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Relationship of Megafracturing Expressed in the Relief of Southeast Kamchatka with Volcanism and Thermal Condition of the Upper Part of the Lithosphere

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Abstract—Geomorphological methods have been used to identify areas of increased megafracture in the southeast of Kamchatka, characterized by high crustal seismicity and low temperature values at a depth of 1 km. It is established that warmer areas of concentration of volcanoes and hot springs are not favorable for the development of surface fracturing, since an increase in temperature leads to the dominance of plastic deformations over brittle ones. Thus, using the example of the selected area, the possibilities of structural–geomorphological and morphometric analysis of the relief are shown to identify areas in different geothermal states, which largely determine not only the relief and seismicity, but also the ecological and landscape appearance of the territory as a whole, including its floristic and faunistic features.

Keywords: southeast of Kamchatka, megafractures, relief analysis

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INTRODUCTION

Setting the Task

The volcanoes of Kamchatka are unique natural sites included in the UNESCO list of World Natural and Cultural Heritage. A significant part of them (including Avachinsky, Koryaksky, and Bakening) are located in the southeast of the peninsula within the Eastern Ridge. Numerous thermal springs and geyser fields are associated with the volcanoes (Kiryukhin and Sugrobov, 2019), including one of the largest in the world: the Valley of Geysers on the territory of the Kronotsky Biosphere Reserve. The high hydrothermal–magmatic activity of Kamchatka as a whole is caused by the subduction interaction of the Pacific and Okhotsk Sea lithospheric plates, accompanied by intense seismicity. Modern volcanism and seismicity not only shape the relief and ecological landscape of the territory, but are also some of the most dangerous geological processes that largely determine the life of large cities on the peninsula: Petropavlovsk-Kamchatsky, Vilyuchinsk, and Yelizovo.

The manifestations of geological processes are mainly determined by the nature of the tectonic fragmentation of the geological environment, since the movement of magmatic masses and the migration of fluids occur along cracks of different scale levels (Kiryukhin et al., 2023) and dynamic movements occur along faults initiate seismic events (Zelenin et al., 2020). Modern capabilities of geomorphological methods and software allow us to quantitatively analyze the relationship between megafractures expressed in the relief, volcanism, and seismicity. We have partially considered this issue earlier using the example of the Malko-Petropavlovsk zone of transverse dislocations (Agibalov et al., 2023). In this study, increasing the area of the selected region and involving a larger number of source materials helped clarify and expand the understanding of the relationship between fracturing, hydrothermal–magmatic activity, and the localization of epicenters of shallow crustal earthquakes in the Kuril-Kamchatka region, supplementing and expanding the existing understanding on this topic (see, for example, (Leonov, 1994; Leonov and Ivanov, 1994; Khrenov et al., 2002; Shkarin and Shapovalov, 2006; Ermakov et al., 2014; Khubaeva et al., 2020)).

MEGAFRACTURE AND THE BIOSPHERE

At present, there is no doubt about the significance of the configuration of fracture zones in the upper part of the earth's crust as one of the factors of volcanism, since these zones can serve as channels through which magmatic masses rise to the surface (Belashev, 2010). In turn, volcanism plays one of the leading roles in the formation of the natural environment and the biosphere as a whole (Rashidov, 2013). It largely determines the dynamics of the processes occurring at its various levels—from the lower boundary located in the bowels of the Earth, through which powerful flows of matter pass (including fluid–magmatic melts), to the very upper one, since volcanic ash can rise to a height of up to ~20 km (Poyarkov and Babanazarova, 2007).

It is known that the entry of large volumes of volcanic ash and dust into the atmosphere changes its optical properties. The reflection of solar radiation from volcanic particles leads to a decrease in air temperature. Volcanic gases largely determine the chemistry of the environment: thus, in volcanic areas there are acid rains with a pH of 2.4–2.5 and mineralization of up to 250 mg/L (Hintuba and Ekba, 2019). According to V.I. Vernadsky (1960), the field of life stability is determined by five main factors: temperature, pressure, phase of the environment, chemistry of the environment, and radiant energy. In addition, volcanic processes form two of the five soil formation factors identified by V.V. Dokuchaev (1950)—parent rocks (which include volcanics) and relief, the main forms of which in Kamchatka are large stratovolcanoes.

As we have shown in our work (Agibalov et al., 2023), thermal springs are associated with megafracture zones of the Malko-Petropavlovsk zone of Kamchatka. In the article (Takhteev et al., 2010), the influence of such sources on the floristic and faunistic features of the Baikal region are given in detail, in which relict (thermo- and halophilic) species and endemics have been preserved. There are works describing the biota of thermal lakes and springs in Kamchatka (see, for example, (Markov and Zelenkov, 2014; Nikulina and Grishchenko, 2017)).

It is known that fluid migration occurs through megafracture zones. According to (Gorkovets and Belashev, 2014), elevated concentrations of subsurface radon contribute to tree growth anomalies and the emergence of large anthills in Karelia. In our opinion, this point of view is debatable: we carried out measurements of the volumetric activity of radon in this region, the positive anomalies of which mark the zones of fractures expressed in the relief (Agibalov et al., 2020). Often they are linear depressions with steep walls, along the sides of which forests grow, and the bottom is swampy or covered with field vegetation. Thus, growth anomalies of trees and large anthills are confined to the edge of the forest, which is characterized by increased illumination. At the same time, the inflow of mineralized waters through fracture zones, reflected in the elemental composition of tree bark, has been well studied (Glavatskikh, 1992), and for the territory of Kamchatka it was shown that mercury degassing is associated not only with volcanoes, but also with mega-fracture zones reaching great depths (Ozerova and Ozerov, 2009). The study of this process is of great practical importance, since mercury is a global pollutant of the first hazard class in all environments and has a toxic effect on biota regardless of the dose (Bogdanova et al., 2020).

From the above it follows that the study of the degree of tectonic fragmentation of the geoenvironment is an extremely urgent task.

BRIEF GEOLOGICAL AND GEOMORPHOLOGICAL OUTLINE OF THE STUDY AREA

The territory we are studying is located within two geomorphological regions—the folded-block Eastern Ridge with volcanoes and the Volcanic Highland (Fig. 1). It extends from north to south from the Kronotsky Peninsula to the village of Pauzhetka and is bounded on the west by the plain of the Central Kamchatka Depression (National..., 2007). The mountainous volcanic relief is developed here; the highest altitude is 3482 m (Kronotskaya Sopka) (see Fig. 1). Its formation began in the late Pliocene and continues actively to the present day under the influence of two main factors—tectonic movements and volcanism (Braitseva et al., 1970).

The areas of most active volcanic activity are located in the eastern and southwestern parts of the territory, where the volcanic Eastern and Southern Kamchatka ranges are located (Koronovsky, 2011). They are composed mainly of Upper Oligocene–Miocene effusive–extrusive and pyroclastic rocks of various compositions: from basalts to dacites and rhyodacites with a predominance of andesites and andesidacites (Avdeyko et al., 2001). These ridges are superimposed on the Easterb Kamchatka uplift of Late Cretaceous–Eocene age, the western part of which belongs to the Achaivayam-Valagin terrane—a paleoisland arc that developed in the Late Cretaceous–Paleocene. After its extinction and subsequent submersion, Paleocene–Early Eocene terrigenous flysch strata were formed. On the Kronotsky and Shipunsky peninsulas, subaqueous suprasubduction volcanics of the Kronotsky–Commander island arc, which existed in the Late Cretaceous–Oligocene, have developed (Shapiro and Soloviev, 2009). All the mentioned island-arc complexes are dislocated into syn- and antiforms and are disrupted by numerous thrusts. To the east of the village of Malki, metamorphic formations of different ages come to the surface according to the rocks of the Omgon-Ukelayatsky (underwater terrigenous plume of the Asian continent) and Achayvayam-Valaginsky (island arc) terranes (Shapiro and Soloviev, 2009; Koronovsky, 2011) (Fig. 2).

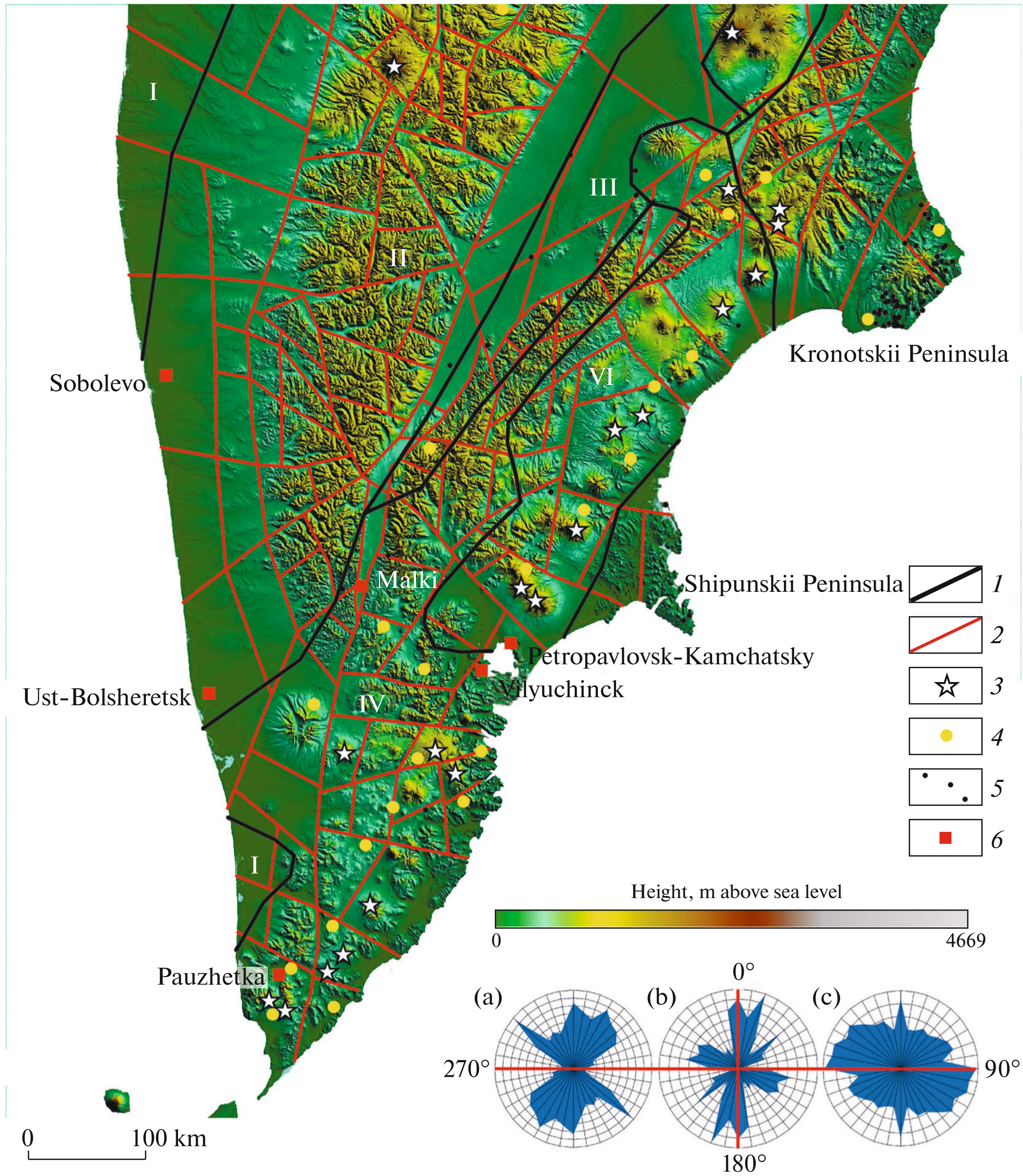

Fig. 1. Scheme of lineaments of South Kamchatka and rose diagrams of fault strikes (a), lineaments (b), and watercourses (c). (*1*) Boundaries of geomorphological regions (according to (National..., 2007)), (*2*) lineaments, (*3*) volcanoes (according to (State..., 1981)), (*4*) hot springs (according to (Geothermal..., 1995)), (*5*) epicenters of shallow earthquakes (according to (Catalog..., 2024)), and (*6*) populated areas. (I–VI) Geomorphological regions: (I) Western Kamchatka coastal plain, (II) folded-block Sredinny Range, (III) plain of the Central Kamchatka Depression, (IV) folded-block Eastern Ridge, (V) Klyuchevskaya group of volcanoes, and (VI) Volcanic Highland.

SOURCE MATERIALS AND RESEARCH METHODS

To analyze the nature of megafractures, a structural and geomorphological analysis of the digital elevation model (DEM) with a resolution of 1″ (~30 m) (SRTM..., 2024) was performed using the method of N.P. Kostenko (1999). The method involves identifying lineaments based on the pattern of the hydrographic network, sharp bends in slopes, and ledges. Lineaments form a block structure, with the blocks having a shape close to rectangular or trapezoidal. The dominant orientations of lineaments reflected in the rose diagrams were compared with the main directions of fault strike shown on the geological maps of scale 1 : 200000 (Database..., 2024) and watercourses (see database in (Lehner and Grill, 2013)). The average circular values of the strike azimuths were determined using the formula given in (Kazhdan and Guskov, 1990). To assess the degree of fragmentation of the upper lith-

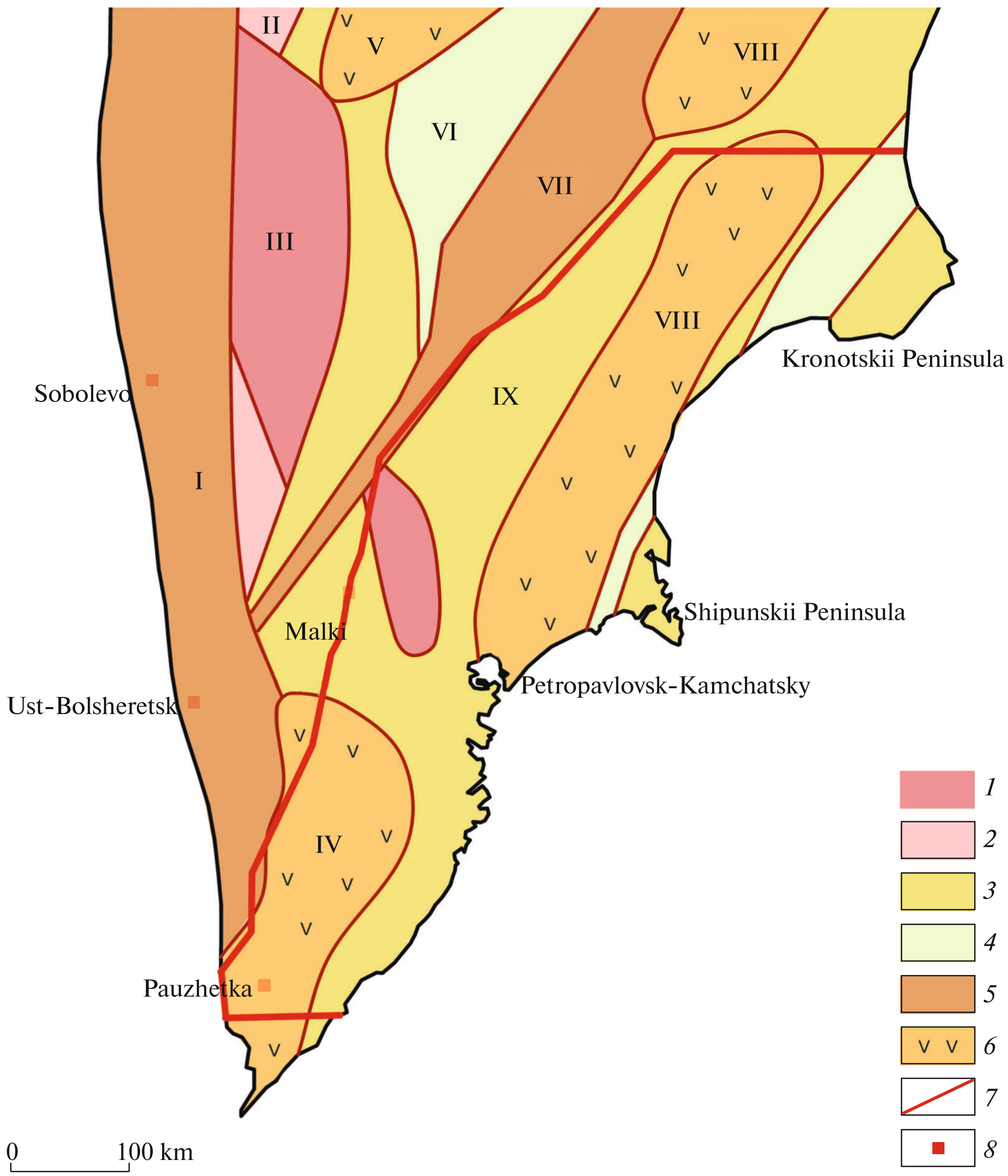

Fig. 2. Main geological structures of South Kamchatka (according to (Koronovsky, 2011) as amended). (*1*) Metamorphic rocks of the crystalline basement, (*2*) Late Cretaceous–Paleocene formations, (*3*) Late Cretaceous–Eocene formations, (*4*) Eocene–Miocene formations, (*5*) Miocene–Quaternary formations, (*6*) formation of volcanic ridges, (*7*) contours of the area examined in more detail in Fig. 3 (southeast Kamchatka), and (*8*) populated areas. (I–IX) Geological structures: (I) Bolsheretsky Trough, (II) Tigil Uplift, (III) Sredinny Ridge Uplift, (IV) Volcanic South Kamchatka Ridge, (V) Volcanic Sredinny–Kamchatka Ridge, (VI) Central Kamchatka Trough, (VII) Sredinny–Kamchatka Graben, (VIII) Volcanic East Kamchatka Ridge, and (IX) East Kamchatka Uplift.

osphere, the density of faults, lineaments and watercourses was calculated in the ArcMap program.

The depth of vertical dissection and the steepness of the slopes are some of the most informative morphometric parameters of the relief that characterize megafracture (Netrebin, 2012; Agibalov et al., 2023). The depth of vertical dissection was determined as the difference in heights in a neighborhood of radius R = 90 m of each DEM point using the Focal statistics tool. In order to quantitatively assess the relationship between the spatial distribution of faults and the morphometric parameters of the relief that we calculated, using the SPSS Statistics 17.0 program, we obtained the values of the Spearman rank correlation coefficient between the density of lineaments and faults, as well as between the density of faults, the depth of vertical dissection, and the steepness of the slopes. This coefficient is used in nonparametric statistics and is chosen because the distribution of a number of parameters differs from normal. The assessment of the significance of

Table 1. Relationship between geoenvironment parameters characterizing megafractures and localization of volcanic structures, hot springs, and epicenters of shallow earthquakes in the southeast of Kamchatka

Geoenvironment parameters	Areas with geoenvironment parameters **below** median values		Areas with geoenvironment parameters **higher** median values
	share of volcanic structures	share of hot springs	proportion of epicenters of shallow earthquakes
Density:			
faults	0.85	0.56	0.88
lineaments	0.70	0.65	≤0.5
watercourses	0.57	≤0.5	≤0.5
Depth of vertical dissection of the relief	0.54	0.64	0.55
Steepness of slopes	0.52	0.67	0.58
Predominant deformations	Plastic		Fragile

the correlation relationship was carried out by comparing the calculated (t_{calc}) and critical (t_{Crete}) values of Student's t-test (Sizova, 2013). In all cases, $t_{calc} \gg t_{Crete}$ for the confidence level $\alpha = 0.99$, so the correlation is significant.

The data on megafractures are compared with information on the location of volcanic structures of different scales (from large stratovolcanoes to monogenic lava cones, $N = 647$) (Database..., 2024), hot springs ($N = 66$) (Electronic ..., 2024), and shallow epicenters ($h \leq 45$ km) of tectonic earthquakes of magnitude $ML \geq 4.5$ ($N = 78$) (Catalogue..., 2024). The depth limitation is set due to the low information content of geomorphological data for studying processes occurring in the deep subsurface. On the diagrams of the density of faults, lineaments, and watercourses, as well as the depth of vertical dissection of the relief and the steepness of the slopes, positive anomalies are highlighted, where the values of the corresponding parameters exceed the median. The proportion of volcanic structures, hot springs, and earthquake epicenters falling within these anomalies was calculated, which made it possible to statistically assess the degree of relationship between megafractures and hydrothermal–magmatic manifestations and seismicity.

The approach tested on the example of southeastern Kamchatka was also applied to the entire territory of southern Kamchatka—from the Kronotsky Peninsula in the north to Cape Lopatka in the south. Since there are no openly available geological maps at a scale of 1 : 200000, the research was carried out at a survey scale of 1 : 1000000. Data on the configuration of faults and the location of the largest volcanoes ($N =$ 20) are given according to (State..., 1981) and those on the main hot springs ($N = 24$) according to (Geothermal..., 1995). The number of shallow earthquake epicenters considered was 89, and the value used to calculate the depth of vertical dissection was $R = 450$ m.

RESULTS AND DISCUSSION

For the territory of southeastern Kamchatka, it has been established that most volcanic structures and hot springs are located in areas characterized by weakly dissected relief, where the values of the density of faults, lineaments, and watercourses, as well as the depth of vertical dissection of the relief, are below the median. The opposite pattern is typical for the epicenters of shallow earthquakes: they are confined to positive anomalies of the mentioned parameters (places where their values are higher than the median), characterizing megafractures (Table 1).

This nature of the relationship indicates a connection between volcanic structures and hot springs with areas of predominant plastic deformations, in which surface fracturing is not actively manifested. The occurrence of plastic deformations can be explained by the heating of the upper part of the lithosphere, caused by the presence of magmatic chambers under volcanic structures: 88% of such structures are located in areas where the temperature at a depth of 1 km exceeds the median. Seismic tomography data indicate the presence of melts and fluid-saturated environments in the upper crust not only beneath active volcanoes, but also beneath hydrothermal–magmatic systems (Bushenkova et al., 2023).

In turn, the epicenters of shallow earthquakes are confined mainly to areas of increased fragmentation of the geological environment, where brittle deformations predominate. These areas are heated to a much lesser extent than by volcanoes: 95% of epicenters are localized in zones where the temperature value at a depth of

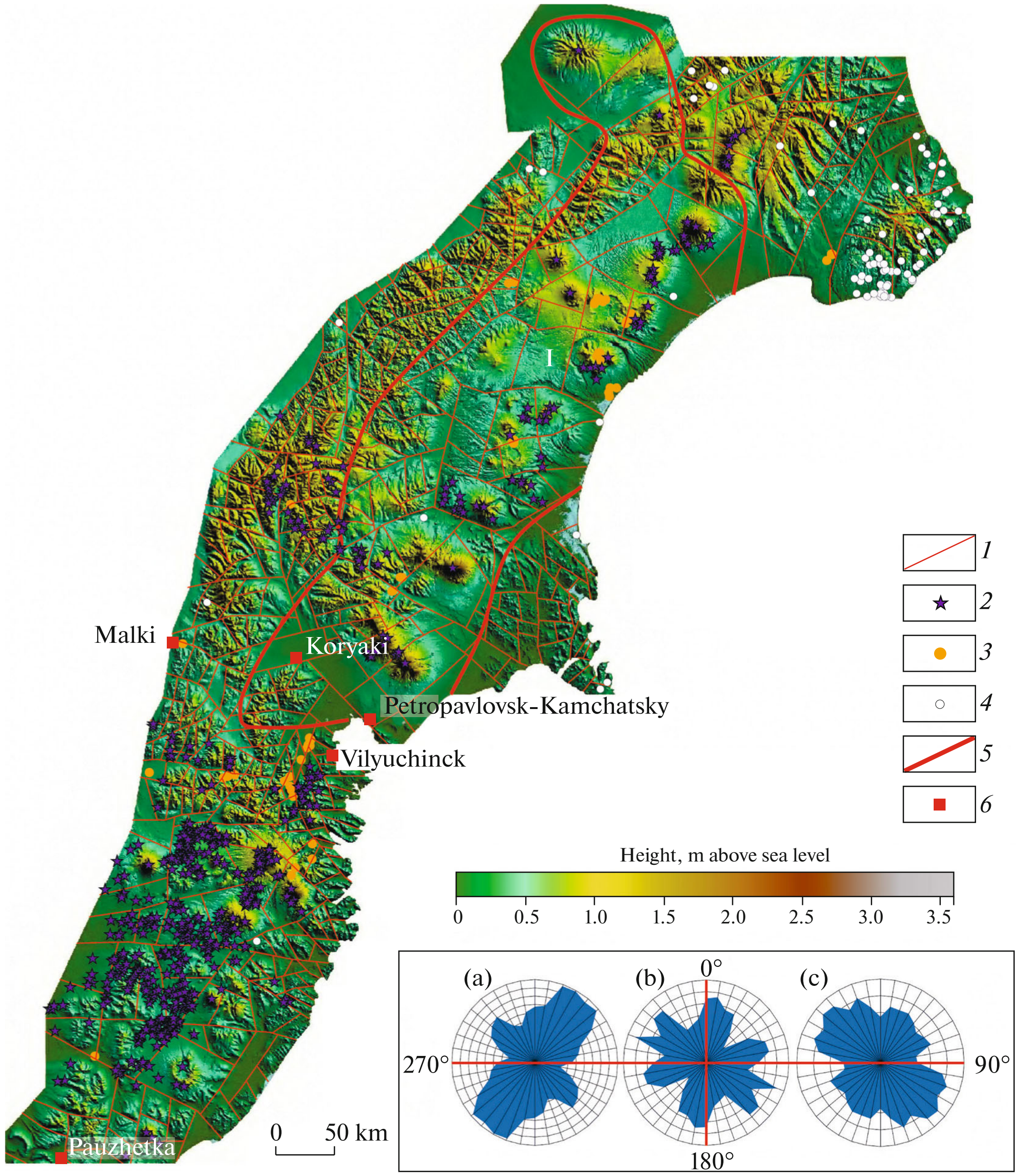

Fig. 3. Scheme of lineaments of southeastern Kamchatka and rose diagrams of fault strikes (a), lineaments (b), and watercourses (c). (*1*) Lineaments, (*2*) volcanic structures, (*3*) hot springs, (*4*) epicenters of shallow earthquakes, and (*5*) the boundary of the Volcanic Highlands (according to (National..., 2007)), and (*6*) populated areas.

1 km is below the median. According to A.I. Kozhurin and T.K. Pinegina (2024), the confinement of most crustal earthquakes and faults to the Kronotsky Peninsula may be associated with varying degrees of deformation of the eastern peninsulas of Kamchatka caused by the collision of the Aleutian Arc.

In addition, a significant (on the Chaddock scale) relationship was established between the density of faults and the expression of lineaments: Spearman's rank correlation coefficient (r) is 0.58. On the rose diagrams of the strikes of faults, lineaments, and watercourses, two main directions are expressed: northwest and northeast, and the average circular values of the strike azimuths are quite close and amount to 74°, 73°, and 88°, respectively (Fig. 3). These data indicate the informativeness of the structural–geomorphological method for identifying areas of brittle and plastic deformations.

A similar result was obtained on a general scale for the entire territory of southern Kamchatka: most volcanic structures and hot springs are confined to areas of low density of faults and lineaments, and shallow earthquakes occur mainly in areas of increased fragmentation, where the density of faults, the depth of

Table 2. Relationship between the parameters of the geoenvironment characterizing megafractures and the localization of volcanic structures, hot springs, and epicenters of shallow earthquakes in the territory of South Kamchatka

Geoenvironment parameters	Areas with geoenvironment parameters **below** median values		Areas with geoenvironment parameters **higher** median values
	share of volcanic structures	share of hot springs	proportion of epicenters of shallow earthquakes
Density:			
faults	0.80	0.54	0.53
lineaments	0.70	0.51	Not correct.
Depth of vertical dissection of the relief	Not correct.		0.76
Steepness of slopes	″		0.74
Predominant deformations	Plastic		Fragile

vertical dissection of the relief, and the steepness of the slopes are higher than the median values (Table 2). Ninety-three percent of earthquake epicenters occur in weakly heated areas, where the temperature at a depth of 1 km is below the median.

In addition, a moderate correlation was established between the density of faults and the depth of vertical dissection of the relief ($r = 0.39$), as well as between the density of faults and the steepness of slopes: $r = 0.38$. These values indicate that faults in the relief correspond to well-defined ledges and steep slopes. However, the similarity of the orientations of faults, lineaments, and watercourses in the territory of southern Kamchatka is significantly less than in the southeast of the peninsula: the average circular values of the strike azimuths are 73°, 55°, and 92°, respectively (see Fig. 1).

CONCLUSIONS

As a result of this research, it was established that the megafractures expressed in the relief of southeastern Kamchatka mark relatively cold areas of predominance of brittle deformations, where most crustal earthquakes occur, while volcanic structures and hot springs are associated with warmer zones of plastic deformations, unfavorable for the development of surface fracturing. This result is interesting from a methodological point of view, since it shows the possibilities of structural–geomorphological and morphometric methods for identifying areas of the earth's crust that are in different geothermal states. In turn, the geothermal state largely determines not only the nature of modern deformation, but also influences the ecological and landscape appearance of the territory as a whole, including its floristic and faunistic features.

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CONFLICT OF INTEREST

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

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