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The Upper Mantle of Kamchatka in Isotopic–Geochemical and Geophysical Anomalies: The Role of Asthenospheric Diapirism

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Abstract—Data of isotopic–geochemical, seismotomographic, and gravimetric studies of the mantle characteristics of the Kamchatka and Bering Sea regions are compared. It is shown that the revealed isotopic–geochemical anomalies are well verified by the geophysical materials. A hypothesis is put forward that the anomalies of the Central Kamchatka and Bering Sea regions are a consequence of the penetration of local diapirs into the lithosphere; their activity is associated with the appearance of rocks belonging to the intraplate geochemical type. The juncture region of the Kuril–Kamchatka and Komandor–Aleutian island arc systems is characterized by the higher participation of crustal material in the composition of the volcanic rocks of the mantle genesis and by a combination of manifestations of the island arc and intraplate types.

Keywords: isotopic–geochemical, seismic tomography, gravimetry, lithosphere, mantle diapirs, Kamchatka peninsula, Bering Sea

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INTRODUCTION

The Kamchatka peninsula refers to one of most interesting regions of the Earth from the viewpoint of abyssal geodynamics. Here, as is well known, three volcanic belts are located—the East Kamchatka volcanic belt (EKVB), the belt of the Central Kamchatka Depression (CKD), and that of the Sredinny Range (SR)—which distinguishes this region from the common volcanic zone typical for island arcs and reflects the abyssal processes occurring in the upper mantle. At present, different models are proposed of the return to the northwest and the formation of two parallel zones of the Quaternary volcanism (CKD and SR); most authors consider it in the context of the plate tectonics hypothesis [1, 15, 24].

In Kamchatka, in addition to properly island arc series, which are indicators of the orogenic situation, a special type of volcanism manifests itself. It is close in petrochemical and geochemical attributes to the intraplate volcanites developed in continental and oceanic regions [9]. The intraplate volcanism is usually distinguished from island arc volcanism because it is commonly accepted [10] that both types have different sources and situations of manifestation. The first type is directly or indirectly associated with the evolution of mantle diapirs, while the second one, with subduction dynamics. However, the spatial and temporal combination of both volcanism types acquires a regularity indicating closer, maybe genetic relations between them [19, 20]. The proposed models of the evolution of the region must be undoubtedly verified by the structural features and properties of the upper mantle. In the last decade, the data that are most informative in this aspect were obtained by geophysical methods, in particular, by gravimetry and seismic tomography (global, regional, and local). The latter ones are represented by three-dimensional images of velocity properties of the medium in the form of anomalies of bodily longitudinal (Vp) and transverse (Vs) waves from earthquakes [11–13, 15, 16, 21, 35–37, 39, 42–44, 46, 47].

It should be noted that the results obtained by different authors contain both similarities and significant distinctions; this concerns not only the features of the developed velocity models but also the following geological interpretation. The former is caused by the ambiguity of the seismic tomography method, the results of which depend to a considerable extent on the type (bulk or surface waves) and amount of data, the configuration of the observation networks, the initial velocity model, etc. The differences in the global models of the Earth according to different authors were very clearly demonstrated in [17]. For the Kamchatka region, we show them in Fig. 1. As for the geological interpretation of the obtained data, the principal significance is determined by the geodynamic hypothesis

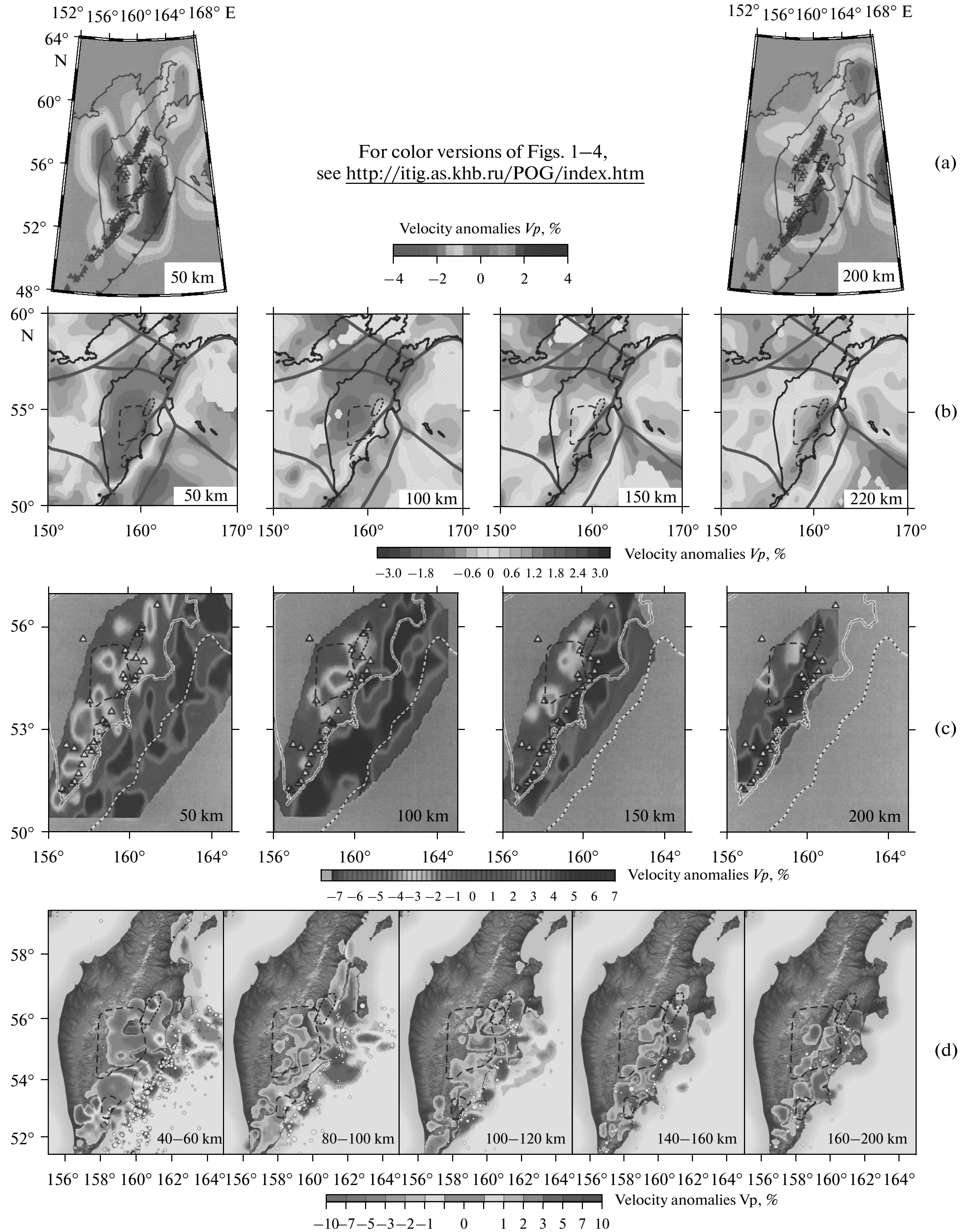

Fig. 1. Comparison of the results of the global (A [39], B [21]) and regional (C [36], D [13, 46]) tomography. Horizontal cross sections of the volume velocity models in the anomalies of the velocity *Vp* are presented. The black dashed lines and dots highlight outlines of the Sr-isotopic anomalies. The triangles are volcanoes.

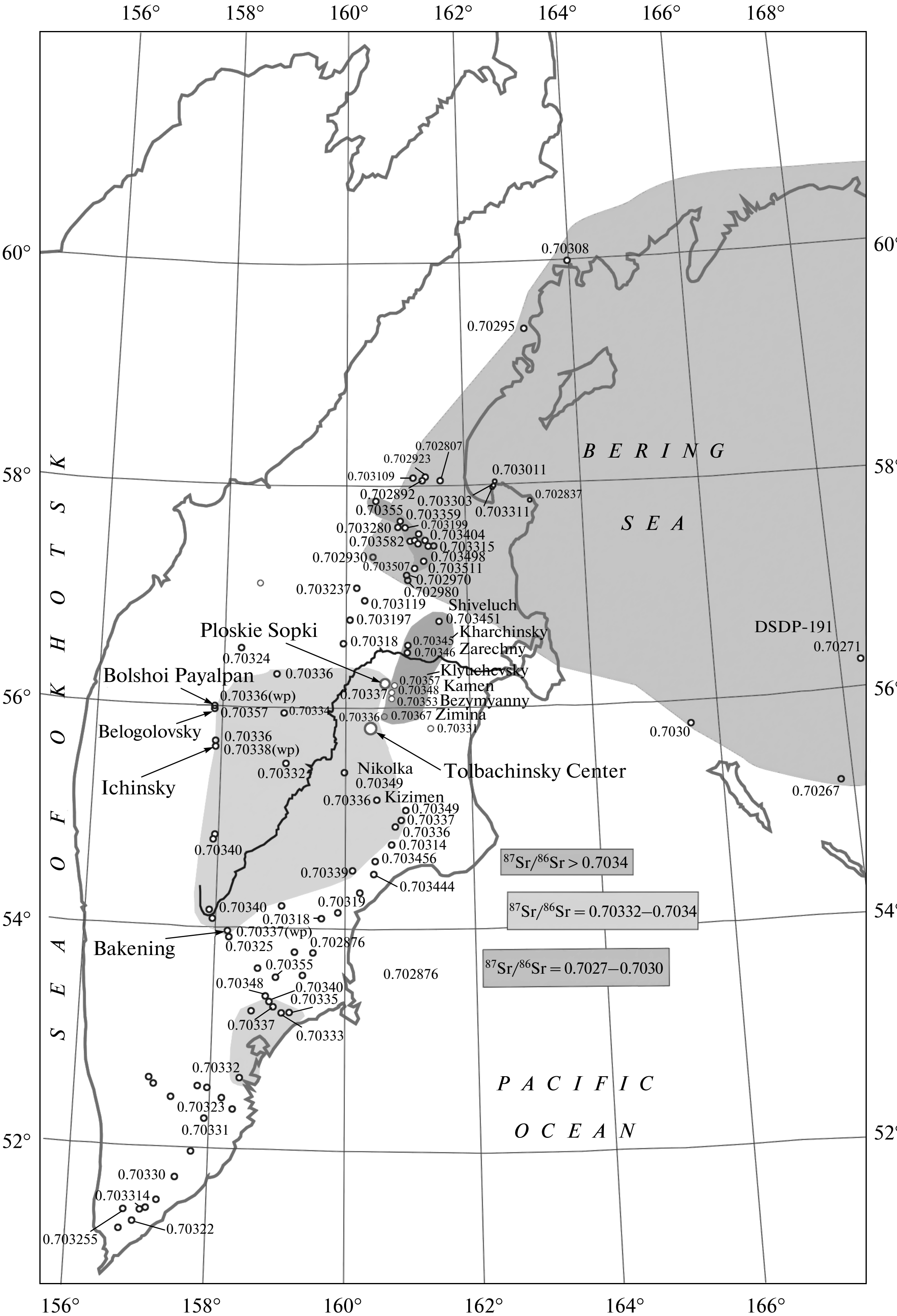

Fig. 2. Spatial distribution of the Late Pliocene–Quaternary volcanoes of Kamchatka and the Bering Sea region with different Sr-isotopic characteristics. The data were taken from [6, 26–30, 33, 38, 40, 41, 45, 48, 52–54].

in the context of which the data are analyzed and the degree of their adequacy concerning the results of other geological and geophysical methods, as well as concerning the present-day tectonics of the region. In almost all the tomographic models of the upper mantle of Kamchatka, two anomalies are distinguished: the high-velocity anomaly being in correspondence with a seismic focal zone (SFZ) and a relatively low-velocity one to the West from it (the mantle wedge region). The differences directly concern the geometry, the shape, the velocity characteristics of the slab, the pictures of the anomalies, and the distribution of the anomalies in the volume model.

Seismic tomography mappings performed using the data of regional earthquakes detected by the network of stations of the Kamchatka branch of the Geological Service of the Russian Academy of Sciences according to the technique developed at the University of Switzerland (Zurich) made it possible to obtain more detailed data about the properties of the upper mantle under Kamchatka down to the depth of ~200 km [13, 46]. However, as was rightly said in [34], hypotheses about the velocity structure of the Earth that lie in the base of seismic tomography data (and, in our opinion, their geodynamic interpretation) must be open to question due to the specificity of the method and, undoubtedly, find further support in the results of other geological–geophysical methods. In this work, an attempt is made to aggregate the results of the analysis of the geological, isotopic–geochemical, and geophysical materials based on which one can obtain information about the abyssal structure of the territory under consideration.

ISOTOPIC GEOCHEMICAL| AND GEOPHYSICAL ANOMALIES: THEIR INTERPRETATION

Petrology models of island arc volcanism in either case use data concerning the transverse isotopic–geochemical zonality. Indeed, the presence of such a zonality that can be associated with the depth up to the seismic focal zone is a serious argument for the postulated subduction mechanism. In reality, we observe a more complicated picture.

For example, the transverse zonality, according to [29], is expressed in the fact that the frontal zone is characterized by low $^{87}Sr/^{86}Sr$ ratios but higher $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios. Then, in the region of the Central Kamchatka Depression (CKD), the Sr-isotopic ratios increase but the Pb-isotopic characteristics decrease. In the rear zone, the Sr isotopy decreases again and that of lead moderately increases. Here, as we can see, there is no direct correlative dependence for these characteristics from the depth to the seismic focal layer.

The first picture of the areal spread of the manifestations of the Pliocene–Quaternary volcanism of Kamchatka with different Sr-isotopic characteristics was presented in [18]. Here, it is clearly seen that, first, a local increase in the $^{87}Sr/^{86}Sr$ ratios in the CKD and Sredinny Range regions is observed; then, this ratio decreases when moving to the rear zone of the island arc system. This regularity does not correlate with the depth to the seismic focal zone.

This picture is presented in Fig. 2 with the addition of later materials. In this figure, we see a series of isolated Sr-isotopic anomalies of different levels.

A large anomaly with a variation range of the isotopic characteristics $^{87}Sr/^{86}Sr = 0.7027–0.7030$ corresponds to volcanism manifestations in the structure of the Bering Sea region. Segmental areals of the Late Cenozoic alkali intraplate volcanism that are connected with extension phases are discernible here along the continental margin of the Bering Sea and in some of its islands. The entire southern part of the region is represented by the convergent boundary, while near Kamchatka, by the slip–thrust boundary of the lithosphere plates. For this region, a model of the volcanism evolution is proposed based on the presence of a thermal anomaly in the mantle in a sort of hot spot or plume [2]. Here, we have knowledge about the initial stage of the geodynamic evolution of the plume both for the Bering Sea block [3] and for the Northeast of Asia [14]. The seismic tomography data indicate the presence of low-velocity decompactified mantle material up to a depth of about 410 km under the shelf of the Bering Sea [37] or for a vast region including the Bering Sea region, Chukotka, Koryakia, and the northern part of Kamchatka [16].

A small anomaly extended to the NW direction with higher Sr-isotopic characteristics ($^{87}Sr/^{86}Sr >$ 0.7034) of the junction zone of the Kuril–Kamchatka and Aleutian–Komandor island arc systems is located in the Western part of the Bering Sea structure. Higher values of these isotopic ratios probably indicate a significant contribution of the crustal material to the compositions of the produced melts.

A similar anomaly with higher Sr-isotopic ratios is located to the south in the region of the northern termination of the CKD with a large amount of active stratovolcanoes. The magmatism of this zone is usually considered within the frames of the subduction model [29, 53–55]. The original adakite-like composition of some volcanic rocks occurring at the Shiveluch volcano, which is closest to the junction zone of the Kuril–Kamchatka and Aleutian–Komandor island arc system, is considered as one of the possible indicators of melts forming upon the melting of the downgoing lithosphere plate. The adakites are high-magnesia andesites with typical parameters of the content and ratio of microcomponents (high concentrations of Sr and large Sr/Y and La/Yb ratios) that are relatively enriched by compatible elements such as Mg, Cr, and Ni. According to [31], adakites and associating magnesia andesites in the situation of lithosphere plate convergence are considered as indicators of melting processes in a relatively young (and heated) subducted oceanic plate. However, the presence of a relatively cold and "not young" (about 50 Ma) subducted oceanic crust under the Shiveluch volcano was an obstacle for the direct use of the subduction model. This fact stimulated the authors of the model [55] to consider a part of this junction as an original "slab window" after the manner of the Californian mantle window and to suppose the existence of an additional heat source in the form of the rising flow of the asthenospheric material. This model, however, also allows the possibility of an isotopic–geochemical contribution to the composition of the volcanic rocks of the considered region from the Bering Sea mantle plume (diapir) in spite of the absence of the intraplate volcanism type in the rock composition of Shiveluch volcano.

The anomalous zone restricted by values of $^{87}Sr/^{86}Sr = 0.70332–0.7034$ in the central part of the peninsula and a small anomaly in the region of the Avacha group of volcanoes with a close isotopic composition are probably of largest interest. The distinguished interval of Sr-isotopic values corresponds to isotopic compositions in the manifestations of the intraplate volcanism in the Kamchatka island arc system on the Ichinsky [9, 29] and Bakening [32] volcanoes and on the one centre in the southern part of the Central Kamchatka Depression [23]. Similar isotopic characteristics were also detected in basalts of Plosky Tolbachik and its areal zone and at Ploskie Sopki [29]. High-potassic aluminiferous basalts of the Southern Vent of the Great Fissure Tolbachik Eruption were referred to a volcanic series of a nonisland arc group by O.N. Volynets as early as in 1990 [8]. Now, it is becoming clear that they also should be referred to the intraplate type. The manifestation of the intraplate geochemical type in the composition of the Kamchatka volcanites means the possibility to use this model of the mantle diapir for an explanation of this anomaly [19, 51].

The spot anomaly in the region of the Avacha volcano group is most remarkable. Here, manifestations of the intraplate type are absent. However, exotic rocks were found in the compositions of the volcanites together with basaltic andesites of the usual island arc type—avachites with a MgO content up to 15–20% [22]. In addition, the Avacha volcano is distinctive in the unusually high content of abyssal xenoliths whose composition varies from lherzolites to harzburgites and dunites. This is probably a special type of abyssal activation, rather an R.M. Bembel' geosoliton [7] than a usual diapir.

It is necessary to note the existence of differences in the character of the volcanism manifestations inside this anomalous zone and beyond it. The first ones are represented by large long-developing centers of Late Pliocene–Quaternary volcanism with pronounced both pre- and postcalderic complexes (Ichinsky and Bakening volcanoes, Tolbachik Center, and Ploskie Sopki). The second ones are local Quaternary stratovolcanoes, which are very rarely represented by calderic and postcalderic formations (most of the volcanoes of the Klyuchevskaya group). It is also necessary to emphasize that the Sr-isotopic anomalies distinguished in Fig. 2 manifest themselves neither in the character of the spread of the neodymium isotopes nor in the lead-isotopic characteristics. In general, for the Kamchatka island arc system, higher values of the Pb-isotopic ratios are observed in its front part. In addition, the analysis of the Pb-isotopic characteristics indicates the presence of an Indian Ocean type mantle domain under Kamchatka, as well as under the Kurils.

According to the data of the regional seismic tomography, the upper mantle (UM) under Kamchatka is characterized by a pronounced vertical and lateral velocity inhomogeneity. This concerns not only features in the structure of the high-velocity focal layer but also of the mantle wedge. Unfortunately, only regions of eastern and, partially, central Kamchatka (including CKD) can be characterized relatively in detail, which is connected with the specificity of the configuration of the regional observation network. The lithosphere layer between the Moho discontinuity conventionally marked along the isoline of the velocity $Vp = 7.5$ km/s and up to the depth of ~80–100 km is characterized in velocity cross sections by positive anomalies of the longitudinal wave velocity Vp and the clearly pronounced block structure (Fig. 3a). The differences in the structure of the anomalous zones of Vp with a negative sign under the volcanic belts (EKVB and CKD) well manifest themselves in the horizontal UM cross sections (Fig. 1d). On the maps, anomalous velocity structures (transverse to the Kamchatka extension) are marked; they are associated with features of the geometry of the high-velocity focal layer and probably correspond to fault zones of the mantle location, in particular, to the Avacha and Kronotsk–Krutogorovsk zones [24]. Under the CKD, a low-velocity abyssal anomaly is visible; it is represented by a narrow linear form at a depth of ~150 km and, higher in the succession at a depth of about 40–60 km, by a vast anomaly that definitely has a continuation under the SR (Fig. 1d, Fig. 4). The configuration of the Kamchatka network of stations does not permit one to perform seismic tomography constructions there; however, the global tomography data [21, 39] agree with this supposition. The outlines of this velocity inhomogeneity are in general well coordinated with the isotopic anomaly (Fig. 2), although, certainly, differ in some details. At the same time, it is uncontroversial that, in the upper mantle in the central part of the peninsula, there exists an abyssal structure that differs in the characteristic the velocity features. In particular, vertical cross sections along and transversely to Kamchatka in anomalies of the velocity Vs allow one to observe these features almost from the crust bottom up

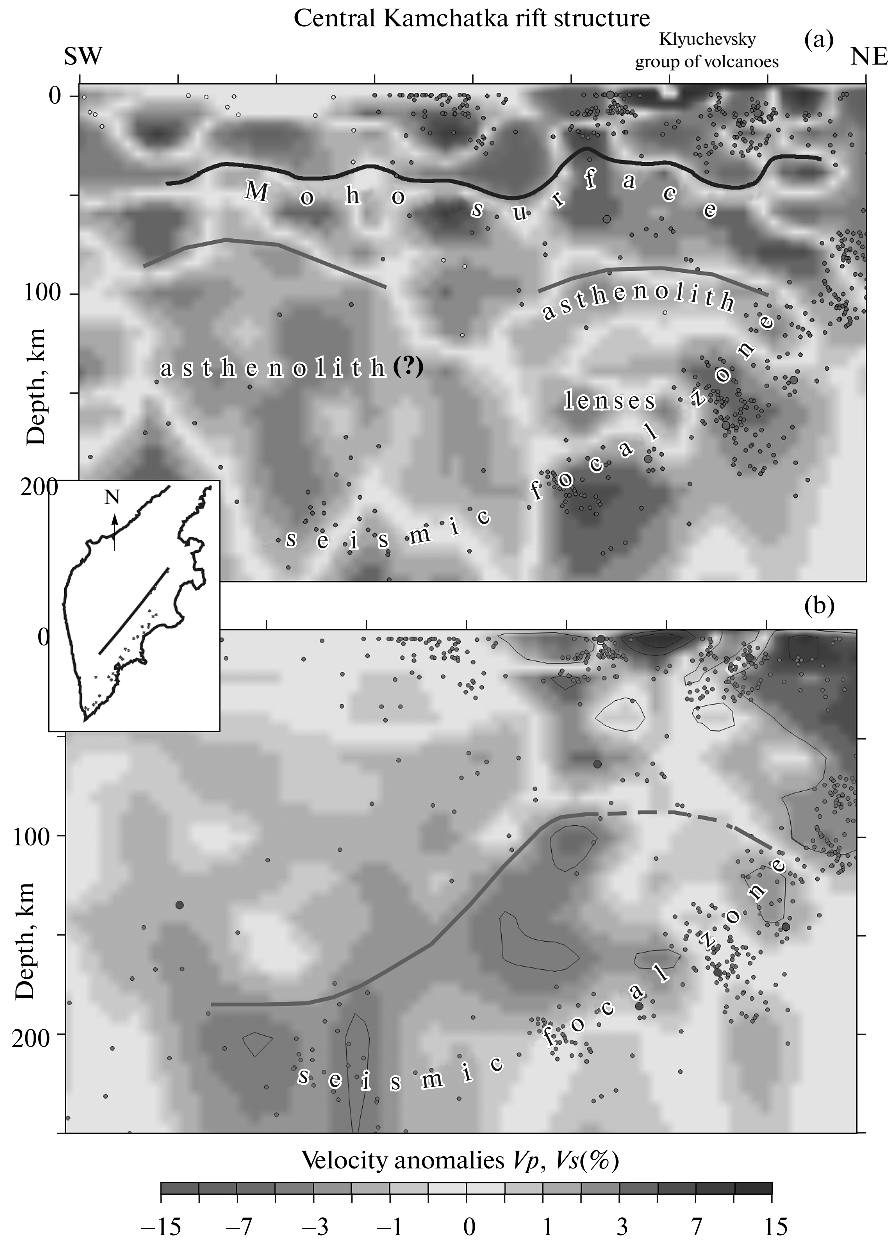

Fig. 3. Vertical cross sections of the volume velocity model over the profile oriented along the Kamchatka peninsula. (a) Distribution of mantle inhomogeneities in anomalies of the velocity *Vp*; (b) the same in anomalies of the velocity *Vs*. The location of the profile in the plan is shown in the insert. Some tectonics elements are written.

to the depth of not less than 150–200 km (Figs. 3b and 4). It seems realistic to suppose that it can be caused by the mantle "asthenolith" (asthenolith "lens" or "diapir"), the activity of which significantly complicates the total picture of the zonal (in the aspect of the distribution of the isotopic–geochemical characteristics of the manifestations) of the Late Cenozoic volcanism of the region. A characteristic and, probably, very demonstrative and significant feature of the regional velocity model presented in the anomalies of *Vs* is a sharp stepwise change in the UM in the region related to the Kronotsk–Krutogorovsk fault zone (Fig. 3b). Jointly with the analysis of the features of the seismic activity and the immersion of earthquake "clusters" in the NE–SW direction along the profile, the obtained results can be used when modeling the abyssal process occurring in this region (this question is not discussed in this paper). In general, the velocity structure of the UM under the Klyuchevsky group of volcanoes seems to be superposed on the deeper Central Kamchatka structure.

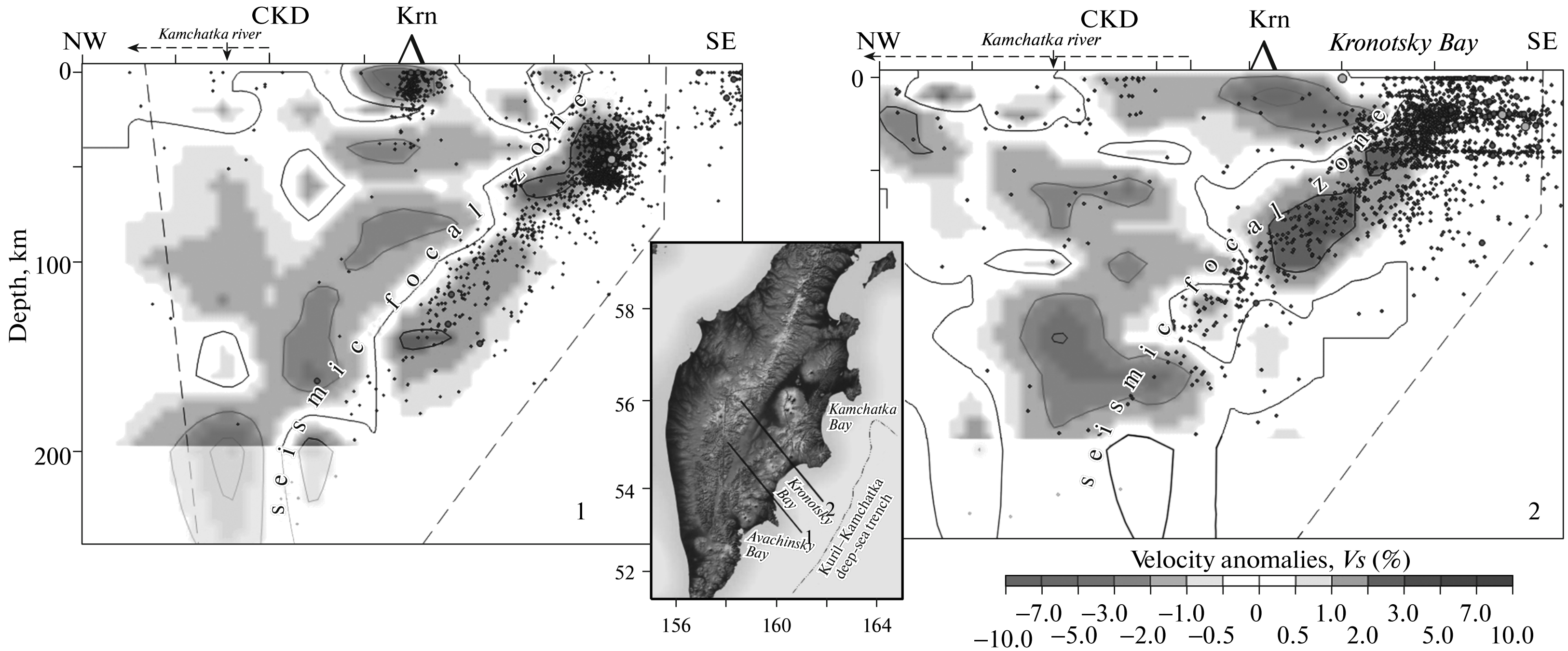

Fig. 4. Vertical cross sections of the volume velocity model transverse to the peninsula (in anomalies of the velocity *Vs*). The triangles mark the Karymsky (Krm) and Kronotsky (Krn) volcanoes. The location of the profiles is shown in the insert. The dashed line with an arrow (see the Kamchatka River) marks the outline of the Sr-isotopic anomaly, while the dashed line, the region of the calculated velocity model.

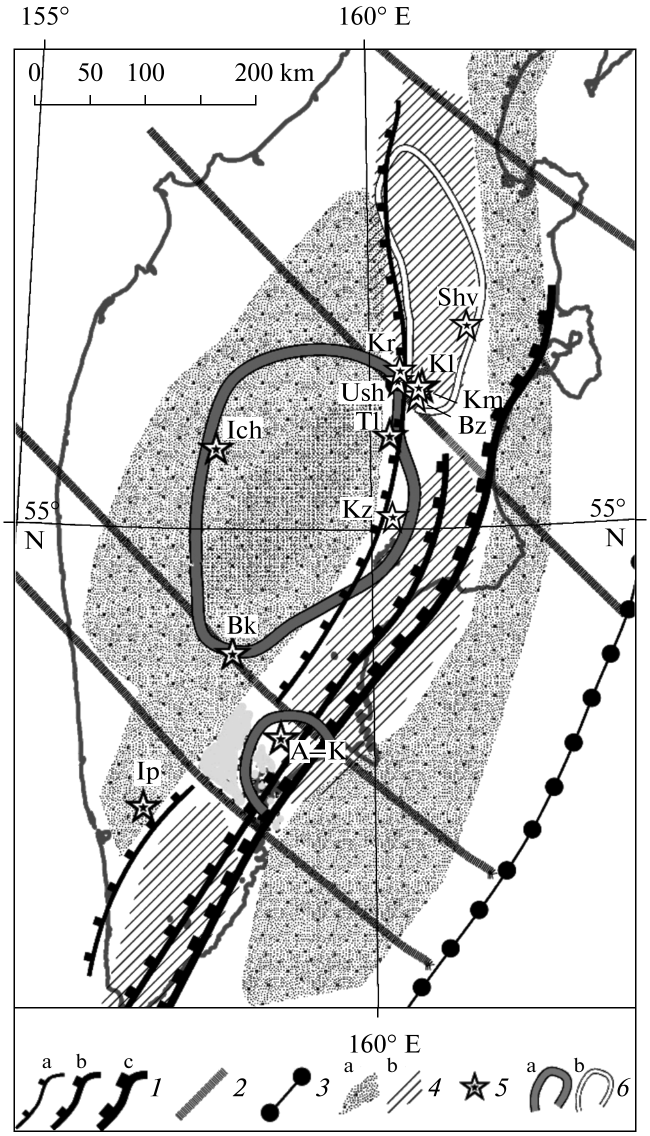

Fig. 5. Scheme of low-frequency anomalies of the Bouguer gravity force field (GFF). (*1*) axes of higher horizontal gradients: (a, b, c) sequentially from relatively low-frequency to high-frequency GFF components; (*2*) large faults supposed according to geophysical data in the N–W direction; (*3*) axis of the Kuril–Kamchatka deep-sea trench; (*4*) GFF anomalies: (a) relative depressions (minimums) and (b) elevations; (*5*) large Quaternary volcanoes: (Kl) Klyuchevskaya sopka, (Km) Kamen, (Bz) Bezymyanny, (Shv) Shiveluch, (Tl) Plosky and Ostry Tolbachiks, (Ush) Ushkovsy, (Kr) Krestovsky, (Bk) Bakening, (Ich) Ichinsky, (Ip) Ipelka, and (A–K) Avachinsky and Koryaksky; (*6*) regions of isotopic anomalies: (a) $^{87}Sr/^{86}Sr$ = 0.70332–0.7034 and $^{87}Sr/^{86}Sr$ > 0.7034.

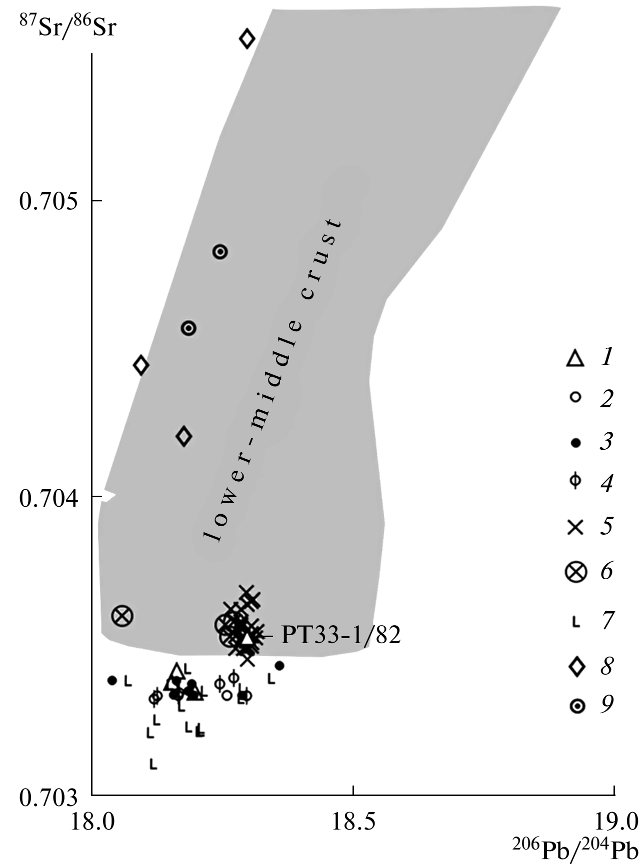

Fig. 6. $^{87}Sr/^{86}Sr$–$^{206}Pb/^{204}Pb$ relation in rocks of different volcanoes of the Klyuchevsky group and intraplate type basalts of the Sredinny Range of Kamchatka.

(*1–3*) Tolbachinsky Center: (*1*) aluminiferous basalts of the Tolbachinsky volcano, (*2*) basalts of areal volcanism of the aluminiferous type and (*3*) magnesia type; (*4*) Ushkovsky volcano; (*5*) Kluchevsky and Kamen volcanoes; (*6*) Bezymyanny volcano; (*7*) intraplate volcanites (Ichinsky and Bakening volcanoes); (*8*) metamorphites of the Khavyvensk Hills; (*9*) metamorphites of the Ganal Range (according [25, 28, 29, 33, 48, 49]). The data on the lower-middle crust were taken from [4].

The analysis of the low-frequency components of the Bouguer gravity force field (GFF), both using the data of regional ground-based gravimetric surveys and maps constructed by the results of satellite altimetry, demonstrates the presence of a vast negative anomaly with an epicenter approximately in the region of the triangle formed by the Ichinsky, Bakening, and Plosky Tolbachik volcanoes (Fig. 5). The shape of the negative anomaly is determined not so unambiguously in schemes of different frequency components; however, one can surely say about its extension in the N–E direction. Not the least interesting feature in the morphology of the low-frequency GFF components is the presence of a zone of relatively higher values rimming the aforementioned minimum from the East. The displacement of the axis of gravity steps (Fig. 5) in the analysis of the field from relatively high-frequency to low-frequency components can indicate the presence of a denser zone in the mantle with a trend of immersion from the East to the West. If this supposition is valid, the region with $^{87}Sr/^{86}Sr$ > 0.7034 for most stra-

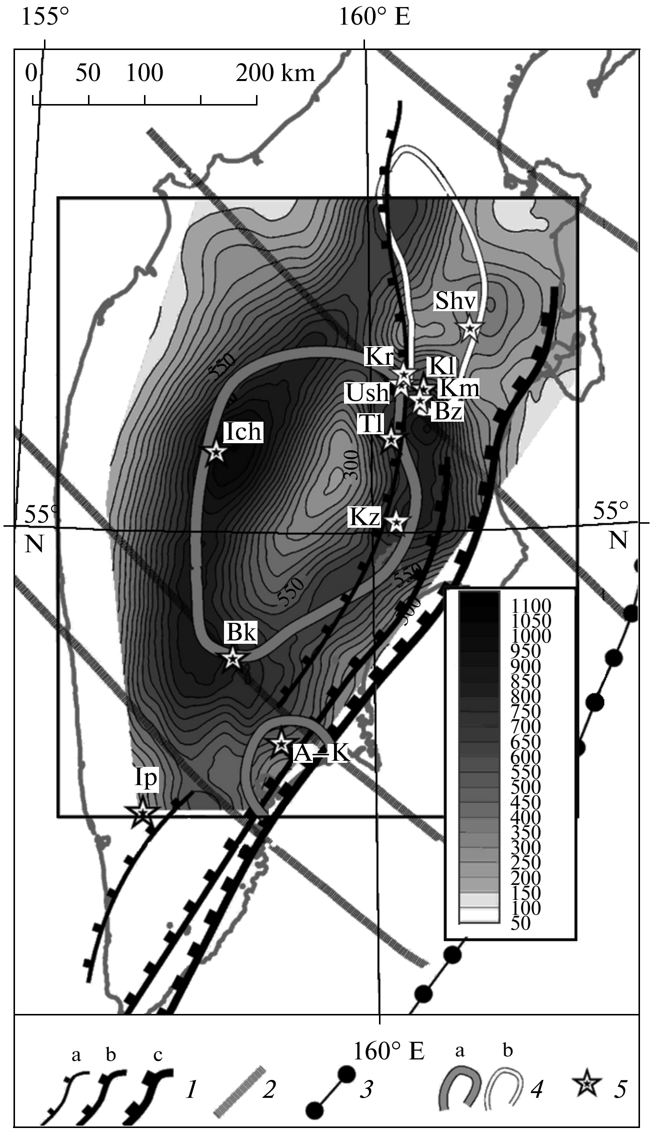

Fig. 7. Scheme of the averaged terrain relief (the scale is the absolute height in meters). The legend to the figure is as follows: (*1–3*) as in Fig. 5, (*4*) corresponds to sign (*6*) in Fig. 5, and (*5*) are Quaternary volcanoes.

tovolcanoes of the Klyuchevsky group and in the junction zone of the Kuril–Kamchatka and Aleutian–Komandor island arc systems can be explained by the fact that the primary magma chamber here, in contrast to the region of the Central Anomaly ($^{87}Sr/^{86}Sr >$ 0.70332–0.7034), is located in the lithosphere mantle or relatively closer to the base of the crust, which leads to a change in the $^{87}Sr/^{86}Sr$ ratio. This statement is illustrated by the diagram in Fig. 6 containing the isotopic compositions of, on the one hand, rocks of the Tolbachik Center and Ushkovsky volcano and, on the other hand, of the Klyuchevsky, Kamen, and Bezymyanny volcanoes. The points of the isotopic compositions of the rocks of the first group are localized in the region of mantle compositions, while those of the second group are shifted to the field of the lower-middle crust, which clearly indicates their different depth of feeding.

The existence of the mantle diapir in the region of Central Kamchatka, in our opinion, is verified also in the neotectonic features of the region under consideration. The features of the present-day relief tell about the contrasting zonal-block character of the neotectonic motions in the considered region. In this case, however, we are interested rather in their generalized character.

It is quite possible that the presence of a hot mantle diapir must anyhow manifest itself in the generalized features of the relief, the volcanism, and the tectonics of the central part of Kamchatka. We can analyze the generalized relief characteristics either using satellite altimetry anomalies in the free air or by considering the features of the averaged relief. The results turn out to be very close. Figure 7 presents the scheme of the averaged relief of the central part of Kamchatka. It is clearly seen that an isometric relief anomaly is observed in the region of the supposed mantle diapir. According to the averaged data, it can be characterized as a bending fold complicated by the Central Kamchatka Depression from the East (the extension zone), by the Malki–Petropavlovsk zone of transverse dislocations from the South, and by the zone of junction with the Aleutian–Komandor island arc system from the North. Similar "outline" restrictions of the anomalous properties of the upper mantle are also presented in the abovementioned results of the regional seismic tomography, which permits us to propose, on the strength of all the evidence, a model of an asthenospheric diapir rising to the lithosphere mantle up to a depth of 40–60 km. This diapir is then implemented as individual flows of mantle jets or "hot fingers" described in [50] for the NE of Japan. A detailed formulation of the asthenospheric diapirism model was described earlier in [5].

CONCLUSIONS

A complex approach to studying the isotopic–geochemical and geophysical anomalies within the considered region allows one to reach a series of sufficiently justified conclusions.

(1) The vast isotopic–geochemical anomaly revealed within Central Kamchatka is reflected in the seismic tomography models and well agrees with the gravimetric data. This allows one to interpret it as a consequence of the penetration of the asthenospheric diapir into the bottoms of the lithosphere mantle up to depths of about 40–60 km.

(2) Features in the material composition of the large volcanic centers of Kamchatka such as the Ichinsky, Bakening, Tolbachik, and Ploskie Sopki are deter-

mined by the influence of this mantle diapir (the formation of intraplate geochemical type basalts).

(3) The compositions of the large stratovolcanoes of the Klyuchevsky group, such as the Kharchinsky, Klyuchevsky, and Bezymyanny, reflect the crust–mantle level of feeding from a lesser depth with a significant addition of the crust material. Rocks of the intraplate geochemical type are absent here.

(4) Manifestations of the alkali-basalt intraplate volcanism in the structure of the Bering Sea region also should be considered in the context of the rising diapir.

(5) In the junction zone of the Kuril–Kamchatka and Aleutian–Komandor island arc systems, one can observe a superposition of the anomaly with higher Sr-isotopic compositions on the Bering Sea anomaly with moderate Sr-isotopic characteristics. Here, one can observe a combination of rocks belonging both to the intraplate and island arc geochemical types.

(6) The analysis of the obtained materials poses a topical problem of the spatial and time-related compatibility of the subduction geodynamics and diapirism models.

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REFERENCES

1. G. P. Avdeiko, A. A. Palueva, and O. A. Khleborodova, "Geodynamic conditions of volcanism and magma formation in the Kurile–Kamchatka island-arc system," Petrology **14** (3), 230–246 (2006).
2. V. V. Akinin and Yu. G. Apt, "Late Cenozoic alkaline—basic volcanism of the Russian Northeast," in *Magmatism and Mineralization of Northeast Russian* (SVKNII DVO RAN, Magadan, 1997), pp. 155–175 [in Russian].
3. V. V. Akinin, A. Kalvert, J. I. Hourigan, et al., Composition and evolution of the alkaline-basaltic magmas of the Imuruk volcanic field, Seward Peninsula, Alaska (Bering Sea volcanic province), in *Geology, Geography, and Biological Diversity of Russian Northeast: Proceedings of Far East Regional Conference, Vladivostok, Russia, 2006* (Vladivostok, 2006), pp. 44–46 [in Russian].
4. V. V. Akinin, A. V. Andronikov, S. B. Mukasa, et al., "Cretaceous lower crust of the continental margins of the Northern Pacific: petrological and geochronological data on lower to middle crustal xenoliths," Petrology **21** (1), 28–65 (2013).
5. G. I. Anosov, A. V. Koloskov, and G. B. Flerov, "Manifestations of the ultramafic rocks of the Kamchatsky region from the position of vortex geodynamics," in *Vortices in Geological Processes* (Petropavlovsk-Kamchatskii, 2004), pp. 129–200 [in Russian].
6. Yu. E. Apt, V. V. Akinin, and J. E. Wright, "Sr, Nd, and Pb isotopes in Neogene melanephelinites and deep-seated xenoliths from Northeast Russia," Geochem. Int. **36** (1), 24–33 (1998).
7. R. M. Bembel', V. M. Megerya, and S. R. Bembel', *Geosolitons: Functional System of the Earth, Concept of Prospecting and Exploration of Hydrocarbon Fields* (Vektor Buk, Tyumen, 2003).
8. O. N. Volynets, V. S. Antipin, A. B. Perepelov, et al., "Geochemistry of island-arc volcanic series: geodynamic implication, Kamchatka," Geol. Geofiz., No. 5, 3–13 (1990).
9. O. N. Volynets, A. V. Koloskov, V. I. Vinogradov, et al., "Strontium and oxygen isotope composition of the Late Cenozoic K–Na alkaline basalts of intraplate affinity, Kamchatka," Petrologiya **3** (2), 207–213 (1995).
10. O. N. Volynets, S. F. Karpenko, R. W. Kay, and M. Gorring, " Isotopic composition of Late Neogene K–Na alkaline basalts of eastern Kamchatka: indicators of the heterogeneity of the mantle magma sources," Geochem. Int. **35** (10), 884–896 (1997).
11. L. I. Gontovaya and V. V. Gordienko, "Deep processes and geophysical models of mantle beneath Eastern Kamchatka and Kronotsky Bay," in *Geology and Mineral Resources of the World Ocean* (Nauk. dumka, Kiev, 2006), No. 2, pp. 107–122 [in Russian].
12. L. I. Gontovaya, S. V. Popruzhenko, I. V. Nizkous, and S. E. Aprelkov, " Upper mantle beneath Kamchatka: the depth model and its relation to tectonics," Russ. J. Pac. Geol. **2** (2), 165–174 (2008).
13. L. I. Gontovaya, S. V. Popruzhenko, and I. V. Nizkous, "Upper mantle structure in the ocean–continent transition zone: Kamchatka," J. Volcanol. Seismol. **4** (4), 223–232 (2010).
14. A. F. Grachev, "Quaternary volcanism and geodynamic problems of Northeastern Asia," Fiz. Zemli, No. 9, 19–37 (1999).
15. N. L. Dobretsov, I. Yu. Kulakov, and Yu. D. Litasov, "Migration paths of magma and fluids and lava compositions in Kamchatka," Russ. Geol. Geophys. **53** (12), 1633–1662 (2012).
16. D. Zhao, F. Pirajno, and L. Liu, "Mantle structure and dynamics under East Russia and adjacent regions," Russ. Geol. Geophys. **51** (9), 925–938 (2010).
17. M. K. Kaban, "Structure of the continental upper mantle from seismic and gravity data," El. Nauch.-Inf. Vestn. ONZ RAN, No. 1 (2002).
18. A. V. Koloskov, "Isotope-geochemical heterogeneity of the Pliocene–Quaternary volcanic rocks of Kamchatka, geometry of subduction zones, model of fluid-magmatic system," Vulkanol. Seismol., No. 6, 16–42 (2001).
19. A. V. Koloskov, "Anomalous magmatic zones of the modern island-arc systems. Koryak–Kamchatka volcanic zone," in *Geodynamics, Magmatism, and Metallogeny of East Russia*, Ed. by A.I. Khanchuk (Dal'nauka, Vladivostok, 2006) [in Russian].
20. A. V. Koloskov and S. A. Khubunaya, "New petrological data on the volcanic rocks of the Chichinautzin

Region: the sources of the magmatic melts and the origin of the Trans-Mexican Volcanic Belt," Russ. J. Pac. Geol. Geol. **7** (4), 247–261 (2013).

21. I. Yu. Koulakov, N. L. Dobretsov, N. A. Bushenkova, and A. V. Yakovlev, "Slab shape in subduction zones beneath the Kurile—Kamchatka and Aleutian arcs based on regional tomography results," Russ. Geol. Geophys. **52** (6), 650–667 (2011).
22. F. Sh. Kutyev, B. V. Ivanov, A. A. Ovsyannikov, et al., "Exotic lavas of Avacha volcano," Dokl. Akad. Nauk SSSR **255** (5), 1240–1243 (1980).
23. A. B. Perepelov, S. A. Tatarnikov, L. A. Pavlova, et al., "NEB-adakitic volcanism of the Central Kamchatka depression," in *Volcanism and Geodynamics. Proceedings of 4th All-Russian Symposium on Volcanology and Paleovolcanology, Petropavlovsk-Kamchatskii, Russia, 2009* (IViS DVO RAN, Petropavlovsk-Kamchatskii, 2009), Vol. 2, pp. 449–454 [in Russian].
24. N. I. Seliverstov, *Geodynamics of the Junction Zone of the Kurile–Kamchatka and Aleutian Arcs* (KamGU im. V. Beringa, Petropavlovsk-Kamchatskii, 2009) [in Russian].
25. I. A. Tararin, S. I. Dril', G. P. Sandimirova, et al., "Isotopic signatures of strontium, neodymium, and lead in metamorphic rocks of the Khavyven Highland in Eastern Kamchatka," Dokl. Earth Sci. **431** (1), 356–360 (2010).
26. P. I. Fedorov, A. V. Koloskov, and S. M. Lyapunov, "Geochemistry and petrology of Late Cenozoic volcanic rocks of Cape Navarin, eastern Koryak highland," Geokhimiya, No. 9, 1284–1296 (1993).
27. V. V. Akinin, A. V. Sobolev, T. Ntaflos, et al., "Clinopyroxene megacrysts Enmelen melanephelinitic volcanoes (Chukchi Peninsula, Russia): application to composition and evolution of mantle melts," Contrib. Mineral. Petrol. **150**, 85–101 (2005).
28. B. Castelana, "Geology, chemostratigraphy and petrogenesis of the Avachinsky volcano, Kamchatka, Russia," PhD No. 981805050 (1998).
29. T. Churikova, F. Dorendorf, and G. Woerner, "Sources and fluids in mantle wedge below Kamchatka: evidence from across-arc geochemical variation," J. Petrol. **42**, 1567–1593 (2001).
30. A. S. Davis, S. H. Gunn, L. -B. Gray, et al., "Petrology and isotopic composition of Quaternary basanites dredged from the Bering Sea continental margin near Navarin Basin," Can. J. Earth Sci. **30** (5), 975–984 (1993).
31. M. J. Defant and M. S. Drummond, "Derivation of some modern arc magmas by melting of young subducted lithosphere," Nature **347**, 662–665 (1990).
32. F. Dorendorf, T. Churikova, A. Koloskov, et al., "Late Pleistocene to Holocene activity at Bakening Volcano and surrounding monogenetic centers (Kamchatka): volcanic geology and geochemical evolution," J. Volcanol. Geotherm. Res **104**, 131–151 (2000).
33. A. Dosseto, B. Bourdon, J. -L. Goron, et al., "U-Th-Pa-Ra study of the Kamchatka arc: new constraints on the genesis of arc lavas," Geochim. Cosmochim. Acta **67** (15), 2857–2877 (2003).
34. G. Ekstrom and A. M. Dziewonski, "The unique anisotropy of the Pacific upper mantle," Nature **394**, 168–172 (1998).
35. A. Gorbatov, V. Kostoglodov, G. Suarez, et al., "Seismicity and structure of the Kamchatka subduction zone," J. Geophys. Res. **102**, 17883–17898 (1997).
36. A. Gorbatov, J. Dominguez, G. Suarez, et al., "Tomographic imaging of the P-wave velocity structure beneath the Kamchatka Peninsula," Geophys. J. Int. **137**, 269–279 (1999).
37. A. S. Gorbatov, S. Widiyantoro, Y. Fukao, et al., "Signature of remnant slabs in the North Pacific from P-wave tomography," Geophys. J. Int. **142**, 27–36 (2000).
38. S. R. Hart, "Heterogeneous mantle domains: signatures, genesis and mixing chronologies," Earth Planet. Sci. Lett. **90**, 273–297 (1988).
39. G. Jiang, D. Zhao, and G. Zhang, "Seismic tomography of the Pacific slab edge under Kamchatka," Tectonophysics **495**, 190–203 (2009).
40. R. W. Kay, S. S. Sun, and C. N. Lee-Hu, "Pb and Sr isotopes in volcanic rocks from the Aleutian Islands and Pribilof Islands, Alaska," Geochim. Cosmochim. Acta **42**, 263–273 (1978).
41. P. Kepezhinskas, DermottF. Mc, J. Defant, et al., "Trace element and Sr-Nd-Pb isotopic constraints on a three-component model of Kamchatka arc petrogenesis," Geochim. Cosmochim. Acta **61** (3), 577–600 (1997).
42. J. M. Lees, J. Van Decar, E. Gordeev, et al., "Three dimensional images of the Kamchatka-Pacific Plate cusp," in *Volcanism and Subduction. The Kamchatka Region*, Geophys. Monogr. Ser. **172**, 65–75 (2007a).
43. V. Levin, N. Shapiro, J. Park, et al., "Seismic evidence for catastrophic slab loss beneath Kamchatka," Nature **418**, 763–766 (2002).
44. V. Levin, J. Park, M. Brandon, et al., "Crust and upper mantle of Kamchatka from teleseismic receiver function," Tectonophysics **358**, 233–265 (2002).
45. E. J. Moll-Stalcup, "The origin of the Bering Sea basalt province, western Alaska," in *Proceeding of the International Conference on Arctic Margins, Magadan, Russia, 1994* (Magadan, Russia, 1994), pp. 113–123.
46. I. Nizkous, E. Kissling, L. Gontovaya, I. Sanina, V. Levina, "Correlation of Kamchatka lithosphere velocity anomalies with subduciton processes," in *Volcanism and subduction. The Kamchatka Region,* Geophys. Monogr. Ser. **172**, 97—106 (2007). 10/1029/172GM09.
47. V. Peyton, V. Levin, J. Park, M. Brandon, and J. Lees, "Mantle flow at a slab edge: seismic anisotropy in the Kamchatka Region," Geophys. Rev. Lett. **28**, 379–382 (2001).
48. F. Pineau, M. P. Semet, N. Grassineau, et al., "The genesis of the stable isotope (O, H) record in arc magmas: the Kamchatka's case," Chem. Geol. **135**, 93–124 (1999).
49. M. Portnyagin, I. Bindeman, K. Hoernle, et al., "Geochemistry of primitive lavas of the Central Kamchatka depression: magma generation at edge of the Pacific Plate," in *Volcanism and Tectonics of the Kam-*

chatka Peninsula and Adjacent Arcs, Ed. by J. Eichelberger J., Geophys. Monograph. Ser **172**, 199–239 (2007).

50. Y. Tamura, Y. Tatsumi, D. Zhao, et al., "Hot fingers in the mantle wedge: new insights into magma genesis in subduction zones," Earth Planet. Sci. Lett. **197**, 105–116 (2002).

51. O. N. Volynets, "Geochemical types, petrology and genesis of Late Cenozoic volcanic rocks from the Kurile-Kamchatka island-arc system," Int. Geol. Rev. **36** (4), 373–405 (1994).

52. G. M. Yogodzinski, J. L. Rubenstone, S. M. Kay, et al., "Magmatic and tectonic development of the Western Aleutians: an oceanic arc in a strike-slip setting," J. Geophys. Res. **98** (B7), 11807–11834 (1993).

53. G. M. Yogodzinski, O. N. Volynets, A. V. Koloskov, et al., "Magnesian andesites and the subduction component in a strongly calc-alkaline series at Piip Volcano, Far Western Aleutians," J. Petrol. **35** (1), 163–204 (1994).

54. G. M. Yogodzinski, R. W. Kay, O. N. Volynets, et al., "Magnesian andesite in the Western Aleutian Komandor region: implications for slab melting and processes in the mantle wedge," Geol. Soc. Am. Bull **107** (5), 505–519 (1995).

55. G. M. Yogodzinski, J. M. Lee, T. G. Churikova, et al., "Geochemical evidence for the melting of subducting oceanic lithosphere at plate edges," Nature **409**, 500–504 (2001).

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