Feeding volcanoes of the Kluchevskoy group from the results of local earthquake tomography

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[1] We present a seismic model of the area beneath the Kluchevskoy volcano group (Kamchatka, Russia) based on the tomographic inversion of more than 66000 P and S arrival times from more than 5000 local earthquakes that occurred in 2004 and that were recorded by 17 permanent stations. Below a depth of 25 km beneath the Kluchevskoy volcano, we observed a very strong anomaly in the Vp/Vs ratio that reached as high as 2.2. This is a probable indicator of the presence of partially molten material with a composition corresponding to deeper mantle layers. The upper part of this anomaly at a depth of 25–30 km coincides with a cluster of strong seismicity that can be explained by strong mechanical stresses in the lowermost crust due to magma ascension, water release and/or phase transitions. In the crust, we observed regular seismicity clusters that link the mantle anomaly with the Kluchevskoy volcano and most likely indicate the paths of magma migration. Between depths of 8 and 13 km, we see several patterns of high Vp/Vs ratios, interpreted as intermediate-depth magma storages. Directly below the Kluchevskoy volcano, we observed a shallow body of high Vp/Vs, which probably represents the activated magma chamber just beneath the volcano cone, which erupted in the beginning of 2005. The existence of three levels of magma storage, based on results of local earthquake tomography, may explain the variety of the lava composition and eruption regimes in different volcanoes of the Kluchevskoy group. **Citation:** Koulakov, I., E. I. Gordeev, N. L. Dobretsov, V. A. Vernikovsky, S. Senyukov, and A. Jakovlev (2011), Feeding volcanoes of the Kluchevskoy group from the results of local earthquake tomography, *Geophys. Res. Lett.*, *38*, L09305, doi:10.1029/2011GL046957.

1. Introduction

[2] Studying magma chambers beneath active volcanoes using geophysical methods is a complex but exciting task that attracts the attention of many specialists. A review by *Lees* [2007] gives several examples of successful application of seismic tomography tools in studying magma chambers beneath different volcanoes. More recent studies have revealed rather clear images of magma chambers beneath the Toba caldera [*Koulakov et al.*, 2009a], Merapi volcano [*Koulakov et al.*, 2009b], and other areas.

[3] In this study, we investigated the crustal structure beneath the Kluchevskoy volcano group located in the Kamchatka peninsula (Russia) (Figure 1a). The Kluchevskoy group consists of dormant and active Holocene volcanoes (Figure 1b) that cover an ellipsoidal area of 100 × 55 km in size [e.g., *Fedotov et al.*, 2010]. These volcanoes are very variable in composition and regimes of eruptions ranging from explosive andesitic to fissure basalt eruptions of Hawaiian type [*Laverov*, 2005]. More details about the main characteristics of the Kluchevskoy group of volcanoes are given in the auxiliary material.[1]

[4] The seismic structure beneath Kamchatka and, in particular, beneath the Kluchevskoy volcano group, has been investigated in a number of tomographic studies on different scales. Regional tomographic models based on body and surface wave data [e.g., *Levin et al.*, 2002; *Gorbatov et al.*, 2001; *Lees et al.*, 2007a; *Koulakov et al.*, 2011] revealed a rather clear shape of the subducting Pacific plate beneath Kamchatka. Data on regional networks were used to study the detailed structure of the crust and the mantle wedge to reveal the shape of the upper surface of the subducting slab beneath the Kamchatka peninsula [e.g., *Nizkous et al.*, 2006]. The detailed structure beneath the Kluchevskoy volcano group based on the information from local earthquakes has been investigated previously. For example, *Lees et al.* [2007b] used data from the local network in the area around the Kluchevskoy volcano group for the time period of 1981–1994. Note that during this time the network included a rather small number of stations and that the average number of picks per events was low (the presented model was constructed based on 6461 P-wave picks from 1444 events). In addition, *Lees* [2007] did not present the S-model and Vp/Vs ratio even though these parameters are the most informative for investigating magma chambers. Other local tomographic studies for the same region by *Khubunaya et al.* [2007] and *Nizkous et al.* [2007] were based on a much larger dataset corresponding to more recent observations with more stations. However, they did not present any verification for the presented model, and it is impossible to assess the reliability and the resolution capacity of their results based on the published materials.

[5] Another problem related to performing the inversion of many-year data in active volcanic areas is that the seismic structure may appear to be strongly variable over time. Our preliminary calculations for a large dataset for the time period from 1999 to 2009 show that obtaining a coherent model

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL046957.

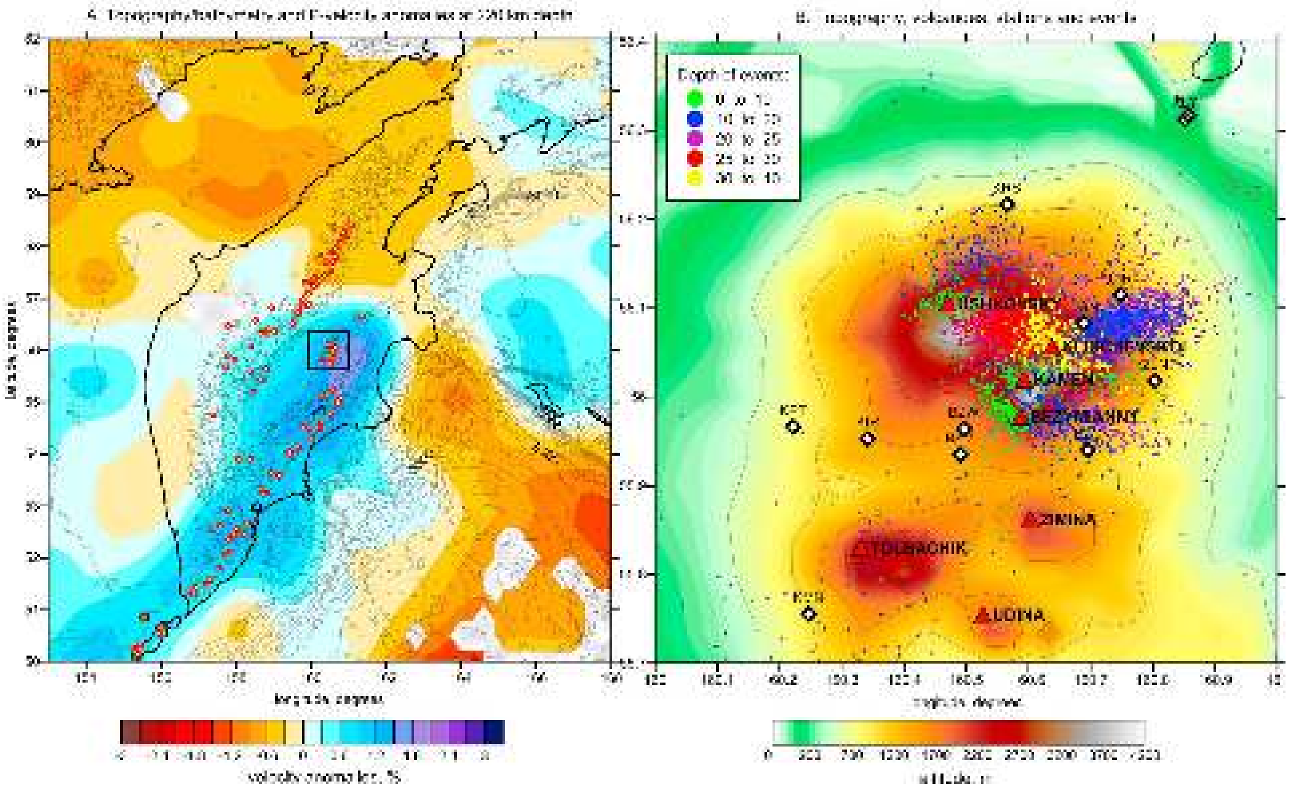

Figure 1. Study area. (a) General view of the Kamchatka peninsula. The background is the P-velocity model derived from regional tomographic inversion [*Koulakov et al.*, 2011]. The orange dots are the Holocene volcanoes. The contour lines depict the topography and bathymetry. The square marks the study area of this research. (b) Configuration of the observation scheme used in this study and general information: diamonds are the stations with names; colored dots depict events depending on the depth; red triangles are the volcanoes with names; and the background is the smoothed topography of the study area.

that satisfies all observations is impossible. Despite using the data from only the most reliable events, the variance reduction after the tomographic inversion for this dataset was very low (approximately 15%). In this study, we used data for one year, 2004, and we obtained much larger values of variance reduction (more than 30%). Similar or larger improvements were obtained for other years. The natural explanation for these results is a strong time variation of seismic velocities beneath the volcanoes (Koulakov et al., Variable feeding regimes of the volcanoes in the Kluchevskoy group (Kamchatka, Russia) derived from time-dependent seismic tomography, manuscript in preparation, 2011).

[6] In this paper, we discuss the results of data processing for the year 2004 corresponding to the start of the eruption activation of the Kluchevskoy volcano. Here, we present both P and S models; however, in our discussion, we will primarily focus on the Vp/Vs distribution, the clearest indicator of the presence of fluids and melts. In the auxiliary material, we present a set of different tests that allow the robustness of the presented models to be assessed.

2. Data and Algorithm for Tomographic Inversion

[7] In this study, we used data provided by the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences. These data include travel times from local earthquakes in the area of the Kluchevskoy volcano group recorded by the permanent seismological network. The total number of contributing stations during the considered time period was 17. The events are widely distributed in space, and most of them are located below 25 km deep, which enables good ray coverage for studying the crustal structure beneath the volcanoes. In addition, for most events, both P and S phases were handpicked by highly experienced specialists. The use of approximately equal numbers of P and S phases enables the determination of high quality source locations.

[8] In this study, we used the data for the time period from January to December 2004. This year corresponds to the starting stage of the Kluchevskoy volcano activation. Before November 2003, no significant eruption activity has been recorded for nine years [e.g., *Ivanov*, 2008]. From November 2003 to January 2004, the first manifestations of magma upwelling were recorded. After another relatively calm year, an eruption of the Strombolian type occurred after 20.01.2005 and continued for almost half a year. Almost simultaneously, a strong eruption occurred in the Bezymianny volcano [*Sobolevskaya and Senyukov*, 2008]. Thus, the year 2004, which was the preparative stage for the eruptions after a silent period, is a time of special interest and was selected for this study.

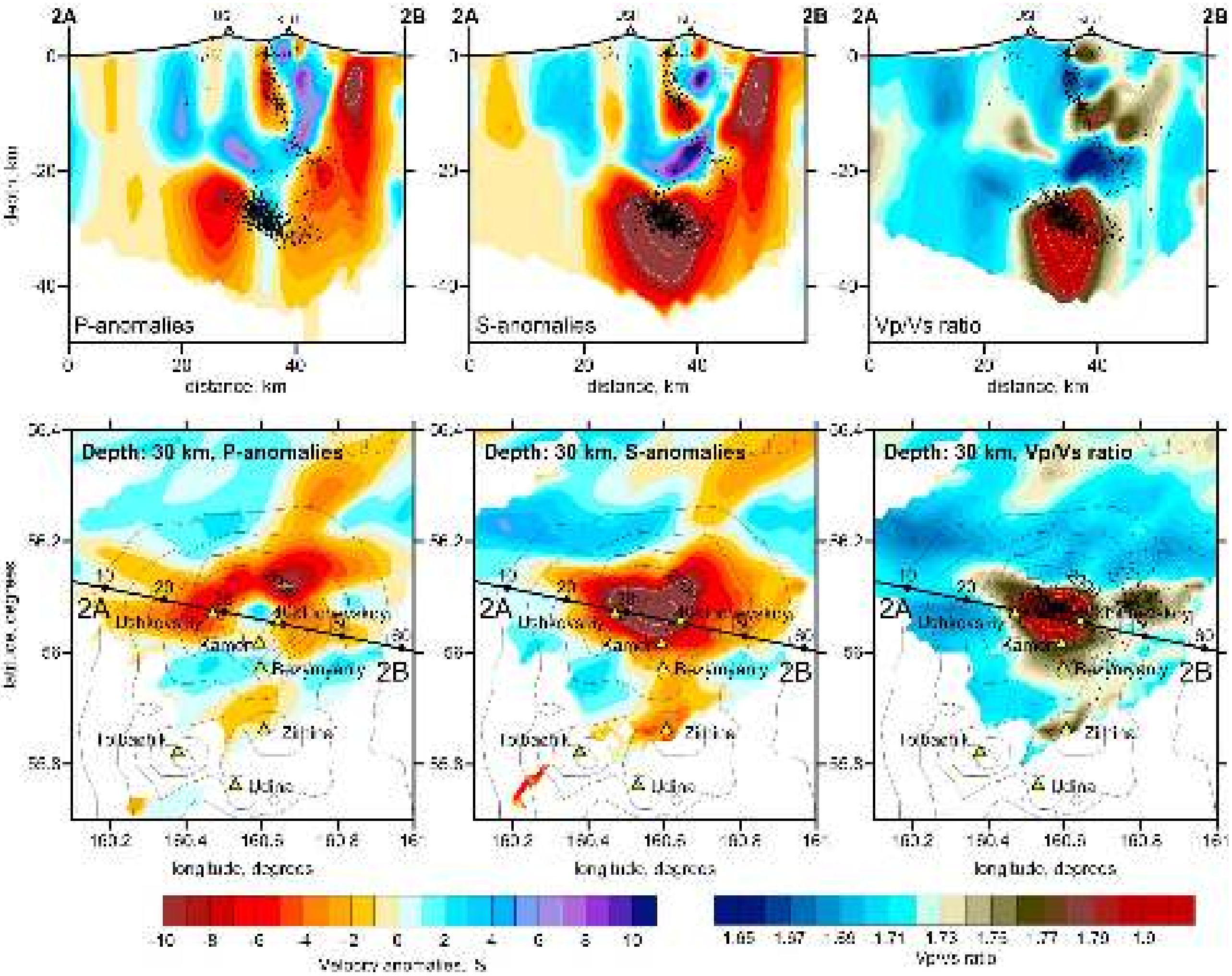

Figure 2. Distributions of the Vp and Vs anomalies and Vp/Vs ratio (top) in one vertical section and (bottom) at 30 km depth. In vertical section: dots depict the events at distances of less than 0.5 km from the profile, and triangles on the surface mark the locations of volcanoes close to the profile. In horizontal section: contour lines indicate the smoothed topography; yellow triangles are the volcanoes; dots are the events around the corresponding depth; and lines indicate the locations of the profiles. Yellow contour lines within high values of Vp/Vs in all plots mark the levels of 1.9, 2 and 2.1.

[9] When selecting data, we used only two criteria: the number of picks per event should be not less than 8, and the values of the P and S residuals after the preliminary location should not exceed 0.5 and 0.75 seconds, respectively. To avoid excessive clustering of events, we limited the maximum number of events in a 3 × 3 × 3 km cell to 50. When the number of events was greater than this limit, the events with maximum number of picks were selected. The total number of events selected in 2004 was 5220; numbers of P and S arrival times were 33428 and 33865, respectively.

[10] To estimate the optimal reference velocity distribution, we determined the preliminary locations of the sources using ten 1D models and selected one that provided the maximum number of picks and the minimum value of the average residual. The tomographic inversion was performed using the LOTOS code [*Koulakov*, 2009] which performs the iterative processing of time picks from local earthquakes. Velocity anomalies were computed in nodes distributed inside the study volume according to the ray density. The lateral grid spacing was 2 km; with depth, the spacing was dependent of ray sampling, but was not less than 2 km. Processing consisted of several iterations; each iteration contained a source location in the 3D velocity model, matrix calculation and inversion. The inversion was performed simultaneously for the P and S velocities, source corrections (four parameters for each source) and station corrections. Free parameters for the inversion (weights and regularization coefficients) were determined based on the results of synthetic modeling. Note that the sources at all stages and the parameterization nodes were allowed to be located above sea level, but they must be located below the topography surface.

3. Inversion Results and Verification

[11] The main result of this study is the 3D distribution of the Vp, Vs anomalies, Vp/Vs ratio and the locations of seismic events, which are presented in one horizontal and one vertical section in Figure 2. The Vp/Vs ratio was derived from the division of the Vp-to-Vs distributions obtained

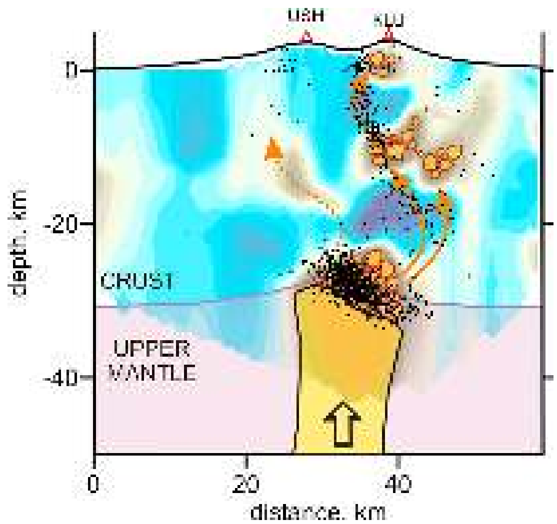

Figure 3. Interpretation of the results. The background is the distribution of the Vp/Vs ratio in the vertical profile 2 (Figure 2). The dots indicate the distribution of earthquakes. The yellow column in the mantle depicts the main feeding channel that transports upward partially molten deep mantle material. Blobs in the crust that coincide with areas of high Vp/Vs ratio mark three levels of magma chambers in the crust. Solid red arrows indicate possible paths of magma transport, which coincide with areas of high seismicity. The dotted arrow is a hypothetical magma path beneath the Ushkovskiy volcano without significant manifestation of seismic activity.

after five iterations of simultaneous tomographic inversion. The results in three depths levels and three vertical sections are presented in the auxiliary material (Figures S1–S3). The interpretation of this result will be discussed in the next section. Now we will focus on assessing the reliability and the resolution of the obtained model.

[12] After five iterations of inversion the average P and S residuals were reduced from 0.156 s and 0.240 s to 0.111 s and 0.143 s (29.12% and 40.41%), respectively. Although these values are higher than the variance reductions obtained after the processing of the entire dataset corresponding to eleven years, it is relatively low compared to those of many other local earthquake studies. When having such a relatively low signal-to-noise ratio, it is important to assess the effect of random noise on the result of the tomographic inversion. This effect can be estimated by the odd/even test, which consists of performing independent inversions for two different data subsets (for example, subsets with odd and even numbers of events). The result of this test is shown in the auxilairy material (Figure S4) in one vertical section for the distributions of Vp, Vs anomalies and the Vp/Vs ratio. Comparing the results of the independent inversions shows that the main features, which are used for interpretation in the discussion section, were robustly resolved in both cases. Thus, the random noise in the data does not considerably affect the results.

[13] The resolution capacity of the inversion was tested in several synthetic tests. In the auxiliary material, we present the result of reconstruction of a synthetic model with realistic configurations of anomalies (Figures S5 and S6). The details of the modeling are given in the auxiliary material. This and other synthetic tests demonstrate that the main features in the central part of the study area that are most important for our interpretation are robustly resolved by the existing configuration of rays. At the same this test shows that we should be careful when interpreting anomalies in marginal areas.

4. Discussion

[14] The most prominent feature of the obtained seismic structure is a large anomaly located beneath the Kluchevskoy volcano at depths below 25 km. In this pattern, we observed positive P-velocity and negative S-velocity anomalies that result in very high Vp/Vs ratios, reaching 2.2. This looks different of the result obtained by *Lees et al.* [2007b] who observed low P-velocity anomaly at 25 km depth based on an older dataset (1996 and earlier). This discrepancy can be explained by strong variability of seismic structure over the time and/or lower resolution of tomographic results in earlier studies.

[15] Very high Vp/Vs ratio below 25 km depth observed in our study can be explained by both compositional and rheological properties of rocks. The P-velocity is more sensitive to the composition, and its higher values may be an indicator of rocks that came from lower depths. At the same time, very low values of the S-velocity indicate a high content of fluids and partial melting. We interpret this pattern as the top of a small plume that probably starts on the upper surface of the slab and reached the bottom of the crust [*Dobretsov*, 2010]. Similar flows, or hot fingers, were found in the mantle wedge beneath northeastern Japan [e.g., *Tamura et al.*, 2002]. The shapes and periodicity of these hot fingers were predicted by *Dobretsov and Kirdyashkin* [1997], based on geodynamical modeling and existing petrological, geochemical and geophysical data.

[16] Active seismic clusters were observed within this high Vp/Vs anomaly only above ~30–35 km in depth (Figure 3). These depths correspond to the lowermost parts of the crust, whose thickness reaches the values of about 30–35 km, based on the results of receiver function analysis [*Nikulin et al.*, 2010]. We propose that these earthquakes in the lowermost crust are due to strong thermal, chemical and mechanical effects of the ascending flow in the mantle channel which reaches the brittle crust. This causes fracturing and the creation of the first level of magma sources between 25 and 30 km in depth.

[17] The distribution of seismicity in the crust forms a regular pattern, marked in Figure 3 with S-shaped orange arrows. This cluster might indicate the paths of fluids and melts that ascend from the deep magma source at 25–30 km in depth to Kluchevskoy volcano at the surface. This ascending may occur through systems of channels that are seen as low-velocity patterns in P and S-velocity models (Figure 2). It is important to note that, at intermediate depths between ~8 and 13 km beneath the Kluchevskoy volcano, we observed another anomaly of high Vp/Vs ratio, which probably marks the second level of magma storage. Clear records of shear waves do not support an idea of the existence of large chambers filled with liquid magma. We propose that these zones of high Vp/Vs ratio represent either sponge-structured areas with small blobs of partially molten material, or fracturing zones with systems of cracks filled

with fluids and/or melts. In any case, these zones should play an important role in feeding the volcano system. Here, the magma migration can cause fracturing of crustal rocks, mixing and differentiation of molten material in magma storages. Thus, the properties of magma in these intermediate chambers might be considerably different from those of the initial magma sources in the lowermost crust. The coexistence of deep and intermediate sources can explain the compositional variability of the eruption products of the volcanoes of the Kluchevskoy group.

[18] Just beneath the Kluchevskoy volcano, we observed another shallow anomaly with a high Vp/Vs ratio, which might reflect the existence of a third level of magma storage just beneath the volcano. This small pattern coexisting with shallow seismicity is a possible indicator of the volcano activation and future eruption.

[19] The existence of several layers of magma storage beneath the volcanoes of the Kluchevskoy group can explain their different composition and eruption behavior. When overheated liquid material of deep chambers reaches the intermediate depth reservoirs, mixing with crustal rocks, differentiation and decompression result in a very wide variety of magma composition and a high content of fluids and gases. These intermediate magma storages may feed, for example, Bezymianny, which is a caldera-forming explosive dacite-andesite volcano [*Bogoyavlenskaya et al.*, 1991]. On the other hand, Kluchevskoy and Kamen volcanoes are basalt stratovolcanoes that are feed directly from the deep magma storages, for example, along the yellow arrows in Figure 3. This is consistent with the results of petrochemical analysis by *Ozerov et al.* [1997] who observed different feeding regimes of Kluchevskoy and Bezymyanny volcanoes through direct channels and intermediate chambers, respectively.

5. Conclusions

[20] In this paper, we present the seismic structure beneath the Kluchevskoy volcano group corresponding to the year 2004, in the end of a relatively silent period before the strong eruptions of the Kluchevskoy and Bezynianny volcanoes that occurred in the beginning of 2005. This seismic model was verified using the odd/even test and synthetic modeling. The resulting 3D distributions of seismic parameters clearly reveal three depth levels of magma storage. The deepest pattern, where the value of Vp/Vs ratio reaches up to 2.2, is located below the depth of 25 km in the uppermost mantle and lowermost crust. It was interpreted as a mantle channel that transports the partially molten material from deeper mantle layers, presumably from the subducting slab. A strong seismicity cluster in the lowermost crust above this channel is probably due to the mechanical, thermal of chemical effects of the ascending mantle flows to the crustal rocks. In the crust, we observed several intermediate magma storages at depths of 8–13 km, which correspond to local areas of high Vp/Vs ratio. Just beneath the Kluchevskoy volcano cone, we found a shallow anomaly that is interpreted as an activated magma chamber that erupted in 2005. We propose that the variety of the composition and the eruption regimes in different volcanoes of the Kluchevskoy group is caused by the multilevel structure of the magma storages in the crust and upper mantle.

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