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Developing the Methods for Multidisciplinary Morphometric Analysis of Relief for Assessing the Tectonic Fragmentation of the Interior

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Abstract—The estimation of the degree of tectonic fragmentation for upper lithosphere following the method of Yu.V. Nechaev (2010) is based on calculations of specific lineament lengths. We used data for three regions—Northwest Caucasus, the Voronezh Anteclise, and the Malko—Petropavlovsk zone in Kamchatka—to test whether other morphometric parameters could be used: specific lengths of “weak” zones, elongation lines and water streams, as well as relief curvature. Their anomalies are confined to seismic areas and to areas of hydrothermal and magmatic activity. We show that the most information is provided by 3D models of tectonic fragmentation that incorporate specific lengths of “weak” zones and water stream lengths.

Keywords: tectonic fragmentation, Northwest Caucasus, Voronezh Anteclise, Kamchatka

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INTRODUCTION

The method of Yu.V. Nechaev (2010), which enables estimation of the degree of tectonic fragmentation for upper lithosphere based on the analysis of lineaments seems to us of current interest, because significant scientific and practical results have been achieved using the method, as, e.g., identification of potential magma chambers beneath Elbrus Volcano (Bogatikov et al., 2002) and of a zone of destruction in the Avacha Bay area (Taskin and Sidorov, 2014), new data have been acquired on tectonic discontinuities on Paramushir Island related to manifestations of hydrothermal and magmatic activity (Khubaeva et al., 2020). The goal of this study is to develop Yu.V. Nechaev’s method further by using various morphometric relief characteristics. The importance of this problem is due to the fact that visual interpretation is largely a subjective process, while the morphometric analysis of a digital topographic model (DTM) can be completely (or to a considerable extent) made automatic. This study uses data on three regions (Norwest Caucasus, the Voronezh Anteclise, and the Malko–Petropavlovsk zone of tranverse dislocations (MPZ) in southeastern Kamchatka) to test schemes of block divisibility following the method of N.P. Kostenko (1999), of elongation lines, of relief curvature, and water streams to develop 3D models of tectonic fragmentation.

THE MATERIAL AND THE METHODS OF STUDY

Our study is based on the method of Yu.V. Nechaev (2010), which aims at estimating the degree of tectonic fragmentation in the lithosphere from specific lineament lengths. Yu.V. Nechaev understood tectonic fragmentation as the total of all crustal and upper mantle inhomogeneities due to their material composition, structure and evolution over time. He proposed to characterize fragmentation by “total” visual interpretation of lineaments, which are linear topographic elements of non-manmade origin. In spite of the fact that the issue of a geological interpretation of lineaments has not been definitively resolved, the founder of the method remarked on a high efficiency in the use of different devices employed in lineament analysis for understanding the structure of the Earth's crust, primarily for identifying discontinuities. Since the algorithm of "total" visual interpretation has not been fully formalized, we used the procedures of N.P. Kostenko (1999). These procedures subdivided an area of study into several blocks of mostly rectangular or trapeze-like shapes that are bounded by "weak" zones. This term means "zones of cracking, rock crushing, and fractures accompanied by displacements". They are expressed in relief as nearly straight segments of erosion networks, straight contours of lake shores, linearly arranged captures of river valleys, vertical walls and escarpments, and pedestals of steep slopes. These geomorphologic signs of "weak" zones are considered in more detail in the monograph of Panina (2019).

The Nechaev method is based on the fact that cracking observed at one face of a cubic specimen reflects the degree of cracking for the entire specimen. The geological medium is seen as a multitude of cubic blocks with an edge of length a. The cracking of the upper face in each cube is estimated by visual interpretation of lineaments, while the specific lineament length equal to the ratio l/a^2 (where l is the total length of the lineaments in a cell of size a) is an indicator of tectonic fragmentation at depth $a/2$. This relationship between the depth and size of a cell was found in an empirical way. We thus see that the variation of a enables the researcher to characterize tectonic fragmentation at different depths.

We wish to note that lineament lengths are also used to estimate stresses in the geological medium, in addition to determining the degree of fragmentation. This method was developed by P.N. Nikolaev (1992) and implies ranking the faults (and the lineaments) into several classes in relation to their lengths; the next step is to reconstruct the paths of the principal normal stress axes for each class corresponding with a definite level of depth.

Northwest Caucasus, the Voronezh Anteclise, and the MPZ were chosen as objects of study based on the following considerations: (1) these areas are substantially different as to geology and geomorphology; (2) detailed studies have been carried out for the seismicity of Northwest Caucasus and for the Voronezh Anteclise, in addition to present-day occurrences of hydrothermal and magmatic activity in the MPZ; (3) our previous studies (Agibalov et al., 2021, 2023) provided reasons for the selection of morphometric relief parameters related to the seismic zones of Northwest Caucasus and the Voronezh Anteclise, as well as to areas of hydrothermal and magmatic processes in the MPZ. We note that the seismicity of this last is not analyzed in the present study, because we know of more than 500 earthquake epicenters in this small area (*Katalog ...,* 2023), which enables us to treat it as a connected seismic area. The locations of earthquake epicenters in Northwest Caucasus and in the Voronezh Anteclise follow the composite seismological catalog incorporating the data from (Nadezhka et al., 2010; Rogozhin et al., 2014; *Seismologicheskii ...,* 2023; Ulomov and Medvedeva, 2022), the locations of volcanic edifices in the MPZ are based on geological maps to scale 1 : 200000 (*Geologicheskaya ...,* 2000a, 2000b, 2013, 2016), and hot springs are given in accordance with the topographic map in (*Elektronnaya ...,* 2023).

We know that the specific length (and density) of lineaments is a geomorphologic parameter related to geological structure, seismicity, and neotectonic morphostructural plan. Along with it researchers are using other morphometric parameters to identify dislocations that are expressed in relief and which were formed under the influence of tectonic processes. These other parameters include, e.g., slope steepness and the depth of vertical relief dissection (Spiridonov, 1975). In this study we estimate tectonic fragmentation using only those morphometric parameters that are related to geological structure and seismicity, and have a metric dimension, since in the "traditional" method of Nechaev (2010) the total lineament length (m, km) is divided by the cell area that is measured in m^2 or km^2. Such parameters include specific lengths of "weak" zones (ε_1), of elongation lines (ε_3), and of water streams (ε_4, km^{-1}), as well as the ratio of the absolute value of total relief curvature to the cell area (ε_2, m^{-3}). The character of mega cracking largely controls the spatial pattern of perennial and temporary water streams (Manuilova, 2022), hence we calculated their specific lengths (ε_4) in order to find the degree of tectonic fragmentation. That quantity reflects the degree of lateral relief dissection (Simonov, 1999). At the same time visual interpretation identifies "weak" zones based primarily on the longest linear relief depressions corresponding with larger water streams, while larger values of ε_4 can be related, not only to the presence of several large water streams, but also to numerous smaller ones. The total length that is used to find ε_4 does not detect these differences, and this produces discrepancies between the use of ε_1 and ε_4. Elongation lines show the change in the mean strike of lineaments, "dashes" (Zlatopolsky, 2007): the configuration of these lines is very similar to the pattern of a lineament field and river networks, but the automated algorithm employed to plot elongation lines enables the researcher to treat ε_3 as a morphometric parameter in its own right. In the general case the relief curvature is a parameter that characterizes relief dissection. The ArcGis environment finds it using the "Curvature" tool as the second derivative of relief. Its positive values indicate that the surface is convex, negative values tell us that it is concave, while zero values reflect the fact that it is a plane (Damshevich, 2017). Areas with

Table 1. Pearson's correlation coefficient for different morphometric relief parameters in Northwest Caucasus calculated in 40 × 40-km cells (N = 272)

	SL of "weak" zones, km^{-1}	SL of elongation lines, km^{-1}	ε_2, m^{-3}	SL of water streams, km^{-1}
SL of "weak" zones, km^{-1}	1	0.76	0.69	0.73
SL of elongation lines, km^{-1}	0.76	1	0.71	0.73
ε_2, m^{-3}	0.69	0.71	1	0.50
SL of water streams, km^{-1}	0.73	0.73	0.50	1

ε_2 is the ratio of absolute value of total relief curvature (m^{-1}) to cell area (m^2); SL stands for *specific length*.

high-contrast, deeply dissected relief that is characterized by higher values of ε_1 and ε_4, contain numerous positive and negative landforms whose curvature differs significantly from zero, while being near zero within poorly dissected areas. In the former case the mean value in a cell may be near zero because of opposite signs of curvature (positive or negative). In order to detach ourselves from this, we calculated the absolute values of total curvature in cells of varying size.

The basic data for structural geomorphologic and morphometric studies was furnished by a SRTM DTM with resolution 3 angular seconds (*Tsifrovaya ...,* 2022), as well as by topographic maps of Northwest Caucasus and the Voronezh Anteclise to scale 1 : 1000000 and a map of MPZ to scale 1 : 200000 (*Elektronnaya ...,* 2023). These were used to plot digitized water streams. The elongation lines were identified in automatic mode by A.A. Zlatopolsky's LESSA program (Zlatopolsky, 2011). Relief curvature was determined by the ArcGis program. Its standard tools were also used to find the parameters ε_{1-4}. Cells with sizes 10, 20,... 80 km were chosen for Northwest Caucasus and for the Voronezh Anteclise, these being large areas, and cells of 5, 10, ... 20 km for the relatively small MPZ, which enabled us to estimate the degree of tectonic fragmentation in the depth ranges 5–40 and 2.5–10 km, respectively.

RESULTS AND DISCUSSION

The profiles illustrating the degree of tectonic fragmentation in Northwest Caucasus and Ciscaucasia show a positive anomaly in ε_{1-4} observed beneath the folded mountain edifice throughout the entire range of depth 5–40 km (Figs. 1, 2). Corresponding with it we find a region of lower rock density recorded beneath the axial part of the Greater Caucasus by the method of microseismic sounding, MMS (Gorbatikov et al., 2015; Rogozhin et al., 2014). The MMS profiles reveal the region as an extensive, wedge-shaped (in cross section) low velocity body (up to –5 dB relative to the regional velocity model) whose top lies at a depth of ~5 km (Rogozhin et al., 2014). The region was also identified by Nechaev (2010) in vertical cross sections of the tectonic fragmentation field. The well-expressed maximum in ε_3 that occurs in the middle of profile IV (see Fig. 2) is confined to the Stavropol Upland which shows higher seismicity compared with Ciscaucasia. The maximum is not observed at the other profiles, which can probably be accounted for by some peculiarities in the method employed to construct elongation lines oriented both along linear lows and along uplifts (mountain ranges). The "weak" zones are mostly related to negative topographic forms that have been developed by river action, while the local maximum in ε_2 lies east of the profile line near the town of Stavropol where the DTM (Fig. 1) shows a region of sufficiently dissected relief (compared with the other area of Ciscaucasia). We note mutual consistency between the voxel models developed for the region, which is supported by an appreciable and high (on the Chaddock scale) numerical correlation between calculated morphometric relief characteristics (Table 1).

The area of the Voronezh Anteclise shows a complicated distribution of the four morphometric parameters considered here over area, but the general feature consists in the fact that positive anomalies in ε_{1-3} are confined to the middle of the region (the Voronezh town area). It is characterized by higher seismicity (Fig. 3) and by small-block structure: geophysical data show small (in area) crustal blocks bounded by faults. The blocks have varying compositions, ranging from granitoid to metabasite (*Litosfera ...,* 2012). On the regional scale this accumulation of faults and epicenters of low magnitude earthquakes is confined to the S-shaped bend in the boundary between the Kursk megablock and the Losevo suture zone treated as an active tectonic center (Efremenko, 2011). The contours of the positive anomaly (parameter ε_2) are wider in the middle of profile III (Fig. 3) than those at profile II (parameter ε_1). In our opinion, this southeastward expansion is in agreement with the character of the seismicity, with the southeastern part of the anteclise showing higher seismicity compared with the northwestern part where some isolated earthquakes have been recorded (see Fig. 3). At profile IV (parameter ε_3), instead of one large anomaly shown at profile III there are two smaller ones (the western and the

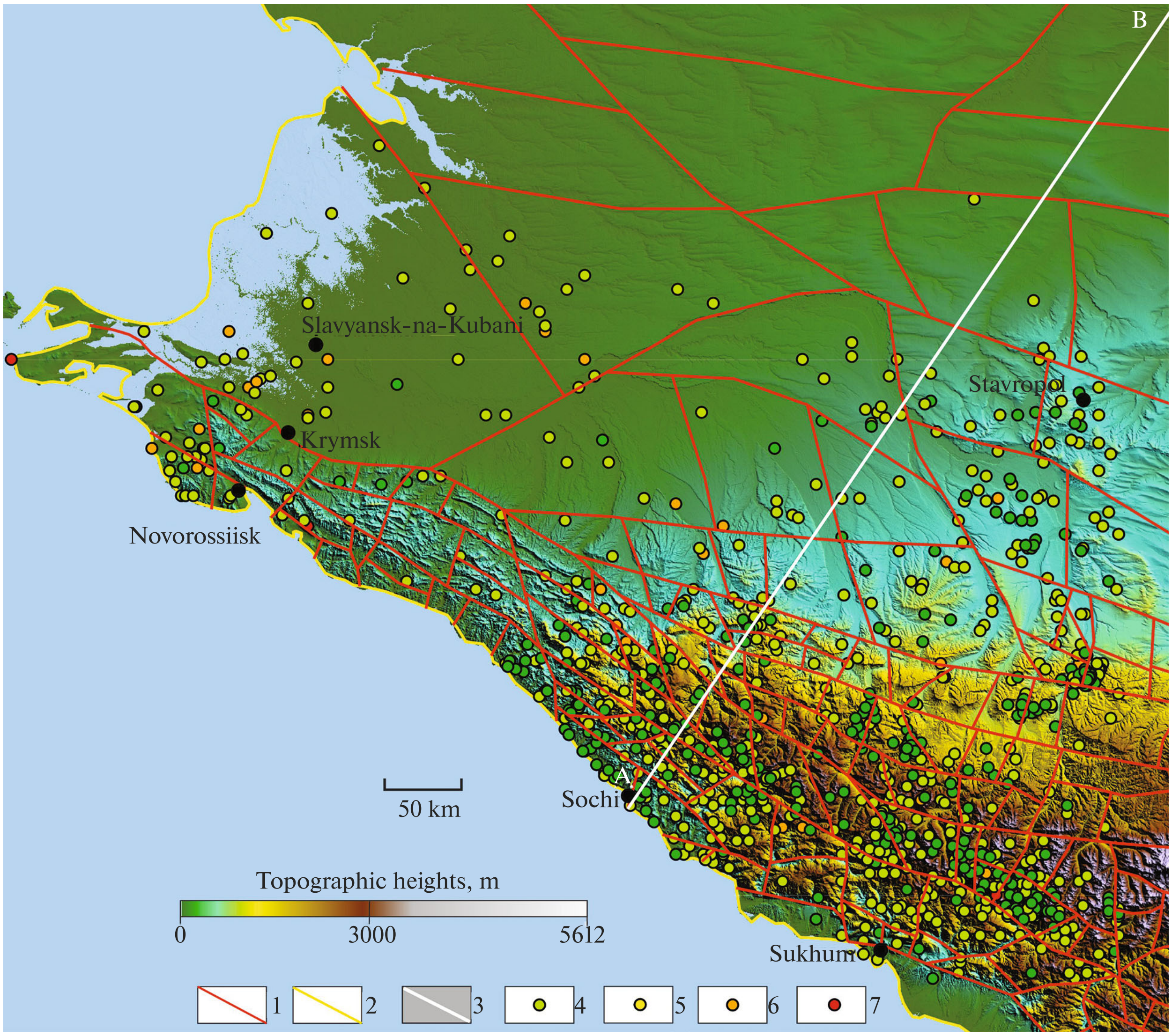

Fig. 1. A sketch map showing “weak” zones in Northwest Caucasus. (1) “weak” zones; (2) shoreline; (3) line of profile; (4–7) epicenters of earthquakes with surface wave magnitudes (M_S): (4) <2, (5) 2–4, (6) 4–6, (7) 6–7.2.

eastern), which coalesce at a depth of ~30 km. The western anomaly marks the abovementioned area of concentrated earthquake epicenters in the area of the town of Voronezh, while the eastern corresponds with the southeastern segment of the Oka–Don megablock (Efremenko, 2011). Overall, the megablock is active enough, although to a lesser degree compared with the Middle Russian megablock. In addition, a positive anomaly in ε_3 occurs in the northwestern part of the profile: the cluster of elongation lines in the Bryansk–Smolensk location corresponds with an interblock boundary of rank II that separates the northeastern and southwestern parts of the Smolensk crystalline basement block (Tregub, 2006). This is not a seismically active feature, but the results of our previous tectonophysical modeling using equivalent materials suggest possible active cracking in the area, since tension faults were formed during the experiment in a shear stress field with the axis of compression striking at azimuth 315° along northwest trending inhomogeneities. Judging from geomorphologic data, this type of external load occurs during the neotectonic phase of evolution in the anteclise area (Agibalov et al., 2022).

Profile V is substantially different from similar profiles (I–IV), since negative ε_4 anomalies occur in its central and southeastern parts. We previously interpreted these areas as ones of active geodynamics based on a set of geomorphologic features (increased depths of vertical dissection, slope steepness, and the density of orthogonal lines), as well as in consideration of the character of seismicity (Agibalov et al., 2022). It may be surmised that the low specific length of water streams in these areas is due to the fact that the degree of riverbed tortuousness is greater under quiet tectonic

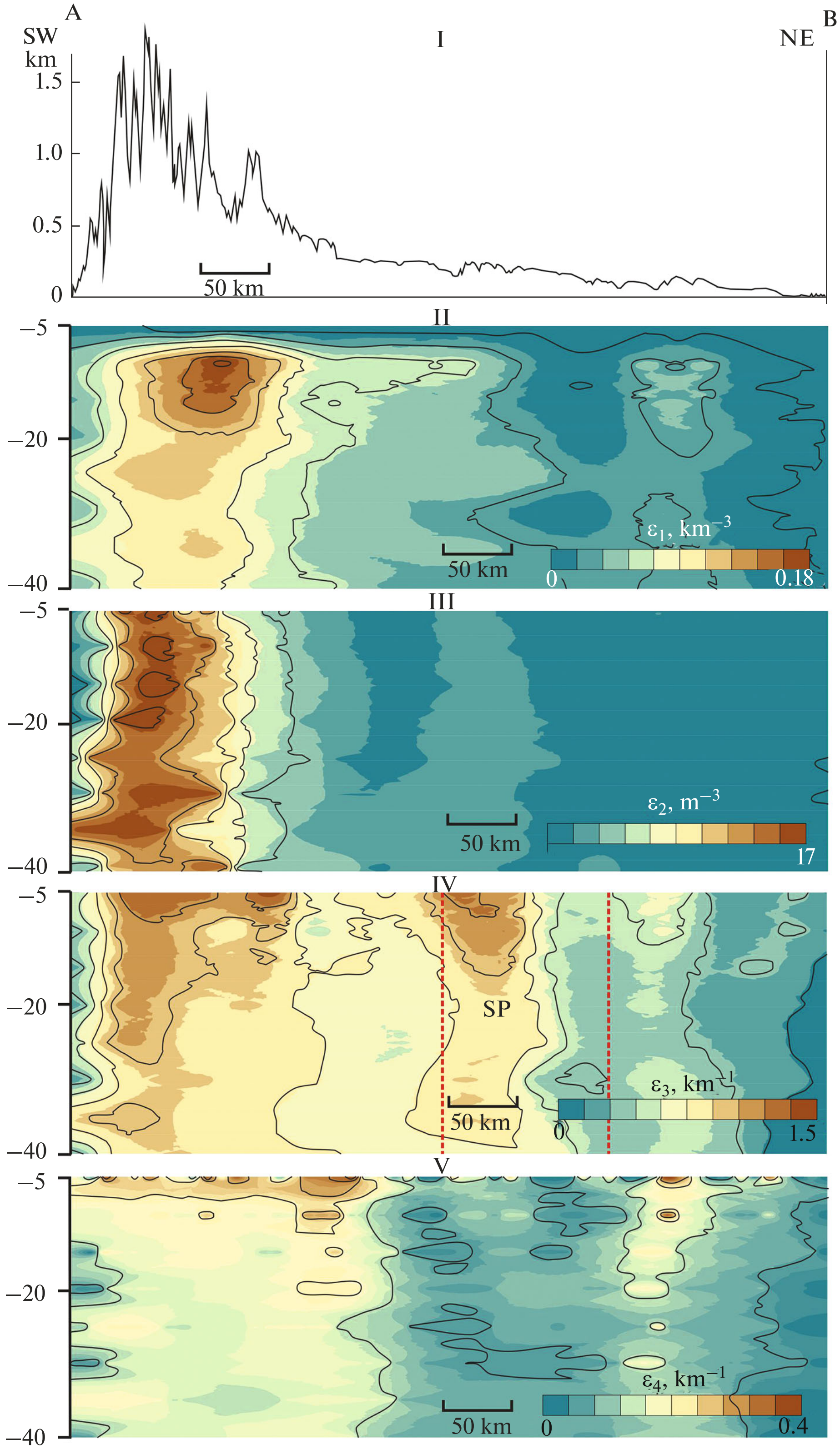

Fig. 2. Relief profile for Northwest Caucasus along line A–B (I) and vertical cross sections across the field of tectonic fragmentation as estimated from the specific length of "weak" zones (II, interval between isolines is 0.03 km^{-1}), relief curvature (III, interval between isolines is 3 m^{-3}), specific length of elongation lines (IV, interval between isolines is 3 km^{-1}) and of water streams (V, interval between isolines is 0.1 km^{-1}). SU denotes Stavropol Upland, after (Milyukov et al., 2022).

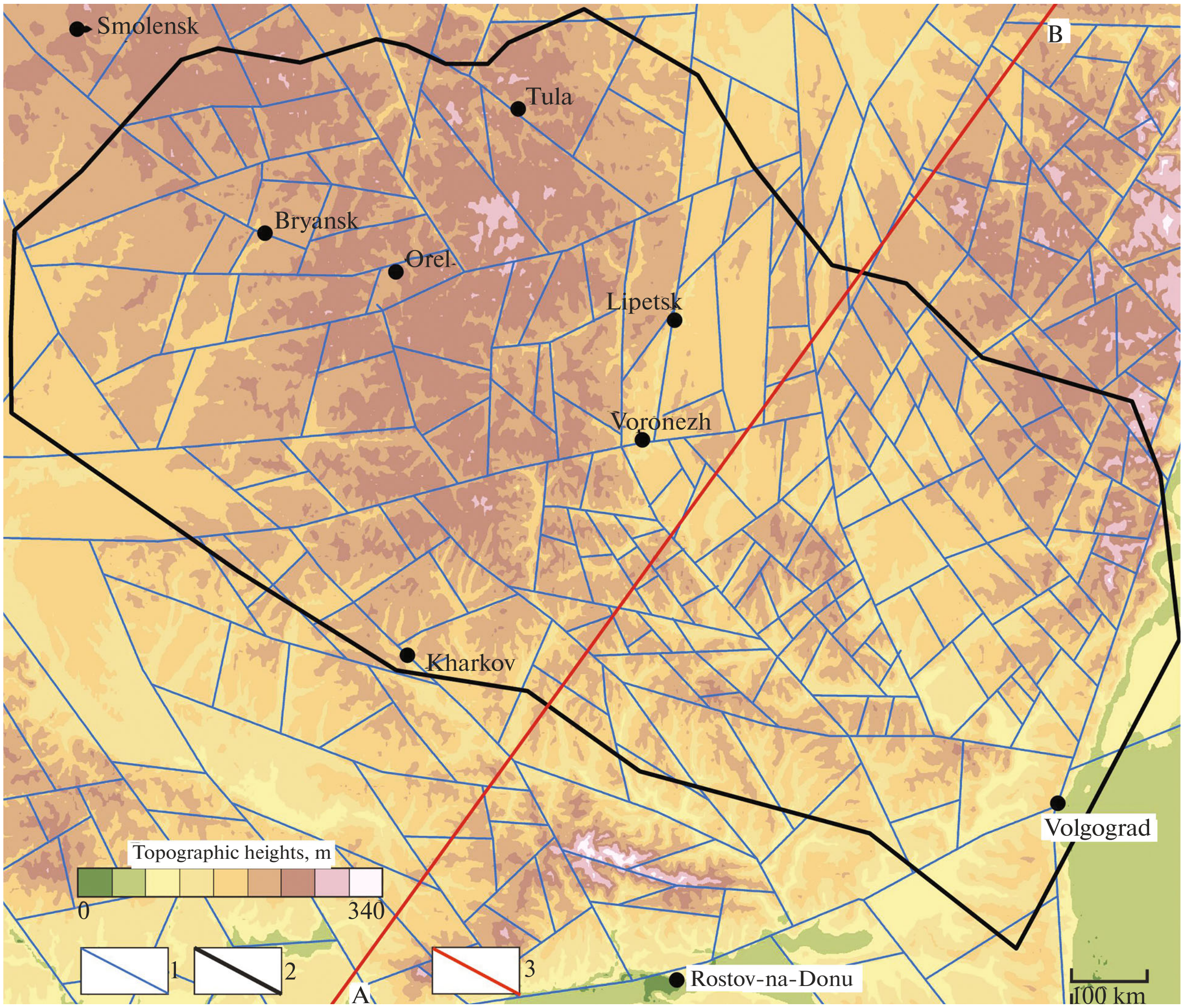

Fig. 3. A sketch map of "weak" zones in the Voronezh Anteclise. (1) "weak" zones; (2) boundary of the anteclise; (3) profile line; (4–7) epicenters of earthquakes with surface wave magnitudes (M_S): (4) <1, (5) 1–2, (6) 2–3, (7) 3–4.

conditions (Panina et al., 2019), hence the total stream length is greater in the cells. In addition, the straighter river valleys can be in part explained by the configuration of the active faults considered in the database (Zelenin et al., 2022).

A morphometric analysis of the relief showed that the parameters ε_{2-3} are not information-rich for understanding mega cracking in the MPZ, because its relief is largely due to volcanic processes, and the elongation lines run concentrically around stratovolcanoes (Avachinsky, Koryaksky, Vilyuchinsky, and Bakening). It is to these that the larger anomalies in relief curvature are confined. At the same time structural geomorphologic interpretation to scale 1 : 200 000 and the calculation of specific stream length based on topographic maps of the same scale have enabled researchers to identify regional zones of mega cracking that are frequently related to the valleys of large rivers like the Malki, Avacha, and Paratunka. Positive anomalies in ε_1 and ε_4 were used to detect areas of higher cracking in the northeastern and southwestern parts of the MPZ where there are most monogenic volcanic edifices that are nearly unexpressed in the DTM and most thermal springs. These zones can be clearly followed along the profiles (Fig. 5) down to a depth of 10 km. We note a high numerical correlation between point elements of the voxel models based on ε_1 and ε_4: Pearson's correlation coefficient is equal to 0.86 (N = 2388). In more detail the relationships between the two areas of higher cracking that we have identified from geomorphologic criteria and the geological structure are described in (Agibalov et al., 2023).

It thus appears that the greatest consistency between the values of ε_{1-4} is characteristic for Northwest Caucasus. This is explainable by a contrasting

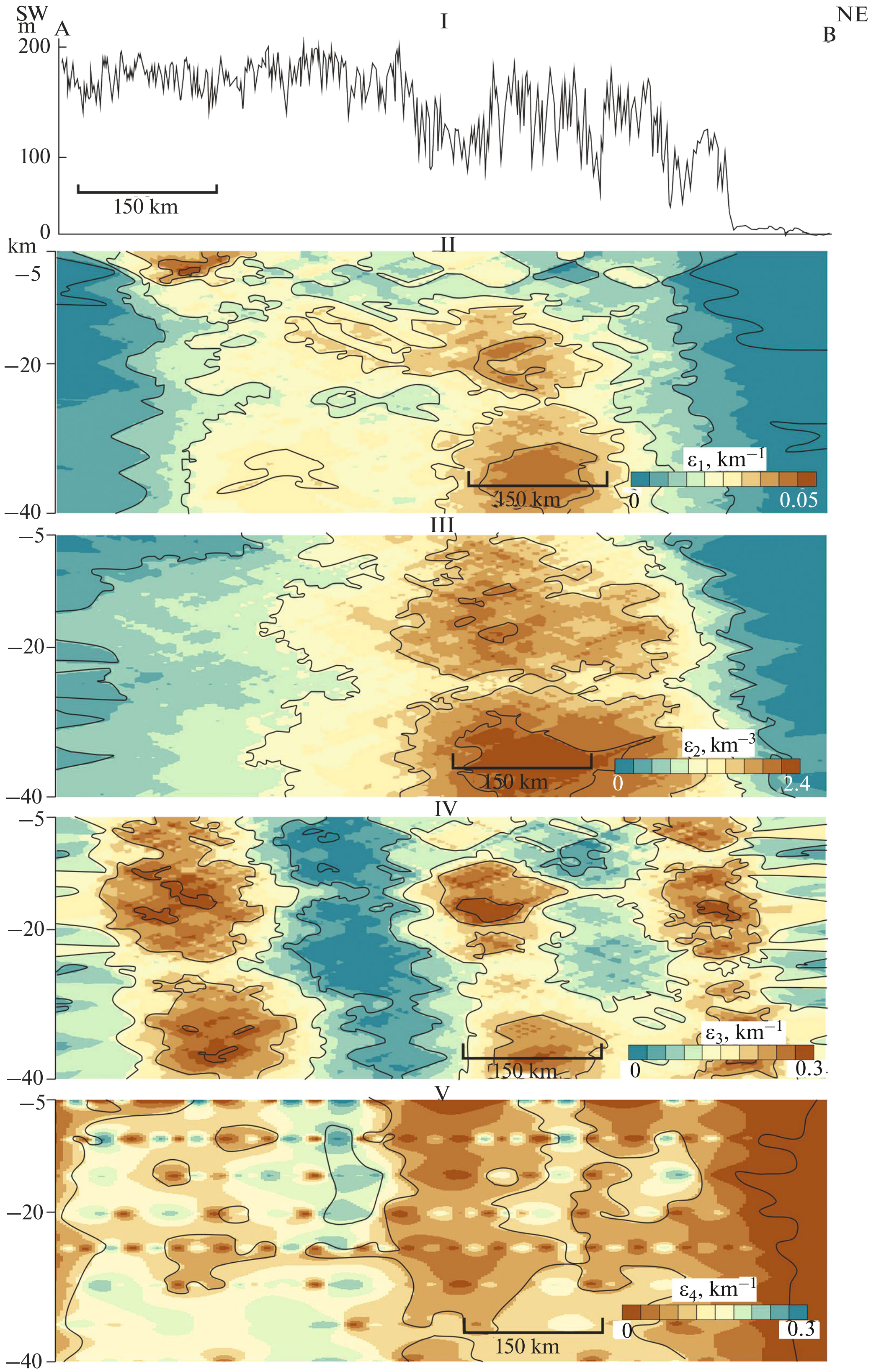

Fig. 4. The profile of relief in the Voronezh Anteclise along line A–B (I) and vertical cross sections across the field of tectonic fragmentation as estimated from the specific length of “weak” zones (II, interval between isolines is 0.01 km^{-1}), relief curvature (III, interval between isolines is 6 m), specific length of elongation lines (IV, interval between isolines is 0.1 km^{-1}) and of water streams (V, interval between isolines is 0.1 km^{-1}).

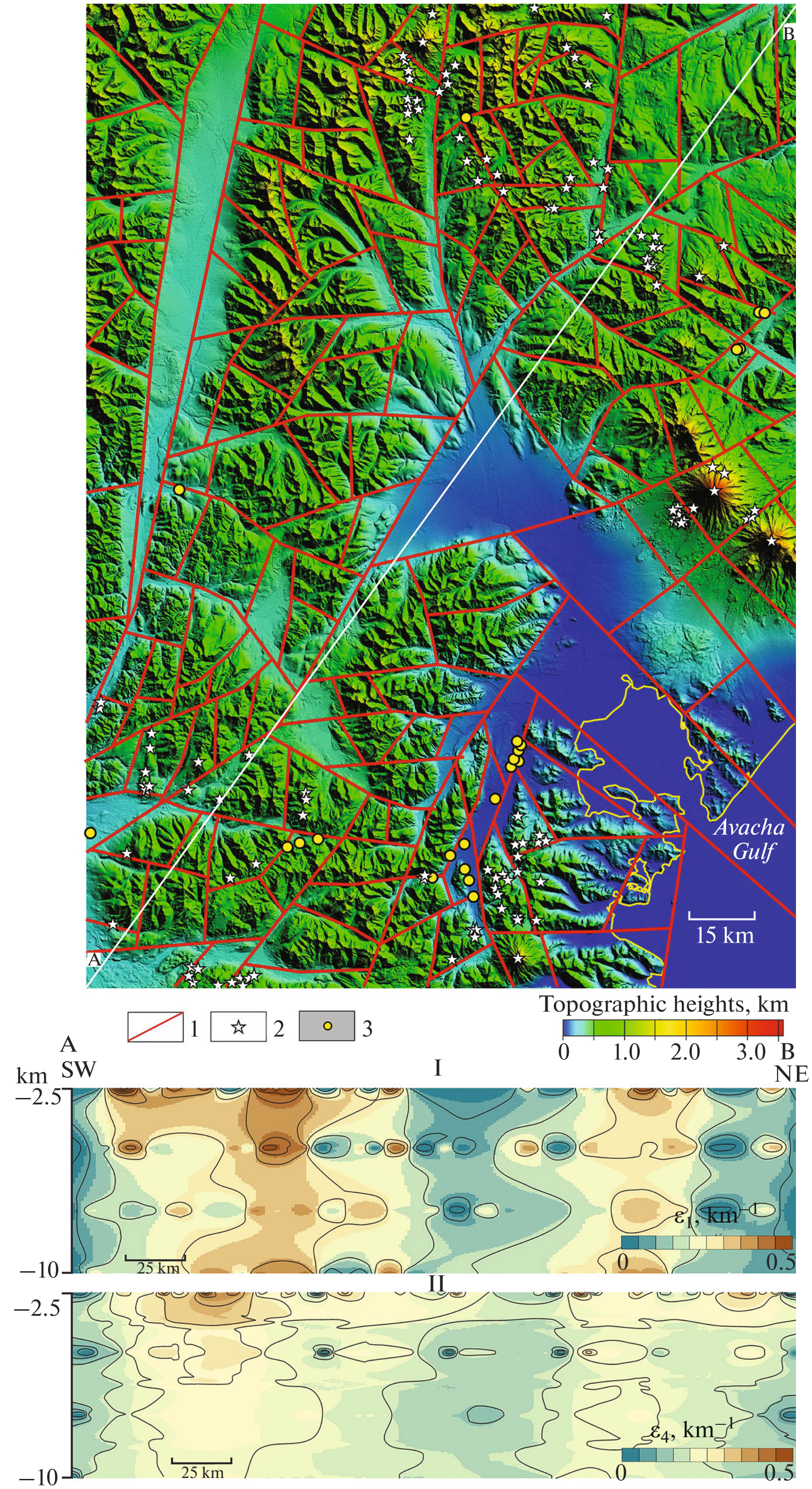

Fig. 5. A sketch map showing "weak" zones in the Malko–Petropavlovsk zone of dislocations. (1) "weak" zones, (2) volcanic edifices, (3) hot springs; (I) vertical cross section of the model of tectonic fragmentation based on the specific length of "weak" zones, (II) vertical cross section of the model of tectonic fragmentation based on the specific length of water streams.

high mountain relief in which well-pronounced "weak" zones occur in maps of different morphometric parameters—slope steepness, river network, and relief curvature. This feature also ensures consistency between the models of tectonic fragmentation in the MPZ based on values of ε_1 and ε_4. We also note that neotectonic movements in both regions serve as one of the leading factors for relief formation. The Voronezh Anteclise shows considerably lower consistency between different models of tectonic fragmentation among themselves compared with Northwest Caucasus and the MPZ. In our opinion, this is due to the fact that the relief is a plain there in which hypothetical zones of cracking and fragmentation are less pronounced. The tectonic movements in the area were not as intensive, hence their role as a factor in relief formation is lower compared with Northwest Caucasus and the MPZ. It is due to this that the pattern of "weak" zones, water streams, and elongation lines is a less clear reflection of tectonic fragmentation, and is largely due to exogenous relief-forming factors such as different stabilities of rocks under denudation. In the general case the differences between various models of tectonic fragmentation are explainable by the methodologies employed to develop them: the morphometric parameters used here are independent of one another, with each reflecting the surface fragmentation of the geologic environment to a certain degree only. It seems that the degree is controlled by the intensity with which tectonic factors and deformations affect the relief.

CONCLUSIONS

Three regions were used to test a set of morphometric parameters (the specific lengths of "weak" zones, elongation lines, water streams, as well as relief curvature) to estimate tectonic fragmentation in a volume of the geological medium. Based on these geomorphologic characteristics, we have identified areas of increased tectonic fragmentation of the lithosphere beneath the folded mountain edifice of Northwest Caucasus and the central part of the Voronezh Anteclise corresponding with areas of highest seismic activity. Increased specific lengths of elongation lines also occur in active morphostructures at a more local scale level, namely, the Stavropol Upland and the interblock boundary of rank II in the territory of the Voronezh Anteclise. However, the zones of cracking lying in the southwestern and northeastern MPZ, and which are characterized by high present-day hydrothermal and magmatic activities, correspond with positive anomalies in only two parameters, viz., specific lengths of "weak" zones and water streams. These are therefore informative for understanding the field of tectonic fragmentation for all regions studied here, hence their use to develop relevant 3D models is a priority.

ABBREVIATIONS AND NOTATION

DTM	digital topographic model
MPZ	Malko–Petropavlovsk zone of transverse dislocations
KB	Kamchatka Branch
FRC	Federal Research Center
MMS	Method of microseismic sounding
UGS	Unified Geophysical Survey
RAS	Russian Academy of Sciences
SL	Specific length

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CONFLICT OF INTEREST

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

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