ISSN 1028-334X, Doklady Earth Sciences, 2024. © Pleiades Publishing, Ltd., 2024.

VOLCANOLOGY

The Role of the Back-arc Basin in the Formation of Slab Heterogeneity and the Origin of Volcanism in the Kuril—Kamchatka Island Arc

O. V. Bergal-Kuvikas[a,*], Academician E. I. Gordeev[a], and Corresponding Member of the RAS I. Yu. Koulakov[b,c]

Received January 10, 2024; revised February 14, 2024; accepted February 20, 2024

Abstract—The origin of volcanism along the Kuril—Kamchatka Island Arc (KKIA) was analyzed. Geophysical observations show variations in the slab parameters. Different widths of the volcanic belt in the northern and southern parts of the KKIA are caused by changes in the slab dip angle. The rift system of the Bussol Strait may be generated by significant changes in the slab velocity in the central segment of the KKIA. We proposed that the back-arc basin plays a predominant role in the formation of various parameters of the slab and manifestations of volcanism along the KKIA.

Keywords: slab, volcanism, back-arc basin, Kurile Islands, southern Kamchatka, Hokkaido

DOI: 10.1134/S1028334X2460141X

INTRODUCTION

The Kuril—Kamchatka Island Arc (KKIA) forms the northwestern sector of the Ring of Fire. The KKIA extends from the Malko-Petropavlovsk zone of transverse dislocations in Kamchatka to the junction with the northeastern Honshu arc on Hokkaido Island (Fig. 1). Within the Kuril Islands, 36 active terrestrial volcanoes [1] and 116 submarine volcanoes of Quaternary age [2] have been identified. Most of the volcanoes are underwater, some volcanoes form isolated islands, and the activity of others can be identified only by finding reference horizons of pyroclastic rocks over a large area. The distribution of volcanoes along the KKIA show that the volcanic front of the arc bends sharply at an angle of 22°—23° in the area of the Bussol Strait [2]. In this area, a series of strong earthquakes with magnitudes up to 8.3 occurred between 2006 and 2009. Comparison of the locations of earthquake sources with the deep structure and tectonics of the central Kuril Islands has shown that they are associated with the regional fault zones and areas of anomalous structure of the Earth's crust [3].

This is reflected in the change in the gravity field in free air and in disturbance of the geochemical zoning in the area of the Bussol Strait [2]. The isotopic—geochemical markers of volcanics of the northern Kuril Islands indicate a depleted mantle source (N-MORB) and the involvement of melts, associated with melting of subduction sediment, in the magma genesis. This fact is possibly explained by the thermal anomaly recorded beneath southern Kamchatka. On the contrary, the compositions of igneous rocks of the central and southern Kurils are displaced to the mantle field of an enriched mantle type (E-MORB) [4]. Active mantle diapirism and volcanic activity in the back-arc Kuril Basin led to heating of the supra-subduction mantle of the rear zone of the southern Kurils [5]. The purpose of the present work is to reveal the origin of the anomaly in the central segment of the KKIA and to identify the role of the back-arc basin in the formation of slab parameters and, correspondingly, the correlated manifestations of the KKIA volcanism.

METHODS

The results of previous studies were used to solve the problem identified. The seismic activity across the subduction zone was analyzed on the basis of data from the Sakhalin Branch of the Geophysical Service, Russian Academy of Sciences (Fig. 2). The type of slab—mantle relations has been studied using mantle tomography (Fig. 3). The geophysical characteristics of the slab along the arc are presented in [8]. The spatial manifestation of volcanism, including the distance to the deep-sea trough, and the volumes of eruption

[a] *Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences, Petropavlovsk-Kamchatsky, 683006 Russia*

[b] *Skolkovo Institute of Science and Technology (Skoltech), Moscow, 121205 Russia*

[c] *Institute of Petroleum Geology and Geophysics, Siberian Branch, Russia Academy of Sciences, Novosibirsk, 630090 Russia*

**e-mail: kuvikas@mail.ru*

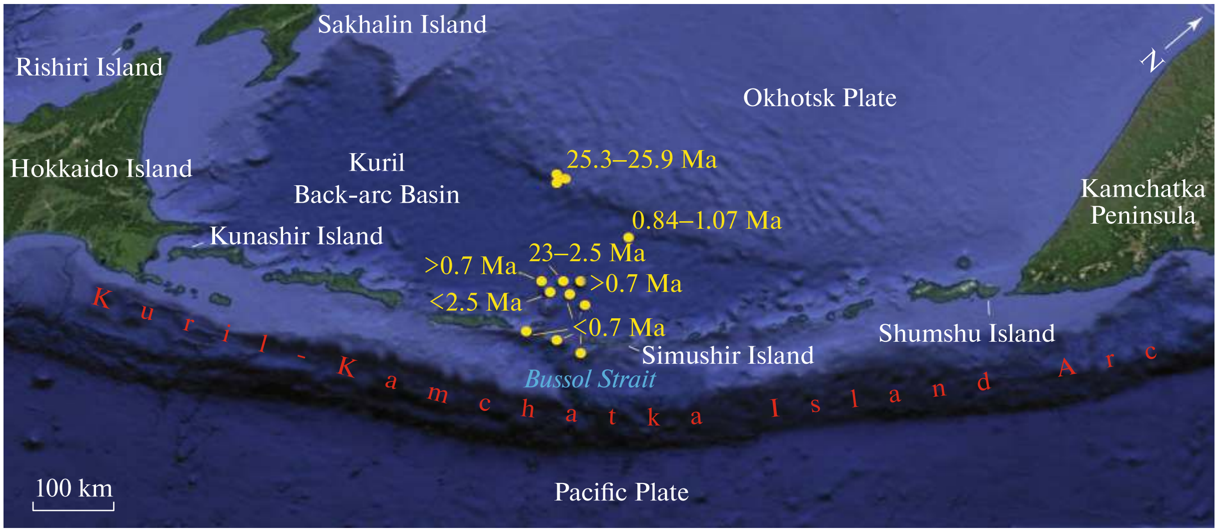

Fig. 1. Geodynamic position of the KKIA. Individual identified volcanoes of the back-arc and forearc graben of the Bussol Strait according to [2, 6, 7] are highlighted in yellow.

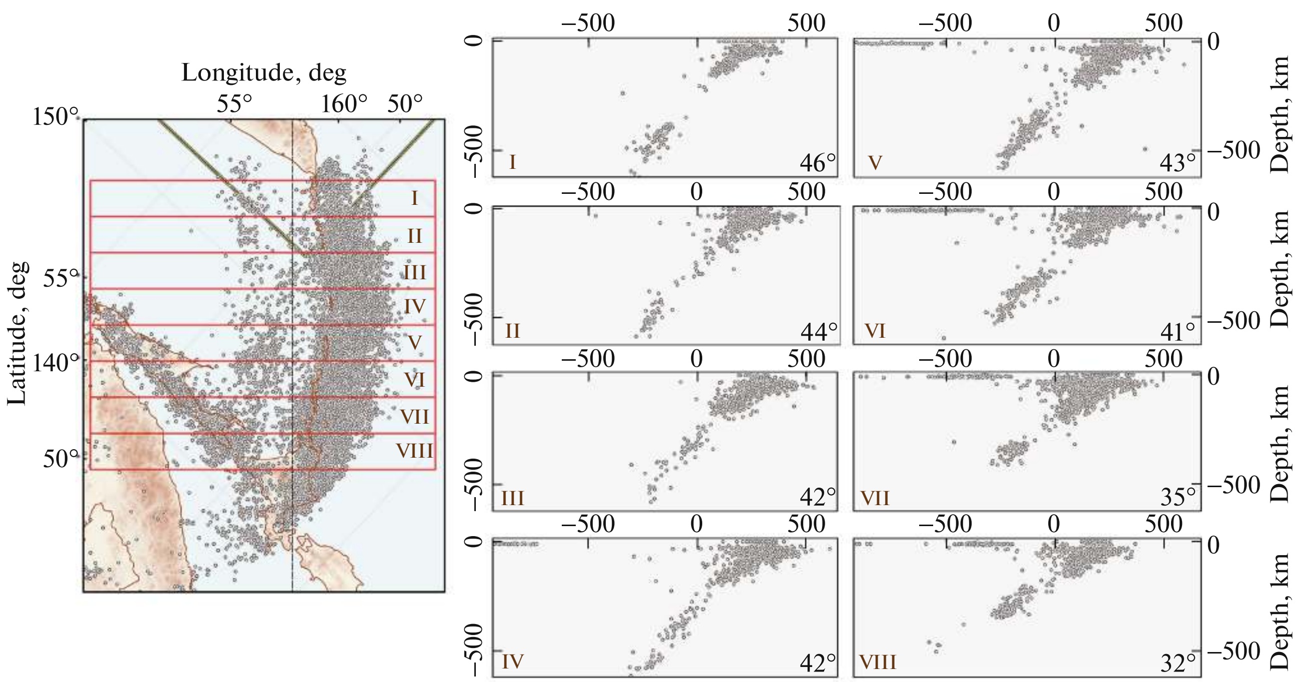

Fig. 2. Manifestation of seismicity across a strike of the KKIA subduction zone. Roman numerals on the sections correspond to the localization of the profiles on the right part of the figure. The numbers at the bottom of the sections indicate the average angle of the slab dip.

products were analyzed from a compilation of numerous sources [2, 9, 10] (Fig. 4).

RESULTS AND DISCUSSION

The distribution of seismicity across the strike of the subduction zone indicates a decrease in the average angle of the slab dip from north to south (Fig. 2). Mantle tomography data also support this conclusion (Fig. 3). A low-velocity anomaly in the rear part of the arc in the southern Kurils and its smaller size in the northern Kurils have attracted attention. In terms of geodynamics, it points to the presence of the back-arc Kuril Basin (Fig. 3).

The parameters of the dipping slab vary. Therefore, the age of the slab increases from the north of the arc

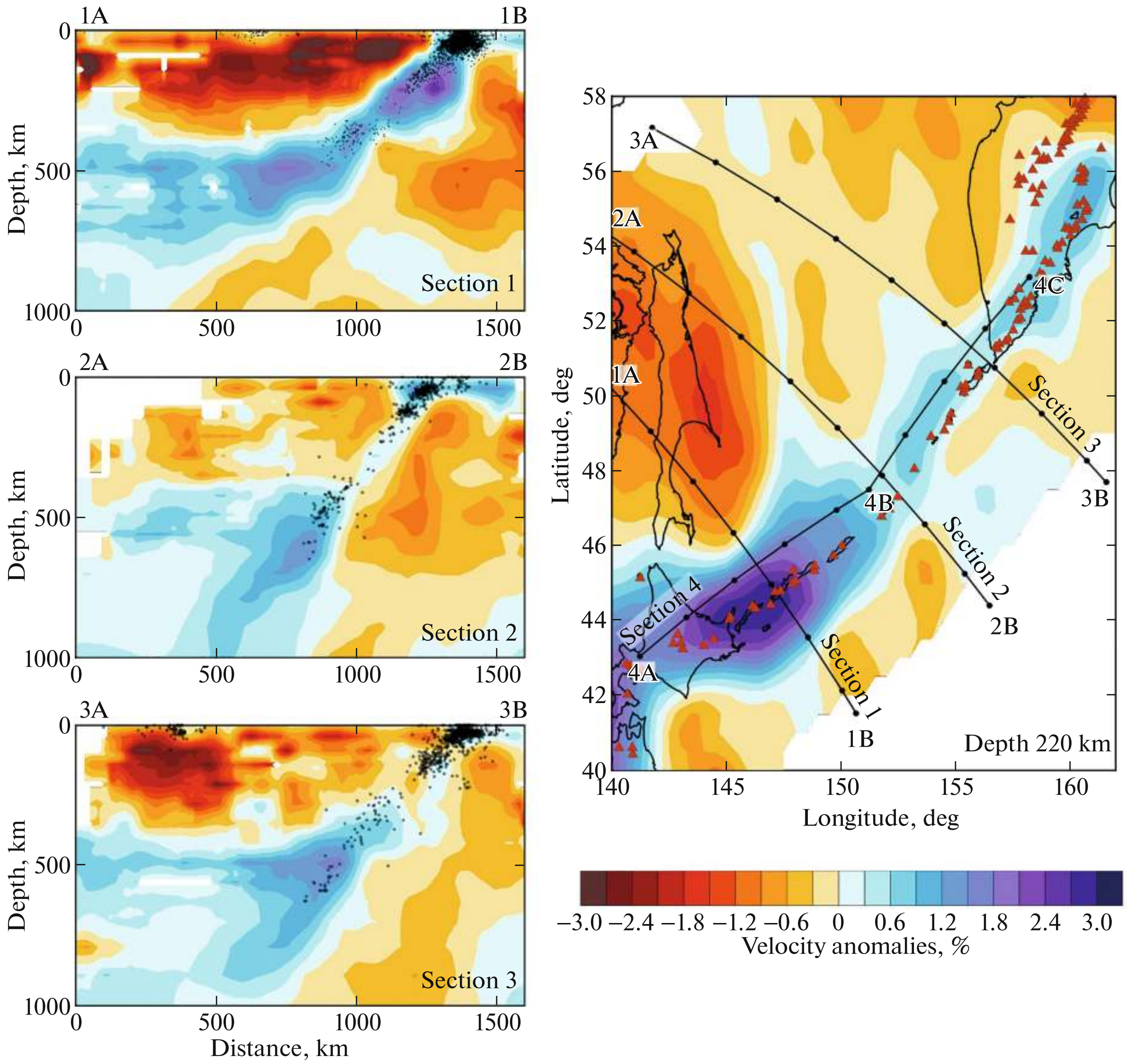

Fig. 3. Anomalies of velocities of *P*- and *S*-waves on vertical sections across the KKIA strike according to [11]. The points are the hypocenters of earthquakes. The position of sections is shown on the map in the right-hand part of the figure.

to the south and varies from 105 to 125 Ma, respectively (Fig. 4). Dramatic changes in the velocity of the plate dipping are observed in the central segment of the KKIA. This is reflected in the formation of the asthenosphere upwelling according to seismic tomography data (Figs. 3, 4). Detailed bathymetry, gravimetry, and seismic profiling suggested a transtension zone in the central Kurils and active destruction of tectonic origin [12]. A comparison of the age of the volcanic formation in the rearward part of the arc indicates a rejuvenation of the structures from 25 Ma [7] to very young structures less than 0.7 Ma at the arc front [2] (Fig. 1). It is important to note the presence of numerous volcanic edifices from Simushir Island to the trench, which is interpreted as the presence of an axial magmotogenic zone of superimposed rifting [12]. The temporal evolution of volcanoes from the back-arc to the forearc suggests the gradual formation of a graben in the Bussol Strait associated with the development of different structures in the northern and southern Kurils. Collision on Hokkaido Island and the development of strike–slip structures in the southern Kurils are associated with the formation of the forearc graben in the Bussol Strait [13].

One of the interesting problems is related to the reason for the formation of different slab parameters of the northern and southern Kurils. Based on the above arguments, it is obvious that the rift-related structure of the Bussol Strait and the rejuvenation of volcanism from the back-arc to the forearc are related to the transtension caused by the difference in the dip velocity and the dip angle of the slab in the area. It is gener-

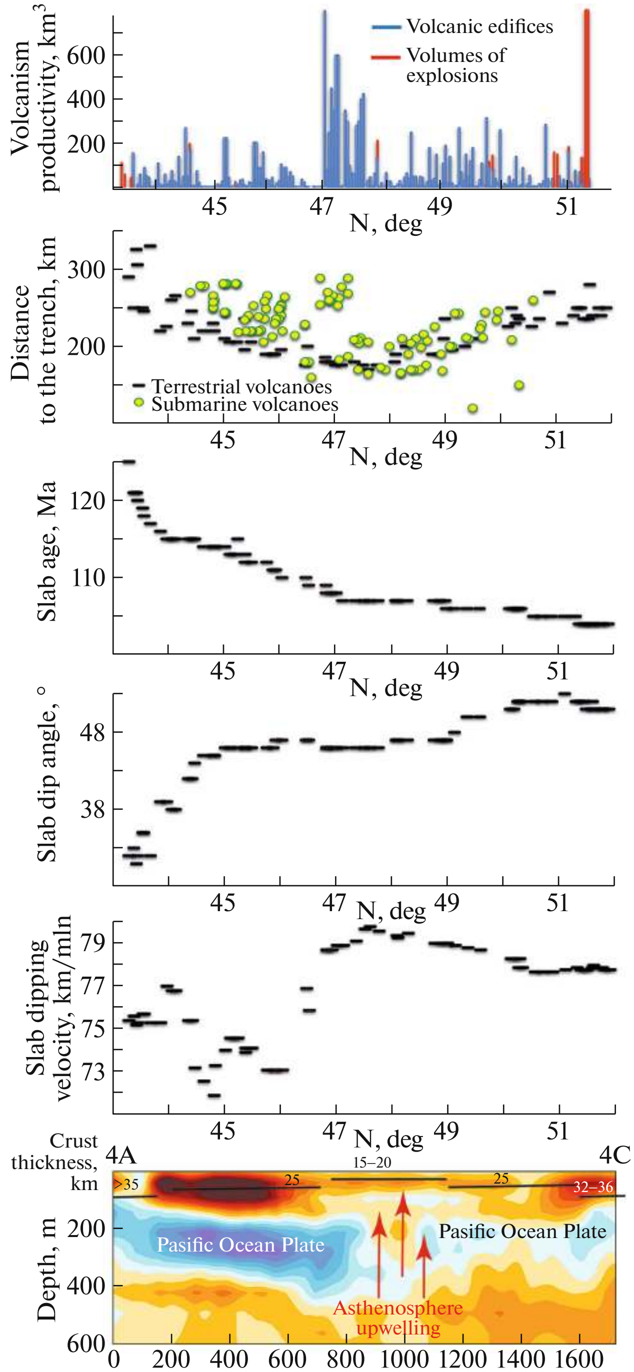

Fig. 4. Geophysical parameters of the slab and productivity of volcanism along the KKIA. The productivity of volcanism is represented according to [2, 9, 10]. The geophysical parameters of the slab are represented according to [9]. The crustal thickness is given on the basis of publications [17, 20]. The localization of the data of section 4 is shown in Fig. 3 according to seismic tomography.

ally accepted that the slab age influences the dip velocity and angle. In the case of KKIA, we see that the age changes gradually (Fig. 4). Thus, it is clear that there is another factor affecting the change in the geophysical parameters of the slab along the KKIA. Modeling of the slab dynamics has shown that one of the important parameters controlling the change in the slab dip angle is the variation of the rheological properties of a mantle wedge [14]. Heterogeneity of the mantle wedge with different rheological properties may be formed by the action of the back-arc basin, as evidenced by numerous publications, mainly in the broad part of the basin opening in the southern part of the KKIA: Hokkaido Island [15], Rishiri Island [2], and Kunashir Island [5]. The spectrum of magma variations and the formation of powerful caldera-forming eruptions on Hokkaido Island are most likely related to the action of the back-arc basin [16]. The change in the rheological properties of the mantle wedge due to the opening of the back-arc basin led to the formation of an oblique zone of subduction in the southern Kurils [17].

The thickness of the crust varies from 32–36 km under southern Kamchatka, >35 km in northern Hokkaido, and it is minimal (15–20 km) in the central segment of the KKIA in the area of the Bussol Strait [18]. The analysis of volcanic productivity along the arc indicates the predominance of explosive eruptions in the southern part of Kamchatka and in the northern part of Hokkaido Island, which is possibly related to the relatively greater thickness of the crust. The maximum volumes (>300 km^3) of volcanic edifices are attributed to the central segment of the KKIA. Changes in the slab dip angle along the arc are reflected in the localization of forearc volcanoes and in the width of the volcanic belt (Fig. 4). Therefore, from the north to south Kurils, the distance to the trench is 160–260 km in the northern part, 155–290 km in the area of the Bussol Strait, and 185–285 km in the southern Kurils [9]. Despite the relatively steep dip angle of the slab in the northern part of the Kuril Islands, the width of the volcanic belt is large, possibly due to the presence of a low-velocity anomaly recorded beneath Shumshu Island and because of the disintegration of the magma generation zone to the rear part of the arc [19].

CONCLUSIONS

Comparison of the parameters of the slab and volcanism along the KKIA allowed us to reveal the relationship between the width of the volcanic belt and the distance to the trench. The localization of the volcanoes with volume of >300 km^3 in the central Kurils, the presence of a rift-related structure, and the rejuvenation of volcanic edifices from the rear to the forearc graben are associated with a dramatic change in the velocity of slab motion and the dip angle, despite the insignificant changes in the slab age. A possible reason for the revealed changes in the slab dip may be heterogeneity of the mantle wedge and enrichment of the mantle source due to the action of the backarc basin on Hokkaido Island and the southern Kurils.

ACKNOWLEDGMENTS

We are grateful to the Sakhalin Branch of the Geophysical Survey, Russian Academy of Sciences, for providing data on the seismicity of the study region.

FUNDING

This work was supported by the Russian Science Foundation, grant no. 22-77-10019, https://rscf.ru/project/22-77-10019/.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Sakhalin Volcanic Eruptions Response Team (SVERT). http://www.imgg.ru/ru/teams/svert. Accessed January 10, 2024.
2. G. P. Avdeiko, A. Yu. Antonov, O. N. Volynets, et al., *Underwater Volcanism and Zonality of the Kuril Island Arc (*Nauka, Moscow, 1992) [in Russian].
3. T. K. Zlobin, L. N. Poplavskaya, and A. Yu. Polets, Dokl. Earth Sci. **428** (7), 1227–1232 (2009).
4. Yu. A. Martynov, A. V. Rybin, S. I. Dril', et al., Vestn. Dal'nevost. Otd. Ross. Akad. Nauk, No. 4, 17–23 (2009).
5. A. Yu. Martynov, Petrology **21** (5), 471–489 (2013).
6. B. V. Baranov, R. Werner, K. A. Hoernle, et al., Tectonophysics **350** (1), 63–97 (2002). https://doi.org/10.1016/S0040-1951(02)00081-1
7. R. Werner, B. Baranov, K. Hoernle, et al., Geosciences **10** (11), 442 (2020). https://doi.org/10.3390/geosciences10110442
8. E. M. Syracuse and G. A. Abers, Geochem., Geophys., Geosyst. **7** (5), 1–18 (2006). https://doi.org/10.1029/2005GC001045
9. O. V. Bergal-Kuvikas, Tikhookean. Geol. **34** (2), 103–116 (2015).
10. Volcano Global Risk Identification and Analysis Project (VOGRIPA). https://vogripa.org/. Accessed July 21, 2020.
11. I. Yu. Koulakov, N. L. Dobretsov, N. A. Bushenkova, et al., Russ. Geol. Geophys. **52** (6), 650–667 (2011).
12. R. G. Kulinich, B. Ya. Karp, B. V. Baranov, et al., Russ. J. Pac. Geol. **1** (1), 3–15 (2007).
13. G. Kimura, Geology **14** (5), 404–407 (1986). https://doi.org/10.1130/0091-7613(1986)14<404:OSACFT>2.0.CO;2
14. M. I. Billen and G. Hirth, Geochem., Geophys., Geosyst. **8** (8) (2007). https://doi.org/10.1029/2007GC001597
15. Y. Ikeda, R. J. Stern, H. Kagami, et al., Island Arc **9** (2), 161–172 (2000). https://doi.org/10.1046/j.1440-1738.2000.00269.x
16. S. Yamashita, K. Shuto, Y. Karihara, et al., J. Geol. Soc. Japan **105** (9), 625–642 (1999). https://doi.org/10.5575/geosoc.105.625
17. E. A. Kneller and P. E. van Keken, Geochem., Geophys., Geosyst. **9** (1) (2008). https://doi.org/10.1029/2007GC001677
18. Z. N. Proshkina, R. G. Kulinich, and M. G. Valitov, Russ. J. Pac. Geol. **11** (6), 436–447 (2017).
19. O. V. Bergal-Kuvikas, M. M. Buslov, N. A. Bushenkova, et al., Russ. Geol. Geophys. **10** (64), 1227–1240 (2023). https://doi.org/10.2113/RGG20234558
20. T. K. Zlobin and A. Yu. Polets, Obshch. Reg. Probl. Tekton. Geodin., No. 1, 333–336 (2008).

Translated by V. Krutikova