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3 **Magma source beneath the Bezymianny**

4 **volcano and its interconnection with**

5 **Klyuchevskoy inferred from local**

6 **earthquake seismic tomography**

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26 September, 2015

27 Novosibirsk, Russia

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Abstract

We present a new 3D model of P and S wave velocities and Vp/Vs ratio to 20 km depth beneath the active Klyuchevskoy and Bezymianny volcanoes (Kamchatka, Russia). In this study, we use travel time data from local seismicity recorded by temporary stations of the PIRE experiment from October 24 to December 15, 2009 and permanent stations operated by the Kamchatkan Branch of Geophysical Survey (KBGS). The calculations were performed using the LOTOS code (Koulakov, 2009). The resolution limitations were explored using a series of synthetic tests with checkerboard patterns in the horizontal and vertical sections. At shallow depths, the resulting Vp and Vs anomalies tend to alternate on opposite sides of the lineation connecting the most active volcanic centers of the Klyuchevskoy Volcanic Group (KVG). This prominent lineation suggests the presence of a large fault zone passing throughout the KVG, consistent with regional tectonics. We suggest that this fault zone weakens the crust creating a natural pathway for magmas to reach the upper crust. Beneath Bezymianny volcano we observe a shallow anomaly of high Vp/Vs ratio extending to 5-6 km depth. Beneath Klyuchevskoy another high Vp/Vs anomaly is observed, at deeper depths of 7 and 15 km. These findings are consistent with the regional-scale model of Koulakov et al. (2013a) and provide some explanation for how very different eruption styles can be maintained at two volcanoes in close proximity over numerous eruption cycles.

Key words: Bezymianny volcano, Klyuchevskoy volcano, seismic tomography, local seismicity, magma sources.

1. Introduction

Klyuchevskoy and Bezymianny are volcanoes in the Klyuchevskoy Volcano Group (KVG) (Figure 1B), located on the Kamchatka Peninsula in the Russian Far East at the northeast corner of the subducting Pacific plate (Figure 1A). Active volcanoes in this group, including Kluchevskoy, Bezymianny and Tolbachik, are some of the most productive in the world. A striking feature of KVG is the diversity of the composition and eruptive styles that vary from explosive andesitic to fissure basalt Hawaiian-type eruptions (e.g., Fedotov et al., 2010). The composition of some volcanoes of the Klyuchevskoy group may significantly change during a short period of time (Laverov et al., 2005; Dobretsov et al., 2012).

Bezymianny is an explosive andesitic volcano consisting of 54.5 to 62.5% SiO₂ (Gorshkov, 1959; Bogoyavlenskaya et al., 1985; Ozerov et al., 1997). This is strikingly different from the basaltic composition of Klyuchevskoy volcano, located just 10 km away (e.g., Ozerov et al., 1997; Fedotov et al., 2010). The current altitude of Bezymianny is 2880 m. Prior to 1956, the altitude of Bezymianny was 3075, and it was considered dormant. Unrest at Bezymianny started on 22 October 1955 with ash eruptions to altitudes of 5-8 km. On 30 March 1956 a catastrophic explosion of the volcano occurred that led to collapse of western rim of volcano (Gorshkov, 1959). During the VEI 5 eruption, 3 km³ of material was deposited (Bogoyavlenskaya et al., 1985). According to Belousov, (1996), the eruption products contained 84% juvenile material (andesite). The massive lateral blast that characterized the 1956 eruption was a similar in style to eruptions of Mount St. Helens in 1980, and of Shiveluch in 1964. The heat energy of the three eruptions is comparable: 1.3 x 10¹⁸, 3.8-4.8 x 10¹⁸ and 1 x 10¹⁷ J for Shiveluch, Bezymianny, and Mount St. Helens, respectively (Bogoyavlenskaya et al., 1985). According to the major element and ICP-MS trace element analyses by Turner et al. (2013), the composition of the Bezymianny eruption products is changing progressively from relatively silicic magma in 1956 (~ 60.4% SiO₂) to more mafic compositions (e.g. 56.8% SiO₂ in 2010). Turner et al. (2013) suggest that these changes might be due to the existence of three magma reservoirs at different depth levels. According to the petrologic data, magmas from the shallowest reservoir erupted first; later eruptions tapped progressively deeper reservoirs. Geological information on the composition and temporal evolution of Bezymianny volcano during 38-40 thousand years of its life is presented by Almeev et al. (2013).

Multi-scale geophysical studies can give insights about the diversity of composition and eruptive styles. Broad upper mantle structures (scales of 100s km) reveal the connection from subducting plates to the volcanoes that overlie them, while crustal structures (scales of 1s-10s of km) can often directly image magma reservoirs and associated structures. The multi-scale seismic structure beneath the Kamchatkan peninsula has been investigated in numerous studies. The shape of the subducting slab beneath Kamchatka and the Kuriles in the upper mantle based on the tomographic inversion of global and regional travel time data were presented in Gorbatov et al. (2001) and Koulakov et al. (2011a). Similar features were obtained using surface wave data by Levin et al. (2002). Evidence for a gap in the subducting plate at the edge of the Kuril-Kamchatka and Aleutian subduction zones was obtained from teleseismic tomography by Lees et al. (2007a). Structures above the subducting slab have been observed by Gorbatov et al. (1999), Nizkous et al. (2006), and recently, by Koulakov et al. (2016). In particular, the later work found inclined low-velocity anomalies connecting the area of

the Klyuchevskoy group with the slab at ~100 km depth that have been interpreted as fluid pathways feeding the volcanoes of the group.

The crustal structures beneath volcanoes of the Klyuchevskoy group were investigated in several seismic and non-seismic studies. One of the first study of Klyuchevskoy has been performed by Gorshkov (1956) based on studying attenuation of shear waves. He proposed that the magma chamber size was 30 km, and it was located as around 60 km depth. The complex interconnections of magma sources beneath different volcanoes of the Klyuchevskoy group based on the volcano-related seismicity have been studied by Tokarev and Zobin (1970). More recently, West (2013) presented the analysis of seismicity beneath Bezymianny volcano activity before, at and after eruptions to identify precursors of large eruptions. Ozerov et al. (1997) provided geochemical analysis of basalts and andesites composing Klyuchevskoy and Bezymianny volcanoes. Based on these results, together with geophysical, petrological and geological data, they presented a basic structure of magma-generating system of these volcanoes to a depth of 150 km depth. Magnetotelluric sounding by Moroz and Moroz (2006) revealed a low resistivity zone beneath the Bezymianny volcano interpreted to be a magma reservoir.

During the 1970s, a large-scale deep seismic sounding experiment was performed in the area of Bezymianny and Klyuchevskoy (Balesta et al., 1977). They found evidence for a fault zone passing throughout the KVG. Based on local earthquake data for the period of 1981-1994, Lees et al. (2007b) constructed a tomography model, which identifies a low P-velocity anomaly beneath the Klyuchevskoy volcano at 20-35 km depth. Similar data were used to build another tomography model, which was compared with petrophysical information by Khubunaya et al. (2007), who estimated the melt fraction in a magma reservoir at approximately 2%. The derived seismic structures generally match with each other as well as with the resistivity distribution computed by Moroz and Moroz (2006). More recent models of the crust beneath the Klyuchevskoy group were presented by Koulakov et al. (2011b, 2013a). The former study used 2004 data, just prior to strong eruptions at Klyuchevskoy and Bezymianny, and identified three levels of magma storage. In the deepest level below 24 km depth, they found a Vp/Vs ratio as high as 2.2. Koulakov et al. (2013a) derived a time series of tomography models based on yearly data subsets in a time period from 1999 to 2009. The changes in the reported 4D seismic model appear to be consistent with the major eruption episodes in the considered time period.

The seismic tomography models in Koulakov et al. (2011b, 2013a), and in other previously published studies, were based on phase arrivals recorded by stations in the permanent seismic

network, with little coverage of Bezymianny itself. The resulting tomographic models have very limited resolution in the Bezymianny region. To enhance seismic observations of the volcano, a temporary network was installed in the framework of the PIRE ([Partnership for International Research and Education](#)) Project (e.g., [Thelen et al., 2010](#); [West, 2013](#)). The target of the work was to obtain a new seismic model using the data of both temporal and permanent stations to improve the seismic model in the upper crust beneath Bezymianny and Klyuchevskoy volcanoes. In turn, this may provide the configuration of magma sources and explain the differences in eruption styles and compositions at the Bezymianny and Klyuchevskoy volcanoes.

2. Data and algorithms

Data from temporary and permanent stations around Bezymianny were used in this work. Six campaign broadband stations were installed within the PIRE Project ([West, 2013](#)) from 2007 to 2010. In addition, we used the data of twelve permanent stations managed by the Kamchatka Branch of Geophysical Survey of the Russian Academy of Sciences (KBGS). The aperture of the network was approximately 40 km; however, denser distribution of stations was achieved in the vicinity of the Bezymianny edifice ([Figure 1B](#)). [All the stations of the both networks provided three-component seismic records](#). KBGS reported the information on picks and source locations. However, to avoid any bias related to different picking style, we have re-picked all the data of both the permanent and campaign stations from October to December 2009. This time window provided the most complete coverage from the campaign stations. All seismograms were band-pass filtered on 1-6 Hz. Manual picking of P and S arrival times was performed using an open software DIMAS (Display, Interactive Manipulation and Analysis of Seismograms), which was developed by [Droznin and Droznina \(2011\)](#) at KBGS RAS for processing seismic data on volcanoes. We chose to include primarily shallow earthquakes (down to 15 km depth) in the vicinity of Bezymianny and Klyuchevskoy. In total we used 2126 earthquakes and picked 8670 P wave arrivals and 8530 S wave arrivals. [The accuracy of picking was similar for the P and S wave arrivals and varied from 0.02 s to 0.2 s](#). For the tomographic inversion, we use only earthquakes with at least 8 picked phases. Travel times with residuals exceeding 0.5s, relative to the starting one-dimensional model were excluded as well. [This threshold is determined by the values of expected anomalies and maximum distances of the pay paths in our experiment. Larger than 0.5 s residuals could not theoretically be produced in short distances between sources and receivers used in this study, and, therefore, are probably caused by](#)

incorrect picking. Using these criteria, the tomographic inversion dataset consisted of 333 earthquakes with corresponding 2256 P wave arrivals and 1951 S wave arrivals (~12.6 phases per earthquake). The locations of these earthquakes are shown in Figure 2.

The calculation of the seismic models was based on the LOTOS code developed by Koulakov (2009). It allows for simultaneous iterative inversion of P and S travel time data and provides the 3D distributions of P and S velocities and source locations. The program starts from rough estimation of source parameters in the 1D starting velocity model using the grid search method and linear ray approximation. The following iterative procedure includes the steps of source locations in the updated 3D velocity models and inversion. The location used the 3D ray tracing algorithm based on the bending method (Um and Thurber, 1987). The location algorithm allowed the sources to be located above sea level, but they were limited by the topography surface. The simultaneous inversion for P and S anomalies and source parameters was performed using the LSQR (Least Squares) method (Paige and Saunders, 1982; Nolet, 1987), which iteratively solve large sparse systems of linear equations. The quality of the solution was controlled by additional matrix blocks enabling amplitude damping and smoothing. The values of the inversion parameters, such as smoothing, grid spacing, and number of iterations were determined according to the results of synthetic tests. All the results presented here were obtained after four iterations.

We provide the full file structures for all models presented here, together with the LOTOS code, instructions, and necessary parameter file to recompute results presented in the following sections (www.ivan-art.com/science/bezym.zip).

3. Testing and inversion results

Synthetic tests demonstrate the resolution limitations of this dataset and algorithm. In the synthetic modeling, 3D velocity distributions are defined as a superposition of the 1D velocity model and 3D anomalies. Synthetic travel times are computed using the bending algorithm for ray tracing all of the actual source-receiver pairs. These travel times are perturbed with random noise. In all tests presented below added noise to the input P and S travel times with a variance of 0.1s, chosen to match the approximate variance of the travel time residuals in the best-fit 3-D model. The reconstruction of the synthetic model is performed using the same workflow and same inversion parameters as the true data inversion. This includes the preliminary step of relocating the earthquake sources in the 1D starting model. This step, ignored in some tomographic studies, strongly disturbs

the synthetic residuals and mimics the real world trade-off between source locations and velocity models.

To test horizontal resolution, we created columnar models with different width anomalies and constant distribution in depth. Figure 3 presents reconstruction results for three of these checkerboard models with anomaly widths of 10 km, 7 km and 5 km and amplitudes of $\pm 8\%$ V_p and $\pm 9\%$ V_s . We defined the opposite signs for the P and S anomalies to ensure strong variations in the V_p/V_s ratio. The results show robust reconstructions of anomalies in areas with sufficient ray coverage. For the case of 5 km size, there is some diagonal smearing, however, the main maxima of the retrieved anomalies align with the input model.

Most local earthquake tomography experiences some trade-off between source location and velocity resolution. This impact is most prevalent in the vertical dimension frequently leading to vertical resolution that is poorer than in the horizontal dimension. To check the vertical resolution of models beneath Bezymianny and Klyuchevskoy, we created models with different depth distributions of anomalies. In Figure 4, we present one of the models with the checkerboard defined in the vertical section. The lateral size of the anomalies is 7 km. In the vertical dimension, we defined three layers with changes of signs at 1 km and 7 km depth. Anomalies are $\pm 8\%$ for V_p and $\pm 9\%$ for V_s . Across the section, the anomalies extend to distances of ± 4 km to both sides. The reconstruction results show that beneath Klyuchevskoy, we can robustly resolve all three depth layers. Beneath Bezymianny, the vertical resolution appears to be poorer, mostly because the ray paths come predominantly from the vicinity of Klyuchevskoy. At the same time, the locations of the main patterns are retrieved correctly. These synthetic tests demonstrate the resolving power of the dataset and indicate the scale of features that should, and should not, be trusted in the inversion of the real data. We limit our interpretations in the following sections to features that the synthetic tests suggest are robust.

The synthetic tests allows estimating the uncertainty of source locations related to velocity anomalies and errors in the data. According to our estimates, the errors in source coordinates is around 0.5-1 km for the central parts of the study area and might be larger than 5 km for deep and out-of-network events. Nevertheless, it was shown that despite of the error, such events are useful for tomography and their adding allows improving the resolution capacity of the model.

The inversion of real data started with determining the optimal reference model. We began with rather simple 1D models with V_p defined at three to four depth nodes and linear interpolation in between. The S-velocity was determined using a constant V_p/V_s ratio. When searching for the best

model, we manually adjusted parameters and performed the full inversion for each case. In total, we performed a number of trials preferring models that provided the smallest travel time residuals. At the same time, we sought a reference model that created a balance between positive and negative anomalies. Figure 5 shows two examples of data inversions using under- and overestimated velocity values in the reference model. At shallow depths, the average anomalies are strongly biased by the reference model, however, the locations of the main patterns remain stable. At depth the pattern of anomalies is substantially different (Fig. 5). This occurs because of strong differences in where the models place the locations of deep earthquakes. When the reference model is too far off, the earthquake source locations are poor enough that they do not meet the criteria for inclusion in the inversion. The optimal reference model, used for computing the main results, provided the best balance of positive and negative anomalies and provided the minimum residual after inversion. In the optimal model, $V_p/V_s=1.75$ and the P-velocities are equal to 3.3 km/s at -5 km, 4.6 km/s at 5 km and 6.7 km/s at 30 km depth.

During three inversion iterations, the average deviations of residuals reduced from 0.168 s to 0.141 s (16.5%) for the P-data and from 0.215 s to 0.170 s (21.0%) for the S data. These relatively low values of variance reduction might be due to a relatively small size of the study area. When passing through the anomalies beneath the volcano, the ray cannot accumulate large anomaly-related residual, even if the anomalies are strong. Therefore, the signal to noise ratio in this case is relatively small, and the variance reduction is weak. It is also possible that extreme small-scale heterogeneity, especially in the top 1-2 km, could not be accommodated by the smooth models. Note that approximately the same variance reduction was obtained during the inversion of synthetic data.

The results are presented in horizontal sections at 0 and 10 km depth (Figure 6) and in one vertical section passing through Klyuchevskoy, Kamen and Bezymianny volcanoes (Figure 7). We present the P- and S-anomalies and V_p/V_s ratio, which was obtained by dividing the resulting P- and S-absolute velocities. The robustness of this method for estimating V_p/V_s was assessed by synthetic tests. Figure 6 also shows the distributions of P and S rays and a manually selected area deemed to have sufficient data coverage. Outside this area, the anomalies are presumed to be not reliable. Further information on the resolution can be obtained from the analysis of the synthetic tests in Figures 3 and 4.

4. Discussion.

4.1. Revealing the fault zone beneath KVG

Most of recent volcanic activity in the Klyuchevskoy volcano group seems to coincide with a line passing throughout the group (yellow dotted line in [Figure 1B](#)). To the south of KVG, it coincides with a long zone of fissure eruptions in the Tolbachinsky Dol. Then it passes through Ostry Tolbachik and follows a chain of cinder cones to Bezymianny. To the north, this line passes through the active Klyuchevskoy volcano and dormant Kamen. This lineation suggests a strong crustal feature, perhaps a fault zone as suggested by previous authors (e.g., [Ermakov et al., 2014](#)), which attracts the volcanic activity. The association of faults and volcanoes has been proposed for many regions including Toba (e.g., [Chesner, 2012](#)) and Kilauea ([Wolfe et al., 2003](#)). It is presumed that tectonic displacements along large faults weaken the crustal rocks creating zones that are favorable for penetrating fluids and magma material. The area of the Klyuchevskoy group is completely covered by thick volcanic deposits; therefore, it is almost impossible to identify any geological manifestations of a fault on the surface. If there is any seismic activity related to the fault displacement, it is impossible to separate it from the tremendous number of volcano-related events beneath Klyuchevskoy and other active volcanoes. Similarly, any lateral displacements along the fault measured by GPS instruments would be masked by strong deformations of the surface caused by eruption activity (e.g., [Grapenthin et al., 2013](#)). Indirect indications of a deep crustal fault in the vicinity of the Klyuchevskoy and Bezymianny volcanoes were derived from deep seismic soundings in the 1970s ([Balesta et al., 1977](#)).

There appears to be some alignment between the primary shallow crustal P- and S-velocity features ([Fig. 6](#)) and this proposed fault line. To the south of Bezymianny, the low- and high-velocity patterns seem to be separated by this line. The same separation is observed in the S-velocity model for the area of Kamen and Klyuchevskoy. In this case, the location of the high- and low-velocity patterns is opposite in respect to the former case. Such anti-correlation of seismic anomalies is typical for some **strike-slip faults** (see, for example, the North-Anatolian fault in [Koulakov et al., 2010](#)). The step-shaped structures may represent lateral shifts of certain geological structures due to the strike-slip displacements along faults. In this case, we do not have enough information to identify these geologic structures in the opposite flanks and then to evaluate the displacement distance. However, the presence of such structures might serve as an indirect argument for the existence of such a fault zone, and we can evaluate that the displacement is approximately 10 km. Note, however, that at 10 km depth, no link between velocity anomalies and this line is observed. We propose that at this depth, the seismic structure is dominated by the presence of magma reservoirs, hot zones and volatiles that overprint relic geologic structures. These results are consistent with the concept of a

significant fault zone striking through the volcanoes of the Klyuchevskoy group (e.g., [Ermakov et al., 2014](#)).

4.2. Magmatic sources beneath Klyuchevskoy and Bezymianny volcanoes

Bezymianny and Klyuchevskoy are located just ten kilometers from each other and have single zone of anomalous seismic attenuation (Tokarev and Zobin, 1970) that may indicate a genetic relationship, however the eruption styles and lava compositions of these volcanoes are completely different (e.g., [Ozerov et al., 1997](#)). Klyuchevskoy erupts mostly liquid basaltic lavas from its summit and peripheral cones, whereas, Bezymianny is characterized by explosive andesitic eruptions (e.g., [Girina, 2013](#)). The close proximity of these very different volcanic styles remains the subject of much debate. There are two schools of thought. One presumes that both volcanoes are fed from a single magmatic system, but from specific sources with different degrees of crystal fractionation (e.g., discussion in [Ozerov et al., 1997](#)). There is some seismological evidence for connections between the eruption processes of Klyuchevskoy and Bezymianny ([Senyukov, 2013](#)) indicating a joint magmatic system. Another concept presumes two completely separate magmatic sources. For example, [Dobretsov et al. \(2012\)](#) proposed that the Klyuchevskoy volcano is fed through a multi-level system of magma chambers, whereas the material for Bezymianny eruptions is brought directly from the mantle. Seismic models by [Koulakov et al. \(2011b, 2013a\)](#) seem to support the latter concept. However they did not have sufficient ray coverage to address the upper crust beneath Bezymianny or any possible connection with Klyuchevskoy. The current results, bolstered with local recording stations, provide far superior resolution in the shallowest crust.

The most suggestive parameter for potential magma is the V_p/V_s ratio, which is especially sensitive to porosity and the presence of fluids and melts (e.g., [Takei, 2002](#)). In the case of porous media with liquid content, the V_p/V_s ratio is usually high. Presence of gas strongly decreases this parameter. For example, in the gas-saturated layers in Campi Flegrei, [Di Siena et al. \(2010\)](#) observed generally low V_p/V_s ratios. For many active volcanoes the coexistence of higher P and lower S velocities is quite typical and is interpreted as penetration of a semi-liquid magma material with contrasted compositions with respect to surrounding rocks (for example, beneath Mt. Spurr in Alaska, in [Koulakov et al., 2013b](#)).

Unfortunately, for the most tomography studies, the direct conversion of seismic parameters to melt content is not possible. First, seismic tomography cannot provide accurate values of the amplitudes of anomalies due to uneven data distribution and trade-off problems during the definition of the damping parameters. Second, seismic parameters are connected with several petrophysical

effects, such as composition, porosity, fluid properties, temperature, fracturing, stress tensor, deformations and many others. The effect of each of these factors might be significant and dependent of the specific case. In this case, we can only interpret the derived anomalies qualitatively.

The distribution of V_p/V_s in the current results is presented in Figures 6 and 7 in horizontal and vertical sections. In the shallower section, we see a prominent pattern of higher V_p/V_s ratios in the vicinity of Bezymianny. At 10 km depth, this anomaly is not present, however, a prominent V_p/V_s feature (>1.9) is observed beneath Klyuchevskoy. In the vertical section (Fig. 7), the two anomalies appear to be independent and clearly separated. The synthetic tests confirm the ability to resolve changes in the sign of the anomaly at 10 km depth, suggesting that the observed patterns are robust. We propose that the anomaly beneath Bezymianny represents a shallow magma reservoir directly feeding the regular yearly eruptions of the volcano. Beneath Klyuchevskoy, the anomaly of high V_p/V_s ratio might represent an intermediate magma reservoir located at 7-15 km depth. Several petrological observations confirm this depth range for the lava sources of the Klyuchevskoy volcano (e.g., Khubunaya et al., 2007; Dobretsov et al., 2012).

The downward continuations of these two anomalies can be explored in a larger-scale model by Koulakov et al. (2013a) who used the regional seismicity catalogue for the same time period. Figure 8 shows the comparison of the V_p/V_s ratio distributions in vertical sections for the model presented in this study and that of Koulakov et al. (2013a). The main patterns in the upper parts of the models look very similar, except for the bright pattern beneath the Bezymianny volcano that could not be resolved by the former model. The new model shows unequivocally that the high V_p/V_s anomalies beneath Bezymianny and Klyuchevskoy are separate features and exist at quite different depths. If these anomalies indicate the potential of magma storage, they are quite consistent with petrology. Shallow, and presumably cooler, magma beneath Bezymianny would be consistent with the more evolved and more viscous andesitic magmas that drive Bezymianny's highly-explosive eruptions. Deep crustal storage beneath Klyuchevskoy would be conducive to a hotter zone of magma storage with less crystal fractionation, preserving the less evolved basaltic compositions erupted from Klyuchevskoy. The tomographic structure does not indicate any clear linkage between the two systems. There is no evidence in this study that the two volcanoes might be fed from the same deep crustal or mantle source. That said, the tomography does not rule out such a connection. Potential pathways that connect these systems could fall below the nominal ~5km resolution of the dataset, could be present only intermittently, or could have a very modest signature as manifest in seismic velocities.

5. Conclusions

Previous tomographic studies of the Klyuchevskoy group of volcanoes have been limited in the shallow crust by the absence of distributed seismic stations, despite prodigious and well-distributed earthquake sources. This study augments the permanent network with campaign seismic stations from the PIRE project in the vicinity of Bezymianny volcano. In this study, we performed the first tomographic inversion using these data to obtain a new seismic model for the upper crust beneath Bezymianny and Klyuchevskoy volcanoes. Synthetic tests indicate that the addition of the PIRE stations has considerably improved the resolution compared to previous models by Koulakov et al. (2013a) computed with approximately the same algorithm.

The topography of the KVG (Figure 1) illustrates that most the centers of recent volcanic activity tends fall on a line striking roughly north-northeast. Previous studies have suggested that it may represent a fault zone, but due to extremely high volumes of volcanic deposits, no surface manifestations of this fault can be identified. In the tomography results, some seismic anomalies seem to be shifted along the axis of this line possibly suggesting left-lateral displacement along this fault. These images are consistent with, and possibly corroborate, the presence of a large fault passing through the group. If this is the case, the fault zone may provide a weak or fractured zone that facilitates the ascent of magma, potentially explaining the presence of the KVG.

The primary finding of this study is the presence of significant high Vp/Vs anomalies under both Bezymianny and Klyuchevskoy, albeit at very different depths. One is centered under Bezymianny and extends to depths of 5-6 km under the surface. This anomaly is strong enough that the presence of partial melt cannot be ruled out. The shallow depth of this possible magma storage zone supports the observation of relatively frequent (annual or more) explosive eruptions consisting of relatively evolved andesite magmas. The second high Vp/Vs anomaly, centered beneath Klyuchevskoy, supports the notion of a mid-crustal zone of magma storage. This region is consistent with the top of a zone of vigorous earthquake activity thought to extend to the base of the crust (e.g., Thelen et al., 2010). If this earthquake activity represents magma sourcing from the mantle, then the Vp/Vs anomaly may represent a zone of magma accumulation near the top of this vigorous seismicity. Its presence in the mid-crust is more consistent with a deep hot zone (e.g. Annen et al., 2006) of magma than the shallower feature under Bezymianny. The mid-crustal location beneath Klyuchevskoy could only be maintained in a substantial zone of hot crust tending to preserve the basaltic character of the magmas. If these high Vp/Vs tomographic features beneath Bezymianny and Klyuchevskoy are indicative of magma storage zones, then the tomography offers an important

addition to the explanation of how two volcanoes, in such close proximity, can maintain fundamentally different eruptive styles over the course of numerous eruption cycles.

Acknowledgments:

Travel time data from permanent stations were provided by Laboratory of Seismic and Volcanic Activity of KBGS RAS. Ivan Koulakov is supported by the Russian Scientific Foundation (grant #14-17-00430). Arseniy Ivanov is supported by RFBR (The Russian Foundation for Basic Research) (grant #14-15-31176-mol_a). West is supported by National Science Foundation award #0909254.

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Figure 1. A: Topography/bathymetry of Kamchatka. The location of the Klyuchevskoy volcanic group (KVG) is indicated by the rectangle. CKD is the Central Kamchatkan Depression. B: Map of the Klyuchevskoy Volcano Group. Major volcanoes of the Group: TOL – Tolbachik, UDI – Udina, ZIM – Zimina, BEZ – Bezimianny, KAM – Kamen, KLU – Klyuchevskoy and USH – Ushkovsky. Yellow dotted line highlights the location of the major active volcanic centers, potentially associated with a deep fault (see discussion in text). Diamonds depict seismic stations: red are the KBGS permanent stations and blue are the temporary PIRE stations.

Figure 2. The distributions of seismic stations (black triangles) and earthquakes (dots) colored by depth. **Black dotted line highlights the location of the major active volcanic centers, potentially associated with a deep fault.** Volcanoes: ZIM – Zimina, BEZ – Bezimianny, KAM – Kamen, KLU – Klyuchevskoy and USH – Ushkovsky.

Figure 3. Checkerboard tests with three different anomaly spacing's: 10 km – upper, 7 km – middle and 5 km – lower rows. Shapes of the starting synthetic patterns are highlighted with black lines. The locations of seismic stations are depicted with white dots. Contour lines represent the topography. All results are shown for anomalies of P and S wave velocities and Vp/Vs ratio at zero depth (sea level).

Figure 4. Results of checkerboard tests defined in a vertical section. This is the same cross section used to present the study results in Figures 7 & 8. The cross section line is indicated in Figure 6. From top to bottom these panels illustrate P wave velocities, S wave velocities and Vp/Vs ratios. The shapes of the initial synthetic patterns are highlighted with black lines. Dots depict the projections of **relocated** seismic events located at distances less than 6 km from the profile. **Volcanoes: BEZ – Bezymianny, KAM – Kamen and KLU – Klyuchevskoy.**

Figure 5. Inversion results based on two different reference models with under- and overestimated velocity values. Examples of the resulting P-wave velocity anomalies are shown at 0 and 10 km depths. Topography contour lines are in black; white dots are the seismic stations.

Figure 6. Resulting P and S wave anomalies at 0 and 10 km depth after inverting observed data. Right column presents the distributions of P and S seismic ray paths (red and blue dot lines, respectively) at corresponding depth intervals. Yellow dotted line highlights the location of the major active volcanic centers, potentially associated with a deep fault. Contours of areas with sufficient ray coverage were selected manually and plotted on the resulting sections. White dots depict seismic stations; thin black contour lines represent topography. The location of the section presented in Figure 7 is shown in all plots.

Figure 7. Vertical section of the resulting P and S-wave velocity anomalies and V_p/V_s along the cross section shown in Figure 6. Dots depict the projections of **relocated** seismic events located at distances less than 6 km from the profile.

Figure 8. Comparison of the current study with the larger scale model from Koulakov et al. (2013). Vp/Vs ratio distribution is presented in approximately the same cross section; the location of the smaller model over the larger one is highlighted by the black box. Black dots depict **relocated** seismic events in the vicinity of the profile.