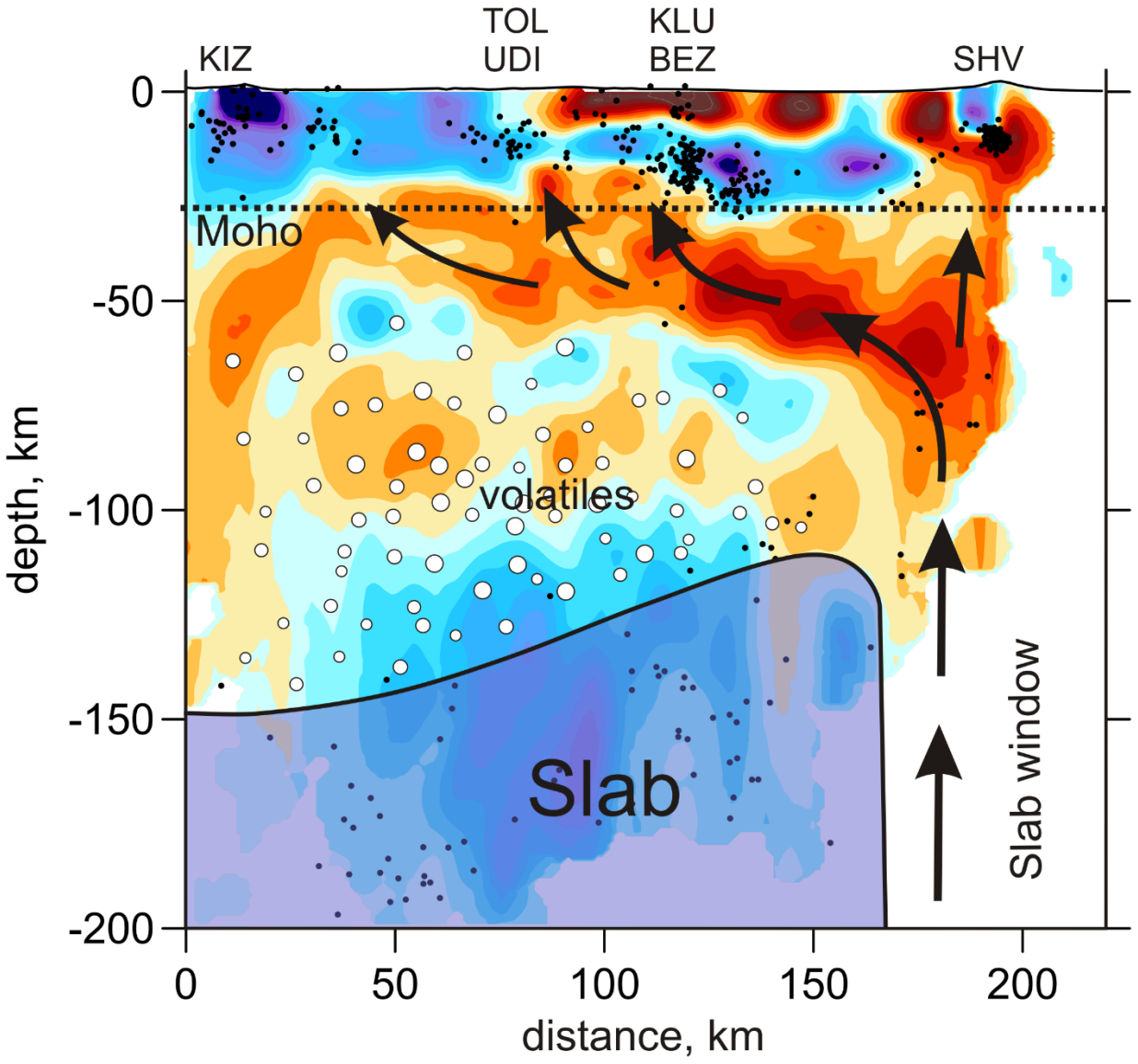






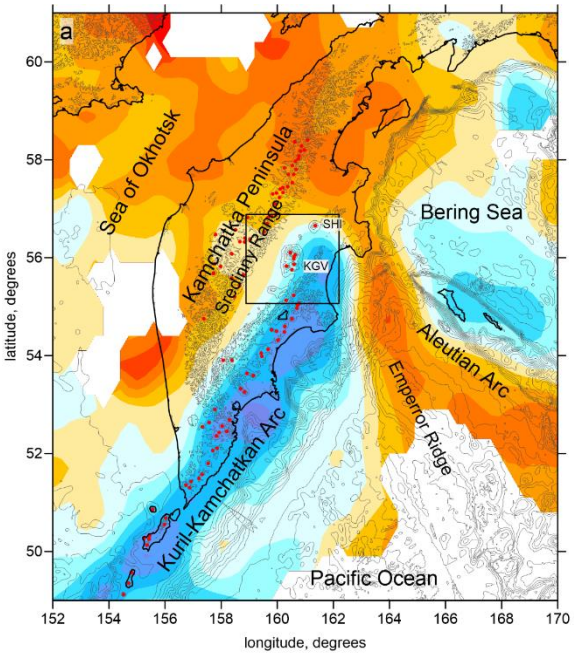


Uppermost mantle structure based on the inversion of the combined dataset

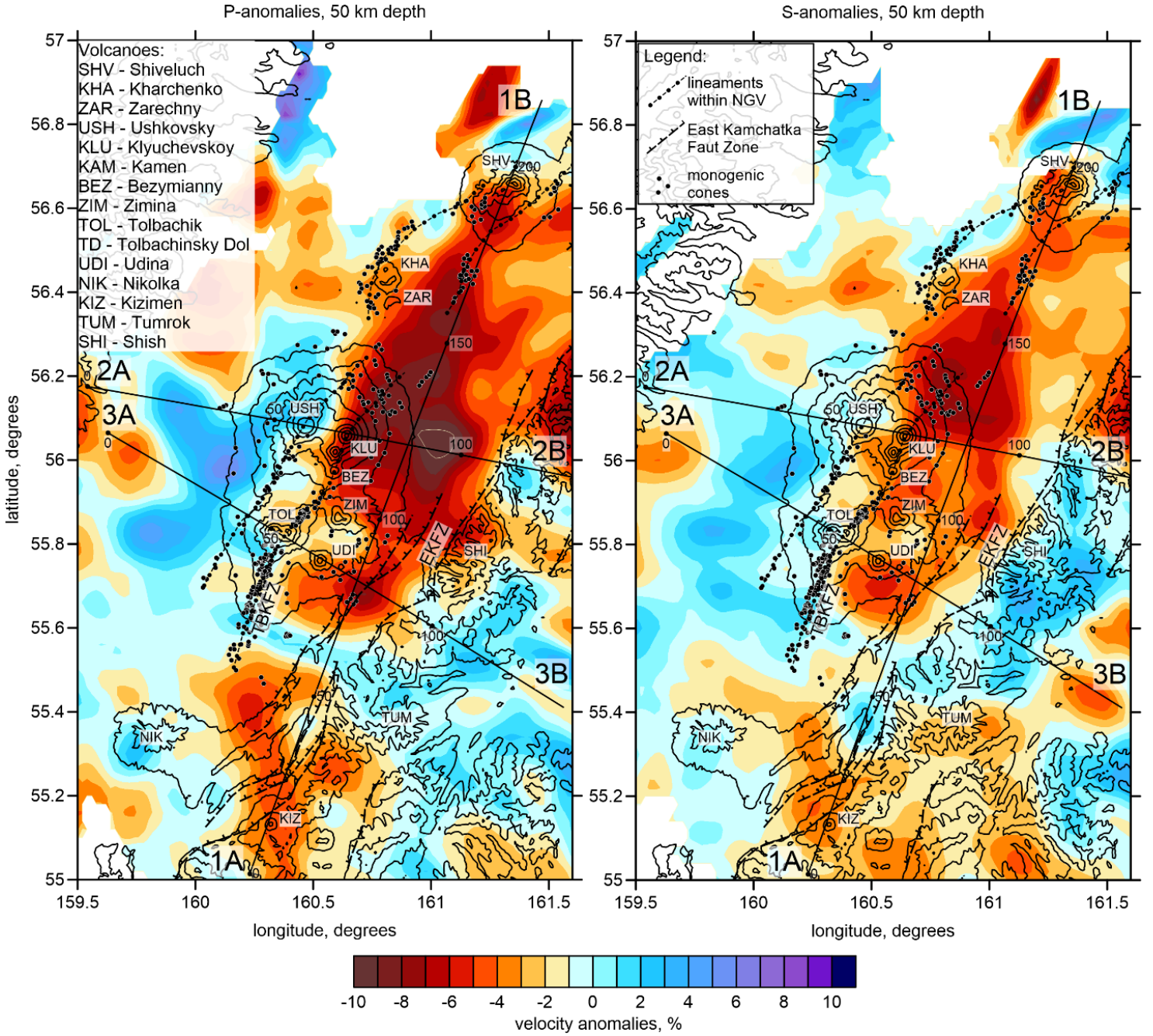


The area of feeding the KGV in the mantle wedge appears to have a single source located above the slab window beneath Shiveluch.

Hot asthenosphere + volatiles coming out from the slab + effect of the Emperor Ridge subduction lead to exceptionally high activity and variability of the KGV volcanoes.



Traces of rifting beneath eastern branch of the Central Kamchatkan Depression

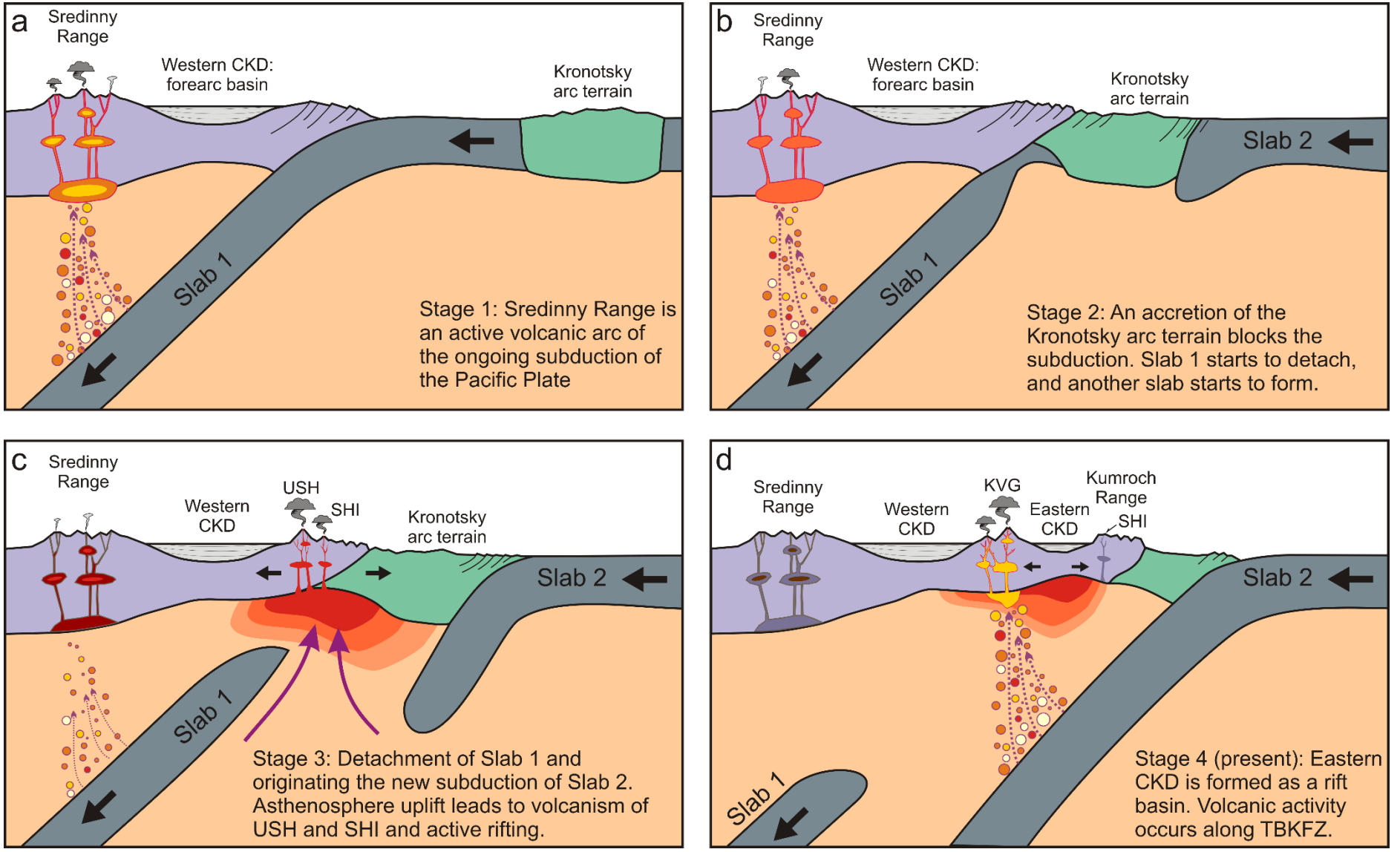


P and S velocity anomalies at 50 km depth:

The low-velocity anomaly is located beneath the Eastern Branch of the Central Kamchatkan Depression between the regional lineament in KGV and East-Kamchatka fault zone.

This might indicate the asthenosphere upwelling due to the rift processes separating KGV from the East Kamchatkan Volcanic Front

Tectonic interpretation based on the tomography model



Scenario describing the major stages of opening the Central Kamchatkan Depression and forming the volcanic centers in Central Kamchatka

Conclusions:

1. Deploying the KISS network in wild hard-accessible regions of Central Kamchatka made possible revealing unprecedentedly high-resolution structures of the crust and upper mantle beneath the Klyuchevskoy volcano and surrounding areas.
2. In the crust, the P and S velocity anomalies are clearly associated with centers of current and previous volcanic activity.
3. The Vp/Vs ratio in the mantle wedge reveals the paths of fluids that escape from the slab at depths of 100-150 km and ascend toward the major volcanoes of the Klyuchevskoy group and Shiveluch.
4. Mantle structures demonstrate that the volcanoes of the Northern Group are fed from an asthenospheric upwelling through the slab window beneath Shiveluch.
5. Low-velocity anomaly in the mantle beneath the eastern branch of Central Kamchatkan Depression indicates the asthenospheric upwelling due to rifting that separated the volcanoes of the Northern Group of Volcanoes from the Eastern volcanic front.

Thank you for your attention!