

The Fractal Geometry of the River Network and Neotectonics of South Sikhote-Alin

V. S. Zakharov^{a, *}, D. A. Simonov^{a, **}, G. Z. Gilmanova^{b, ***}, and A. N. Didenko^{b, c}

^a*Department of Geology, Moscow State University, Moscow, 119991 Russia*

^b*Kosygin Institute of Tectonics and Geophysics, Far Eastern Branch, Russian Academy of Sciences, Khabarovsk, 680000 Russia*

^c*Pacific State University, Khabarovsk, 680035 Russia*

**e-mail: zakharov@geol.msu.ru*

***e-mail: dsim_0@mail.ru*

****e-mail: gigulya@yandex.ru*

Received November 20, 2019; revised February 20, 2020; accepted July 23, 2020

Abstract—The proposed complex Parameter of River Network Self-similarity (PRNS), which is a combination of the exponents in the equations for distribution of channel lengths, the fractal dimension of channels, and the fractal dimension of points of change of the order of the channel, matches neotectonic movements more accurately. A comprehensive analysis of the self-similarity of the southern Sikhote-Alin River network model derived from the Digital Elevation Model (DEM) based on the Shuttle Radar Topography Mission image (SRTM) has been performed. Comparison of the results of morphostructural and fractal analyses showed the good consistency of these two methods. The relative PRNS maxima coincide with areas with the largest amplitude of ascending neotectonic movements (increment of relief), while the minima coincide with the areas either with the lowest increment of relief or with greatest erosion rates. Most of the crustal earthquakes are confined to the boundaries between PRNS relative maxima and minima, that is, uplifts are surrounded by seismic areas, which is due to the block nature of neotectonic vertical movements.

Keywords: river network, neotectonics, fractal and morphostructural analyzes, southern Sikhote-Alin, Russian Far East

DOI: 10.1134/S181971402006007X

INTRODUCTION

In two previous articles [6, 33], we carried out a comprehensive analysis of the self-similarity of seismicity areas and a network of faults within the Sikhote-Alin orogenic belt and adjacent areas. One necessary step for identifying the general structure and nature of seismic-tectonic movements in seismically hazardous regions, e.g., in the south of the Russian Far East, is to compare data on seismicity with those on the modern tectonic movements. This is all the more important, since such a comparison would distinguish the role of secular neotectonic processes (epeirogenesis and isostasy) and that of the “instantaneous” seismotectonic vertical and horizontal displacements of crustal blocks. GPS observations carried out in the south of the Russian Far East over the recent 15 years confirm and significantly supplement the ideas about the latest tectonics of the region. After the Tohoku Earthquake (2011) with a magnitude of 9.1, the data obtained at ten stations of the GNSS network of the Far Eastern Branch of the Russian Academy of Sciences, have shown that the coseismic displacements in the continental part of the Russian Far

East reach maximum values (~4 cm) in the south of Primorye and decrease towards the north [5]. The work [5] considered horizontal displacement; however, after the accumulating and processing substantial amount of data, the vertical movements were also established. The northern, eastern and vertical components of the coseismic displacement for the ZMEY point (coordinates 48.10° N and 135.59° E) were found to be -10 ± 2 , $+5 \pm 2$, and -8 ± 4 mm, respectively [20]. As indicated in [20, 27], during earthquakes with a magnitude of 8 or more the area of irreversible coseismic displacements extends over more than 1000 kilometers. A selection of the strongest earthquakes in an area of 35°–55° N and 130°–150° E (Fig. 1a) from the beginning of the last century to October 19, 2019, from [29], showed that 105 earthquakes with a magnitude of 7 or more occurred in this area, including 11 crustal earthquakes with a magnitude of 8 or more. We believe that the deformation waves that resulted from the largest seismic events, both those that were recorded and those that occurred before the period of instrumental observations, sig-

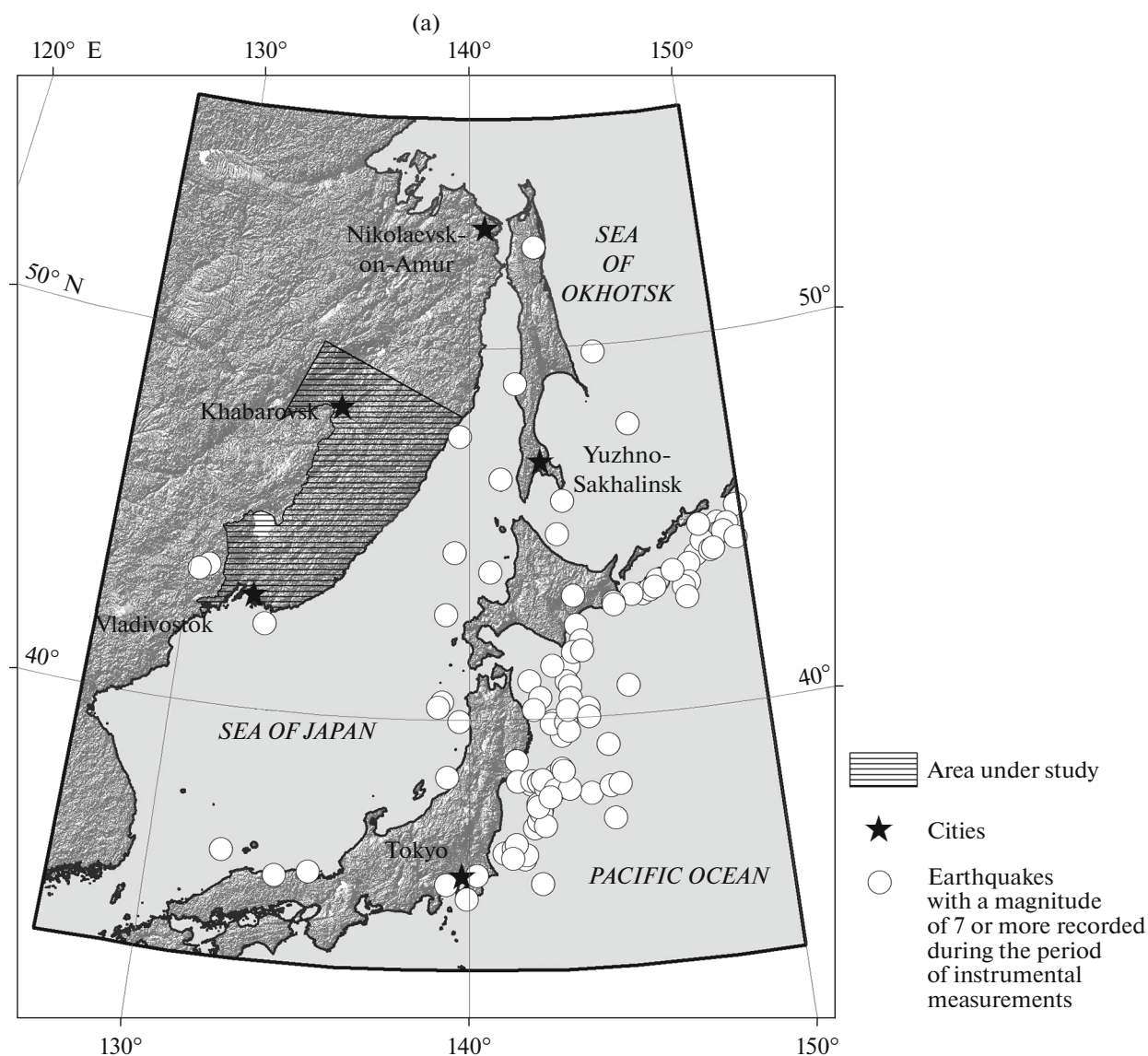


Fig. 1. The river network of the studied area: (a) map; (b) model.

nificantly affected the neotectonic regime of the Sikhote-Alin region.

In the recent 20 years, few studies have been conducted on the neotectonic movements of the Sikhote-Alin Orogen; these are the works of Garkusha et al. [4], Korotkii et al. [10] and Onukhov and Merkulova [15], as well as a small section written by Myasnikov in a collective monograph [3]. All these works indicate that after the end of the Mesozoic stage of the region evolution, as determined by subduction and accretion, in the Cenozoic time the area was involved in an orogeny, which was most intensive in the Pliocene and Quaternary times and was associated with block movements [4].

It has been repeatedly shown that fractal analysis of the river network pattern can be used as an additional

independent method for studying neotectonic movements [12, 13, 16, 23, 24, 30]. The river network reacts quite naturally and quickly to the recent tectonic movements; with positive vertical movements the river cuts into the bedrock, with negative vertical movements it accumulates alluvial sediments; and if the territory is stable numerous meanders are formed. It was found that the value of the self-similarity index (fractal dimension) of the river network reflects the network density [12, 13, 16, 24] and there is a tendency towards a general increase in fractal dimension with the relief height [16, 23, 24], as well as a certain correlation with the direction of vertical movements [12, 13, 24, 25]. The fractal approach significantly broadens the scope of quantitative description of river and erosion channel networks. At the same time, there are a number of uncertainties in the application of this type of analysis,

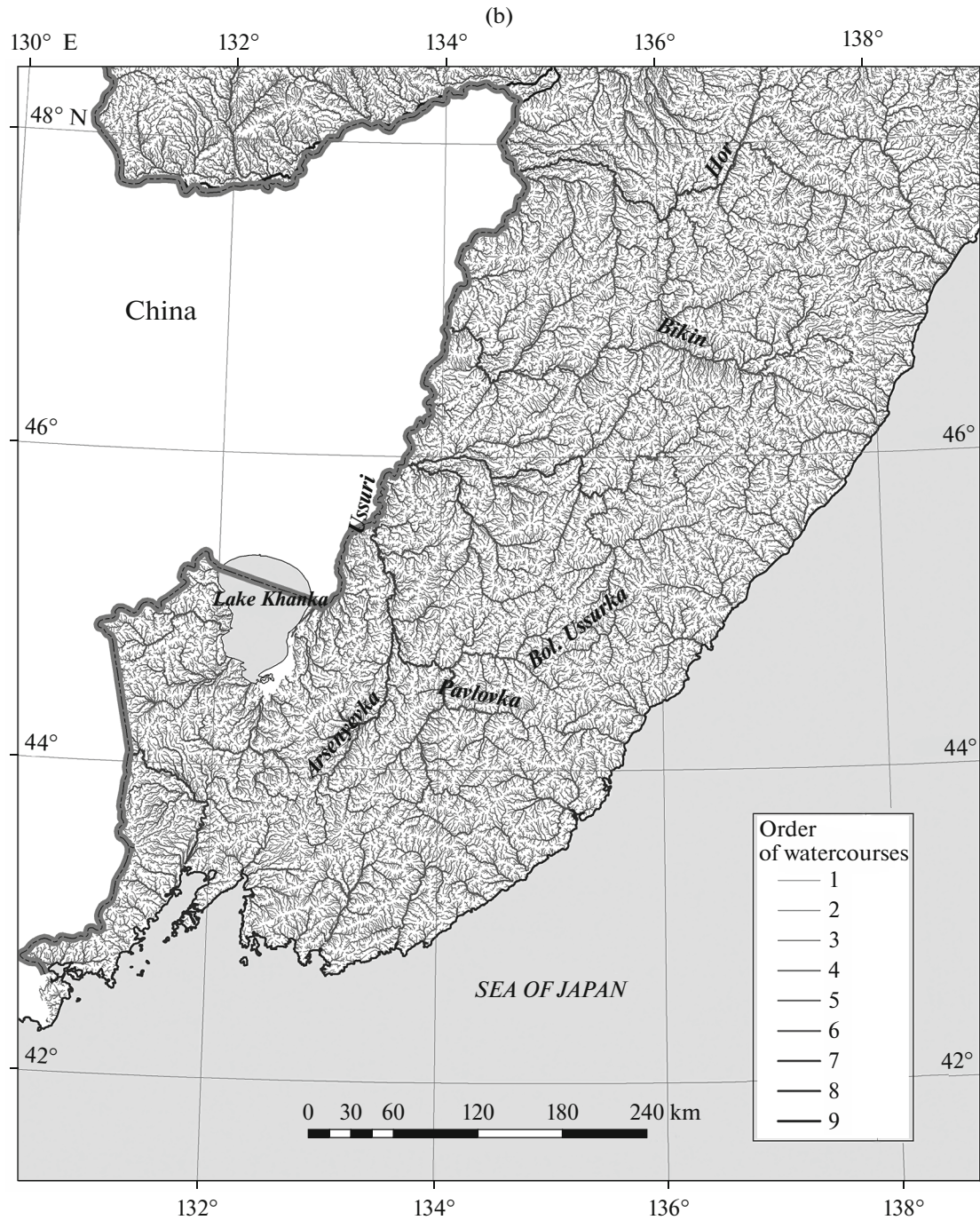


Fig. 1. (Contd.)

including the methodology, the choice of the scale, and the correlation with neotectonics, which makes work in this direction highly relevant. The purpose of the study was to analyze the characteristics of the self-similarity of riverine networks of South Sikhote-Alin (Fig. 1b) and compare its results with the neotectonic features of the region. The results can be used in combination with other data (seismicity, relief, rock and soil lithology, etc.) to predict the landslides, which, as

recent events (a landslide of more than 24 million m³ on the Bureya River on December 11, 2018) have shown, is very relevant for the mountain regions of the Far East.

PROCEDURE AND SOURCE DATA

The river network is formed under the influence of various climatic and hydrological factors, features of

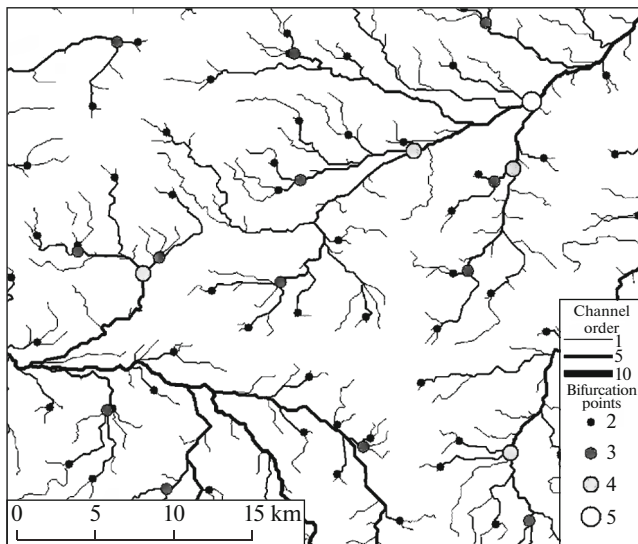


Fig. 2. An example of the classification of watercourse order. Note that the order of the valley increases when two watercourses merge. The thickness of the lines is proportional to the channel order, the circles indicate the points of the change of the channel order (bifurcation); bigger circle size corresponds to a larger order (2, 3, 4, 5).

the geological structure and lithological composition of rocks, fracturing, etc. [1]. A significant, if not decisive, influence is exerted by recent vertical tectonic movements, which makes the river network pattern one of the most sensitive markers of these processes. This pattern has a pronounced property of self-similarity on a fairly wide range of scales. The main relationships that connect the basic parameters of river basins, i.e., the length of a basin of a given order L , the water catchment area A , the basin topography for a stream of a given order R , the number of streams N of given order, and the slope along the stream of a given order S were considered in [8, 11, 21, 28, 30, 31]:

$$N \sim A^p, \quad L \sim A^q, \quad S \sim A^r, \quad R \sim A^s, \quad (1)$$

where p , q , r , s are exponents. In the summarizing work [28], the estimated values of these exponents were given: p varies from -0.99 to -0.95 , q from 0.5 to 0.55 , r from 0.3 to 0.4 , and s from 0.20 to 0.35 . Since all these relationships are exponential, quantitative description of a river network based on the fractal geometry approach can be used in addition to a qualitative analysis.

There are a number of techniques for a direct quantitative assessment of the relationship between the intensity of neotectonic vertical movements and the relief. Most of them, however, are only capable of reflecting the overall direction and amplitude of movements for the entire neotectonic stage, while neotectonic structures can develop unevenly, both spatially and temporally. The amplitude and direction of the newest movements can change over time, the

rate of uplift in different areas and at different time intervals can be different, which has a significant impact not only on the relief, but also on the pattern of the river network. The morphometric method developed by M.F. Filosofov [22] not only identifies active tectonic structures, but also allows their evolution be traced. A comprehensive analysis of the datum surfaces (interpolated surfaces constructed from stream thalwegs of each order) of different order streams allows the stages of topography development, which reflect the evolution of the newest structures, to be traced. This approach, in our opinion, makes it possible to more accurately determine the relation of the latest movements and the latest structures to the pattern of the river network. To study the latest vertical tectonic movements, we chose the method of morphometric analysis, as adapted for neotectonic studies [17]. The river network pattern of the area (Fig. 1b), which was used for subsequent fractal and morphometric analyses, was created on the basis of the SRTM digital topography model (DTM) with a resolution of 90 meters [32] using the so-called eight-direction pour-point model, an algorithm for determining the flow direction in elementary cells used in most modern geographic information systems [24, 26]. Watercourses calculated in this way (Fig. 1b) were divided into orders according to a scheme where the stream order increases by one when two streams of the same order merge (Fig. 2), while merging of two streams of different orders does not lead to an order increase [22, 30]. The analysis considered the watercourses with the catchment area of at least 1300–1400 thousand m^2 (200 unit cells of the DEM SRTM). The streams with indicated catchment areas were assigned to the first order. In total, with the given parameters of the identification of streams within the study area, nine orders were identified. The Amur River was deliberately and conditionally assigned to the 10th order. This assumption does not affect the result, since there is only one 10th order watercourse and it is not included in further processing and analysis.

THE FRACTAL CHARACTERISTICS OF THE RIVER NETWORK

In the course of the study, several characteristics describing the self-similarity of the river network, and a newly proposed complex parameter were determined.

1. The length of watercourses. One of the widespread characteristic is the exponent α in the distribution of the watercourse lengths:

$$N \sim L^{-\alpha}, \quad (2)$$

where N is the number of streams of a given order (or range of orders) and L is their length. When calculating alpha, the $N(L)$ dependence is plotted on a double logarithmic scale; the range of L values, for which the

dependence has the form (2), is then approximated by a straight line:

$$\log N = -\alpha \log L + c. \quad (3)$$

The parameter α characterizes the channel lengths. When the share of the short channels is relatively high, a significant maximum appears in the area of small L values, and then the distribution will rapidly decrease, which is expressed in large values of the parameter α . If the proportion of long channels is relatively large, the distribution will be flatter, which is expressed in smaller values of the α parameter. Since the length of the channels is associated with neotectonic movements (a relatively large number of short channels and a frequent change in order indicates the uplift regime), this parameter quantitatively characterizes the manifestations of neotectonics in the river network pattern.

Let us highlight some features of the method. In our analysis L was defined as the length of continuous channel segment of a given order bounded by two points of order change (or boundaries of the analysis area). A river network constructed as described above may contain channels consisting of separate segments, including the channels of the same order. Therefore, before analyzing the lengths, one should carry out a preliminary procedure for combining channels of the same order into connected segments. When the distribution of lengths in a small area (or in a sliding window) is considered, connected sections of high-order channels may go beyond the size of the window. This leads to distortion of the length distribution: there is a certain "deficit" of large lengths. Therefore, it is advisable to carry out this analysis for the channels with average lengths not exceeding the size of the averaging window. The share of high-order channels, as noted above, is extremely small.

The calculation of the α parameter for the entire study area in the range of scales 2–100 km is shown in Fig. 3a, $\alpha = 3.07 \pm 0.08$ (correlation coefficient $r = 0.98$).

2. The self-similarity of the river network. To characterize the self-similarity of the river network the fractal dimension $2D$, which is an exponent in the power law, was calculated:

$$N \sim \delta^{-D}, \quad (4)$$

where δ is the scale and N is the number of elements of a given scale, which reflects the measure of self-similarity and complexity of the considered hierarchical structure. The self-similarity is estimated by the range of scales where the homogeneous power law is fulfilled and the relative degree of complexity is determined by the absolute value of the fractal dimension.

The measure of self-similarity can be estimated for both linear and point objects and their aggregates (sets). A set of linear objects on a plane is characterized by a fractional dimension in the range from 1 to 2;

the possible range of D values for point sets varies from 0 to 2. The more complex a fractal is and the more densely its elements fill the space the closer its dimension is to 2.

In the course of this work, we estimated the fractal dimension of the river network in two complementary versions: (1) the pattern of the river network as such (D_r) and (2) the set of channel bifurcation points (D_b). To calculate the fractal dimension D , we used the box dimension method [11, 21], when the object under study is covered by a grid with a cell side equal to δ . With each subsequent covering, δ changes (for example, by a factor of 2); the number of cells N required for this is calculated for different values of δ . As in the calculation of α , the dependence $N(\delta)$ is plotted on a double logarithmic scale and the scaling region is approximated by a straight line:

$$\log N = -D \log \delta + c. \quad (5)$$

The slope of the line makes an estimate of the fractal dimension D and c is a constant.

Each section of the channel involved in calculation and analysis of the fractal dimension of the river network, was regarded as a structureless linear object. The fractal dimension D_r for the entire area studied in the range of scales of 5–160 km was found to be 1.83 ± 0.05 with a correlation coefficient $r = 0.99$ (Fig. 3b). The increased value of the fractal dimension of the channel network pattern can be associated with the tortuosity and roughness of the lines, as much as with the network density caused by its branching. From the point of view of the formation of the watercourse system and its relation to modern and neotectonic movements, these are two different cases that must be distinguished: a meandering pattern is formed in relatively stable regimes, while the formation of a branched river network is characteristic of tectonic uplifts. In both these cases, the fractal dimension D_r is increased; therefore, the tectonic regimes of uplift and subsidence cannot be sufficiently confidently distinguished with this parameter alone.

To characterize the branching of the river network, the fractal dimension of the set of branch points (bifurcations) of channels was calculated. Only the points of change of the stream order, i.e., the points of confluence of channels of the same order and the birth of a channel of a higher order were taken into account (Fig. 2). The fractal dimension D_b for the entire study area in the scale range of 5–160 km was found to be 1.74 ± 0.05 with a correlation coefficient $r = 0.99$ (Fig. 3c). Increased values of this parameter correspond to areas with frequent branching (change of order) of channels, which corresponds to uplifts.

3. The distribution of the fractal characteristics over the research area. The next step in our research was the selection of the scale and size of windows for calculating the fractal dimensions α , D_r and D_b over the studied area. The parameters of the windows and scales for

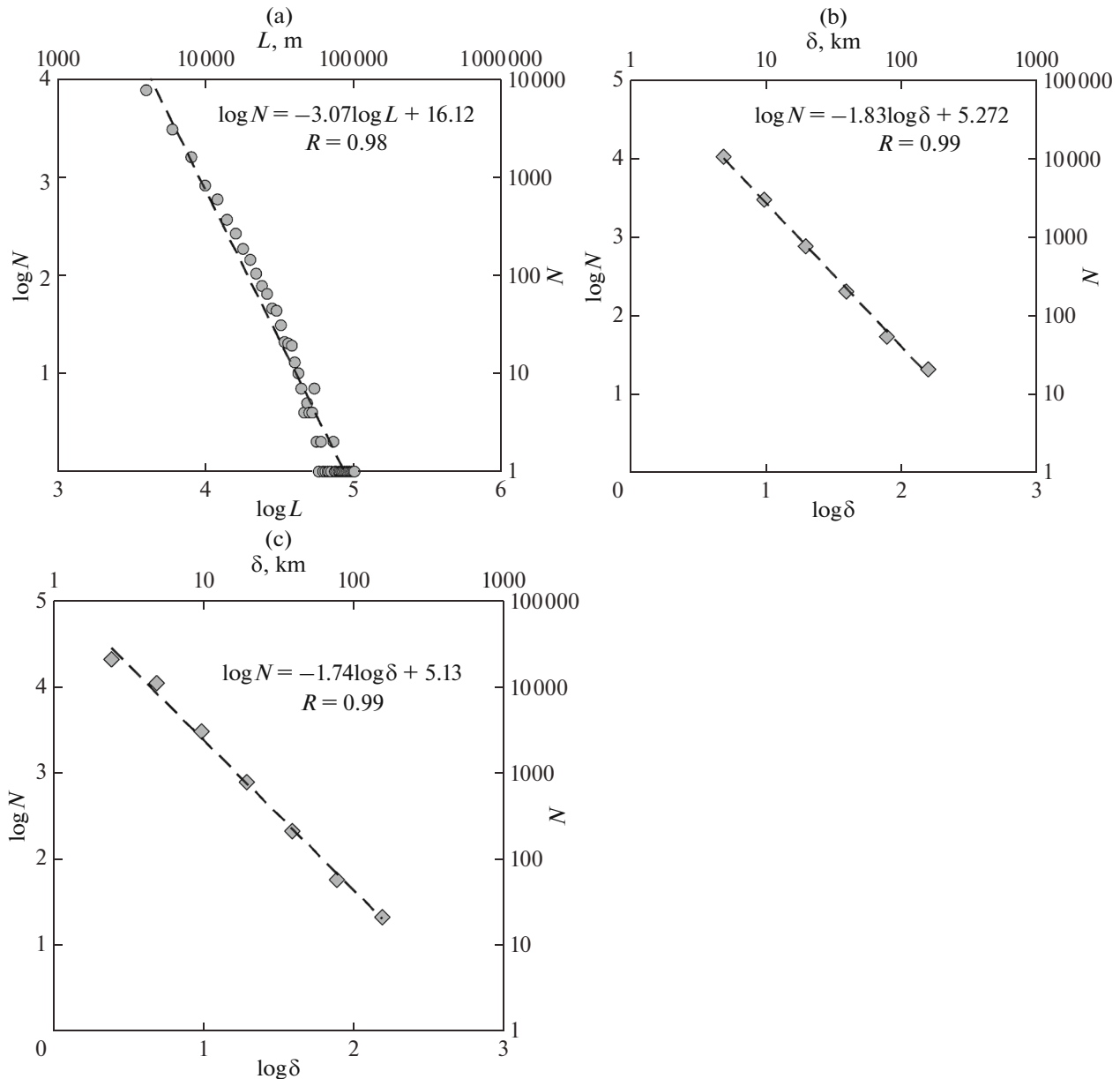


Fig. 3. Characteristics of the self-similarity of the river network. (a) α index in the distribution of channels by length; (b) fractal dimension D_f of the river network density; (c) bifurcation points of channels D_b for the entire area under study.

combined analysis of all three characteristics of the river network self-similarity were selected taking the following considerations into account:

- (1) To reliably determine the self-similarity parameter, its scale range δ should be at least of order 1;
- (2) The lower boundary of the scale range must belong to the scaling area;
- (3) To create a detailed picture of the spatial variations of the analyzed characteristics the upper bound of the scales should allow the analysis window to be fitted into the area by several times over;

(4) The number of points of the channel order change is much less than the total number of confluence points in the river network, since some confluences do not change the stream order (Fig. 2); such streams appear as a broken line on the map;

(5) The possibility of an adequate comparison of the river network self-similarity with the results of fractal analysis of seismicity and the network of active faults. The detail of the latter is much less than that of the former.

The following parameters were deduced from the test calculations: (a) for all stream orders, the window size was $0.5^\circ \times 0.5^\circ$ ($\sim 40 \times 40$ km at a given latitude);

(b) the window shift (overlap) was 0.25° (~ 20 km); and (c) the range of cell sizes used for the calculation was from 0.05° to 0.5° (~ 4 – 40 km). To reveal the spatial features of the fractal dimension variations of the river networks in the area, it was calculated in a sliding window using the author's FrAnGeo v.3.3 program [7], which was improved for this work.

The distribution of the channel length exponent (α) across the study area is characterized by linear almost meridional zones of alternating higher and lower values (Fig. 4a). As mentioned above, higher values of this parameter correspond to the uplift mode, while lower values characterize either subsidence or relative stability. The distribution of the fractal dimension of the river network pattern (D_r) across the study area is also characterized by linear zones of alternating higher and lower values; however, their orientation is not submeridional, as in the case of α parameter, but rather of a NW–SE strike (Fig. 4b). As mentioned above, the meandering pattern of the river network is formed in relatively stable regimes, while the formation of a branched river network is characteristic of tectonic uplifts. In both these cases, the values of the fractal dimension D_r are elevated. The distribution of the fractal dimension of the set of points of channel bifurcation (D_b) across the area is characterized, in contrast to the two above presented α and D_r , by a mosaic pattern (Fig. 4c). The increased values of this parameter correspond to the areas with more frequent branching of channels (with order change), that is, to uplifts. We note that the reduced values of the D_r and D_b dimensions in the eastern part of the area near the Sea of Japan are an artifact that is due to the fact that the rivers terminate there.

4. The complex parameter of self-similarity. The fractal characteristics presented above reflect upward and downward vertical movements in some way; none of them, however, is appropriate to make a direct comparison with neotectonic movements and to clearly distinguish the conditions of uplift and subsidence (see above). It appears that a more distinct result could have been obtained via comprehensive analysis of all three parameters, yet a straightforward superposition of their fields, although technically easy to implement using GIS technologies, is imperfect regarding perception and analysis in a printed version. This prompted the authors to look for another way to combine all three parameters of the river network self-similarity.

Comparison of the fractal analysis results with the amplitudes of neotectonic movements focuses not so much on the values of the parameters as such, as on their variations. Hence, we proposed a complex (combined) parameter of self-similarity PRNS (Parameter of River Network Self-similarity), calculated according to the following method. Since the variation ranges of D_r , D_b and α differ, their correct combination

requires normalization, for which each of the parameters underwent the following transformation:

$$\langle D_r \rangle = \frac{D_r - \min(D_r)}{R(D_r)}; \quad \langle D_b \rangle = \frac{D_b - \min(D_b)}{R(D_b)}; \quad (6)$$

$$\langle \alpha \rangle = \frac{\alpha - \min(\alpha)}{R(\alpha)},$$

where min and max are the minimum and maximum values of each parameter, respectively and $R = \max - \min$ is the range of values. The sum of the normalized variations of all parameters is proposed as the PRNS:

$$\text{PRNS} = \langle D_r \rangle + \langle D_b \rangle + \langle \alpha \rangle. \quad (7)$$

Such a combination allows the range of vertical tectonic movements of either sign to be reflected more correctly in the resulting values of the PRNS parameter. At the qualitative level, the dependence is as follows:

—in the case of subsidence, $\langle D_r \rangle$ increases, while $\langle D_b \rangle$ and $\langle \alpha \rangle$ decrease; therefore, expression (7) takes relatively small values;

—in the case of uplifts, all three parameters have increased values and Eq.(7) would take larger values.

Since each of the normalized parameters is in the range from 0 to 1, theoretically, their sum can vary from 0 to 3. However, actual values should be expected in the range of 0.5–2.5; those approaching 3 are quite unlikely. In our case, the range of PRNS varied from 1 to 2.3, its distribution over the study area is shown in isolines in Fig. 5. We note that the proposed parameter is new and its efficiency is being tested in this work.

COMPARING THE RESULTS OF FRACTAL AND MORPHOSTRUCTURAL ANALYSES

A set of datum and difference surfaces reflecting the landscape evolution in the period between the emergence of the streams of different orders [22] was constructed using the available data and the algorithm described by Ngumanov et al. [14] that we modified for the ArcMap GIS. Datum surfaces were interpolated linearly with smoothing by the nearest neighbor method. The analysis was carried out only for water-courses from the first to sixth orders, since the water-courses of the higher orders are predominantly transitory, have an equilibrium profile, and their number is insufficient for reliable interpolation of the datum surfaces.

Since the pattern of the river network was formed throughout the entire neotectonic evolution stage, it seems most reasonable to compare the results of the self-similarity analysis with the difference surface of the first to sixth orders, reflecting the total change in the relief from the Oligocene to the end of the Pleistocene, which occurred both due to the vertical neotectonic movements and to the erosion and denudation processes (Fig. 5, marked by colors). This difference

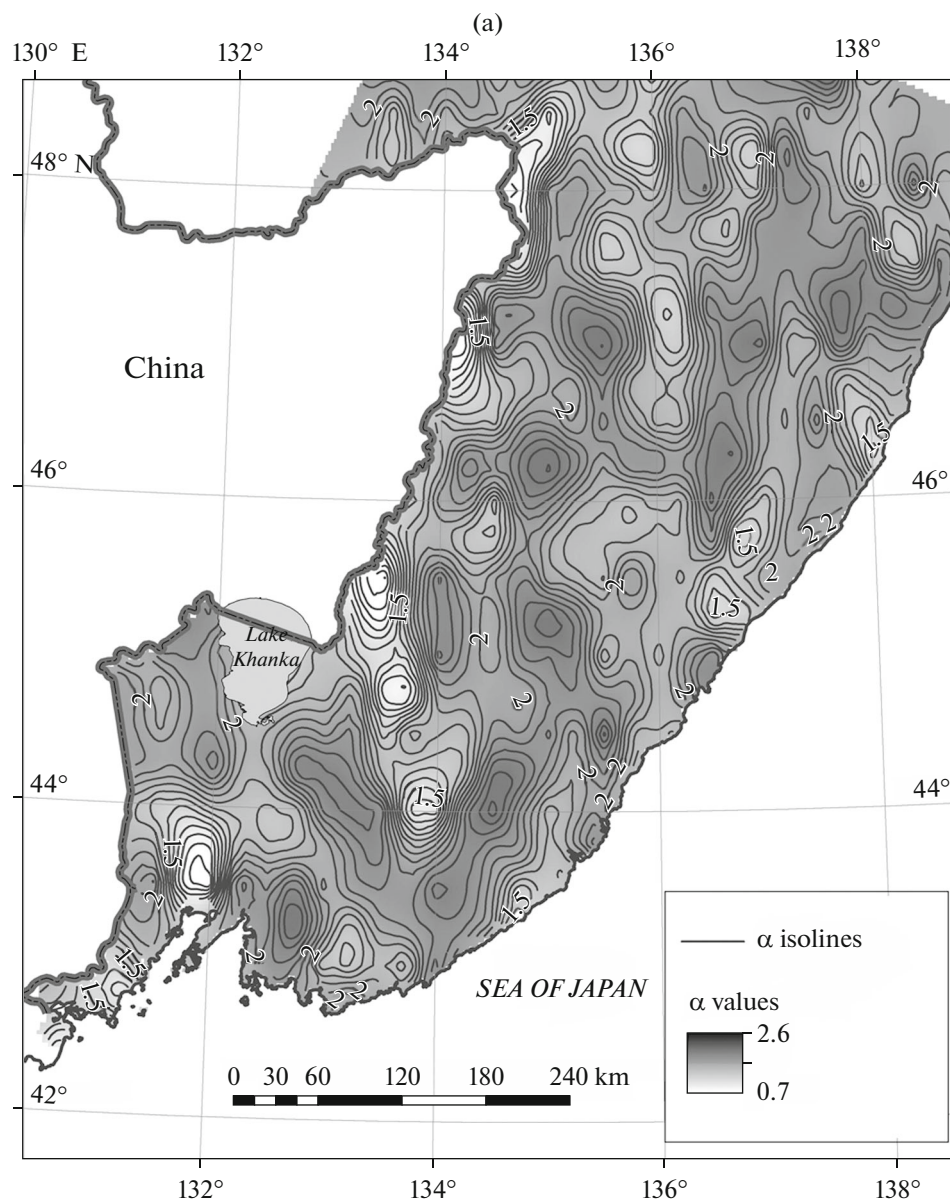


Fig. 4. Characteristics of self-similarity of the region's river network, calculated in a sliding window. (a) Parameter α of the distribution of channel lengths; (b) fractal dimension of the river network D_r ; (c) fractal dimension for the set of bifurcation points of channels D_b .

surface reflects the general trend towards uplift east of the Central Sikhote-Alin fault and the predominance of denudation and erosion processes of the more ancient relief west of it during the neotectonic stage, but does not reveal the history of its evolution. The stages of the relief evolution have a noticeable effect on the formation of the river network pattern [18]; however, the subject is quite extensive, therefore it is considered in a separate work [19].

The morphostructural analysis does not allow negative movements to be correctly identified and evaluated; however, the wide valleys and depressions occurring west of Central Sikhote-Alin fault (the Middle

Amur in the north, Suifun-Khankayskii in the south and Alchanskii between them), with an elevation close to zero may indicate that these areas were subject not only to the denudation of the more ancient relief, but also to subsidence with compensating sedimentation within the sedimentary basins. Without going into the history of the formation of the Mesozoic and Cenozoic sedimentary basins within this area (from north to south: Middle Amur, Alchanskii, Razdolnenskii and Partizansko-Sukhodolskii), we point out that almost all of them owe their existence to the formation of half-grabens initiated by a combination of large left-lateral strike-slip shifts along the Tan-Lu faults and

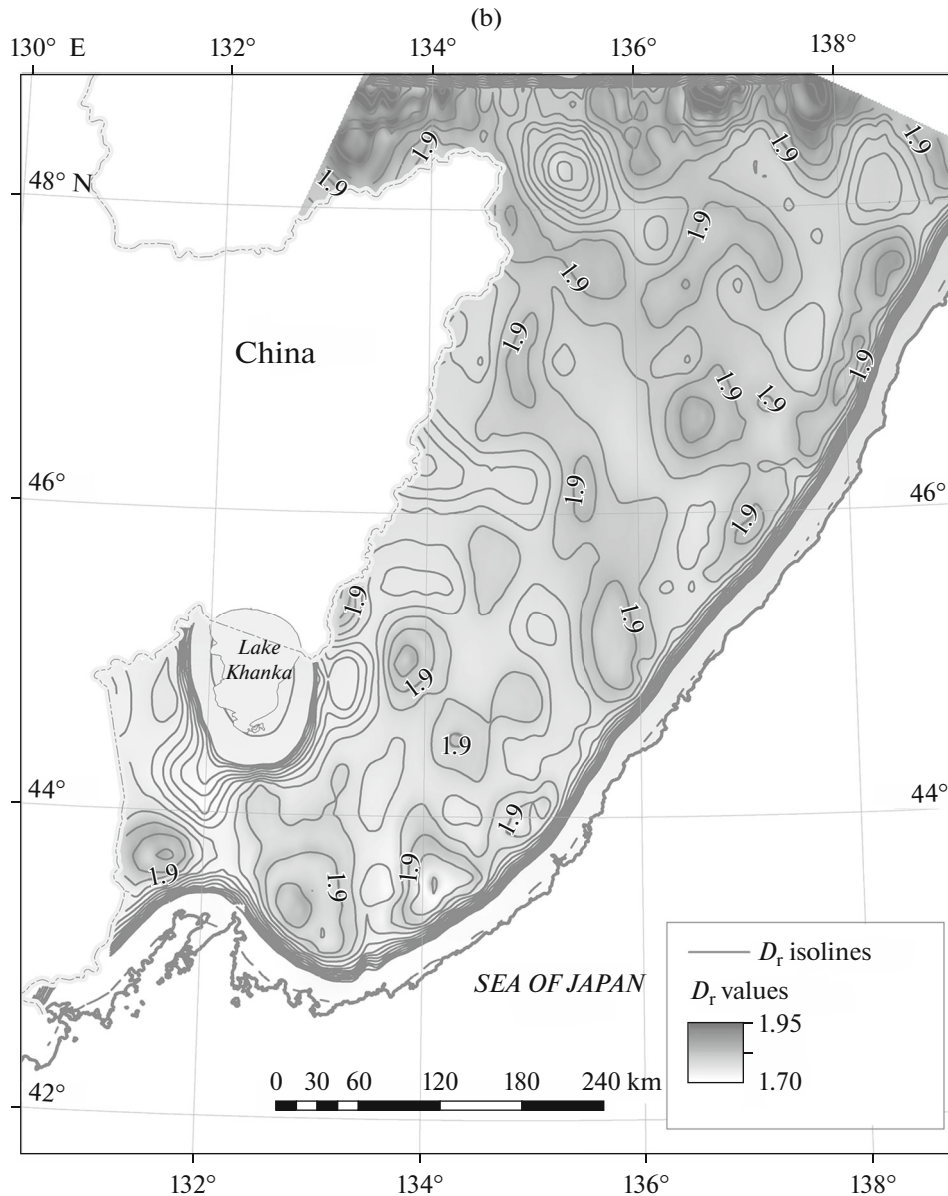


Fig. 4. (Contd.)

isostatic alignment of the areas of the collision and accretion zone, which had an increased thickness of the crust [3].

East of the Central Sikhote-Alin fault, the uplift of the ridge was also uneven: it is more intensive (up to 1 km and more) in the south and north of the area, with erosion manifested along with uplift, and less intense in the central part, between the South Primorye and Bikinskii fault zones (on average, up to 400–600 m), where denudation processes were more pronounced.

Comparison of the difference surface of the first and sixth orders with the spatial distribution of the complex parameter PRNS of the river network (Fig. 5)

shows that the maxima of the PRNS parameter generally coincide with the areas of the highest uplift, and the minima correspond to the areas with the smallest one or with the regions of the most intense erosion. However, such agreement is not full; there are areas that are inversely correlated. In our opinion, this can be explained precisely by the stages in the relief evolution, i.e., by the fact that at different stages within the same area could have a tectonic regime of different intensity or even inverse intensity. While the younger river network formed a pattern characteristic of younger movements, the older and more mature river network pattern might be conserved and reflect the direction of the movements that occurred at the previous stage of the relief evolution, which was reflected in the results

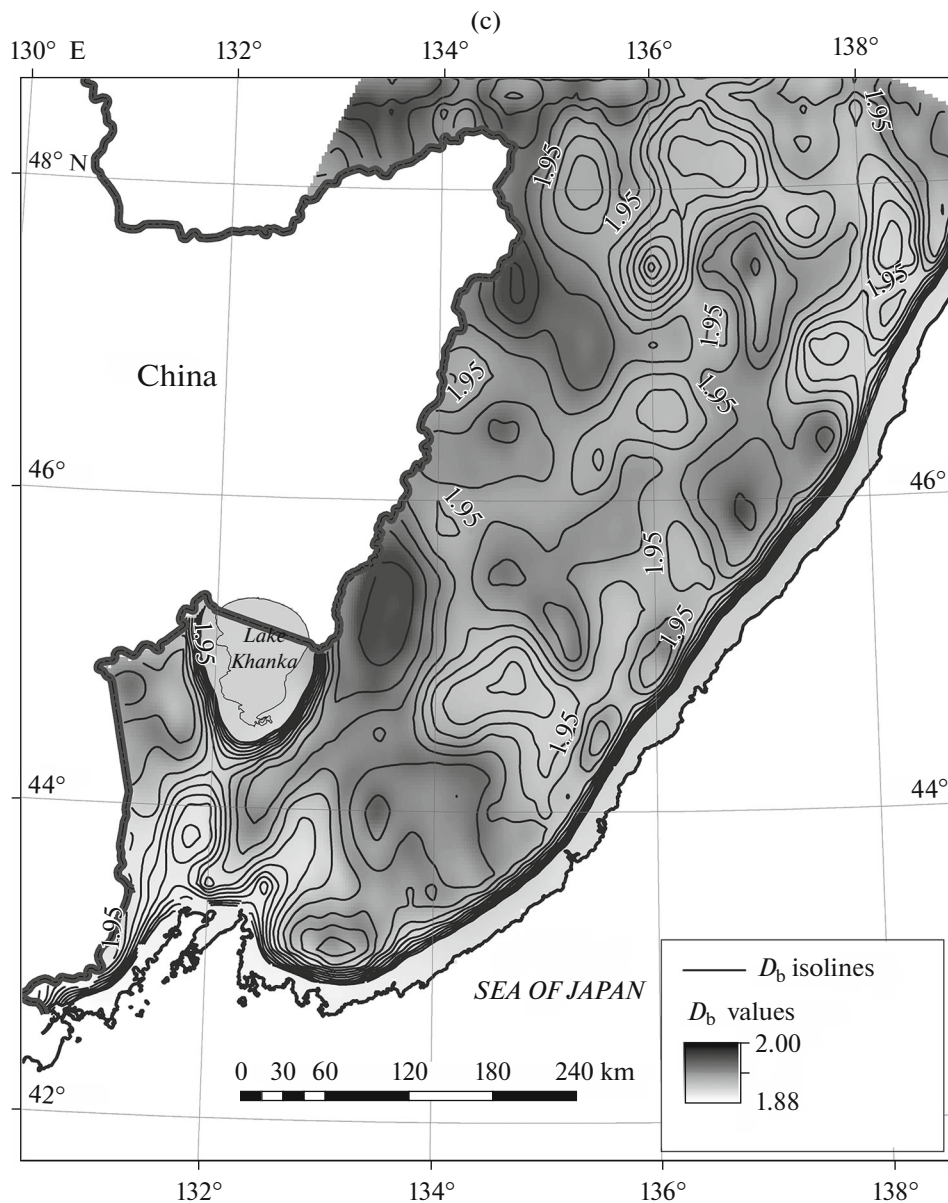


Fig. 4. (Contd.)

of fractal analysis [19]. The maxima and minima of the PRNS field, shifted relative to the actual topographic structures, especially small ones, narrow troughs and uplifts, can be attributed to the values that are “smeared” by averaging in a sliding window.

COMPARISON OF THE RIVER NETWORK FRACTAL ANALYSIS WITH THE PREVIOUS NEOTECTONIC RECONSTRUCTIONS

We used two published works: (1) the neotectonic scheme of the south of the Russian Far East (Fig. 6a) by Gorkusha et al. [4] and (2) a map of the latest tectonics of Northern Eurasia (Fig. 6b) edited by Grachev [9] to compare the data on the self-similarity

of the river network obtained in this work. The neotectonic reconstructions for south Sikhote-Alin in these works show that the relative maxima and minima of the newest vertical movements (Figs. 6a and 6b), as well as the absolute values of negative vertical movement (the maximum values for the Middle Amur depression were estimated as -1 km in both cases) generally coincide, while in the case of positive vertical movements there is no such agreement. There is a significant difference from 500 m in the south to 1 km in the north for almost all positive landforms of the Sikhote-Alin block east of the Central Sikhote-Alin fault (Figs. 6a and 6b). We believe that this may be due to different ideas of the duration of the neotectonic stage. According to the datum surfaces calculated for the

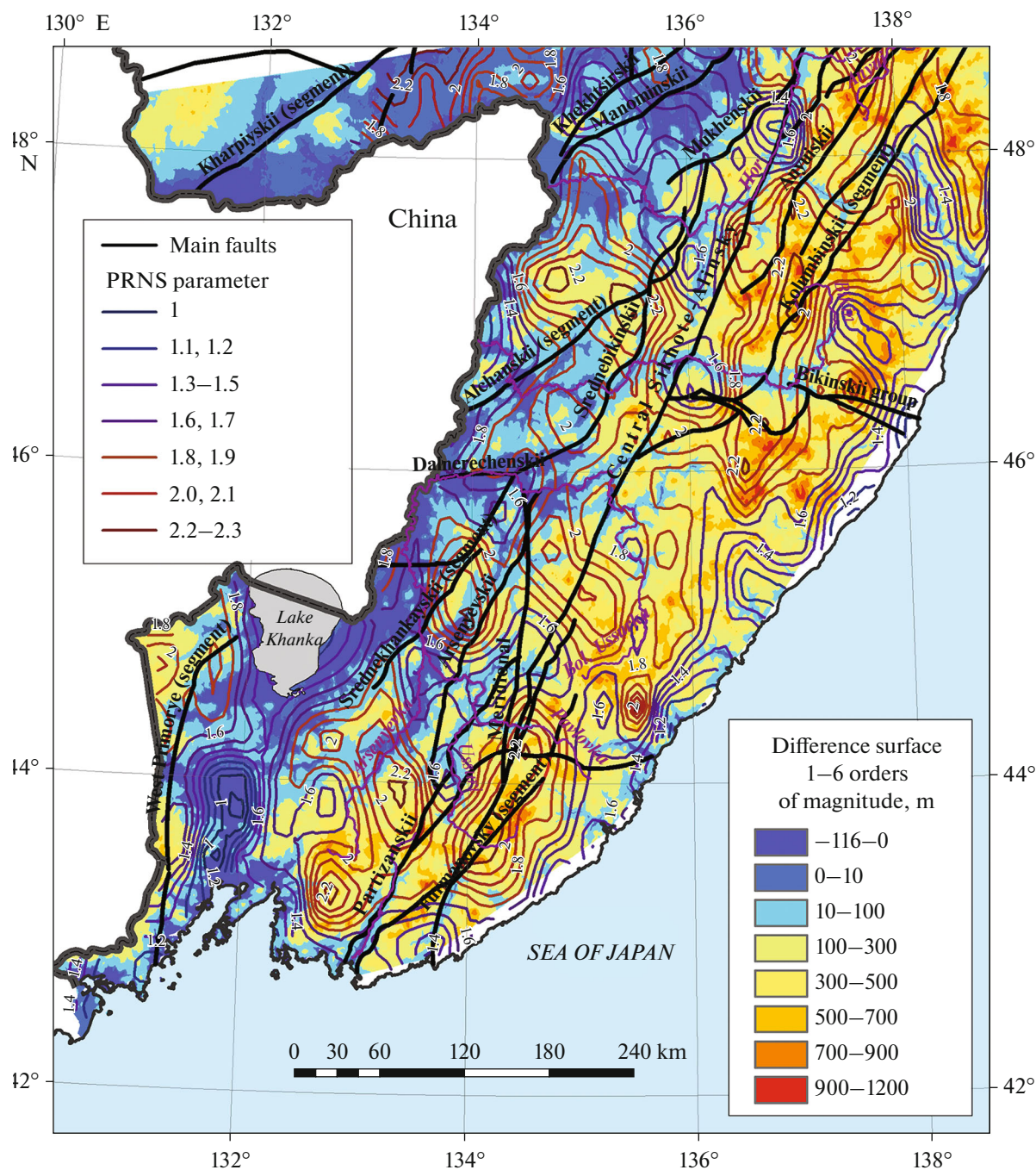


Fig. 5. A comparison of the complex self-similarity parameter PRNS to the difference surface between datum surfaces of the first and sixth orders.

watercourses of the first to sixth orders, the values of the maximum positive vertical movements here reach 1200 m, with an average value of 700–900 m (Fig. 5).

A comparative analysis of previous neotectonic reconstructions (Figs. 6a and 6b) and the PRNS map presented in this work (Fig. 6c) shows general agreement of the results: the locations of the relative maxima and minima of the PRNS parameter are similar or

coincide with the centers of positive and negative vertical neotectonic movements. Nevertheless, it should be noted that there are also differences, which are mainly expressed in the details and shape of the maxima. It appears that such differences may appear due to the complex and multistage history of the formation of the stream network, which significantly affects the self-similarity parameters. At the same time, as noted above, in most cases, the neotectonic maps reflect the

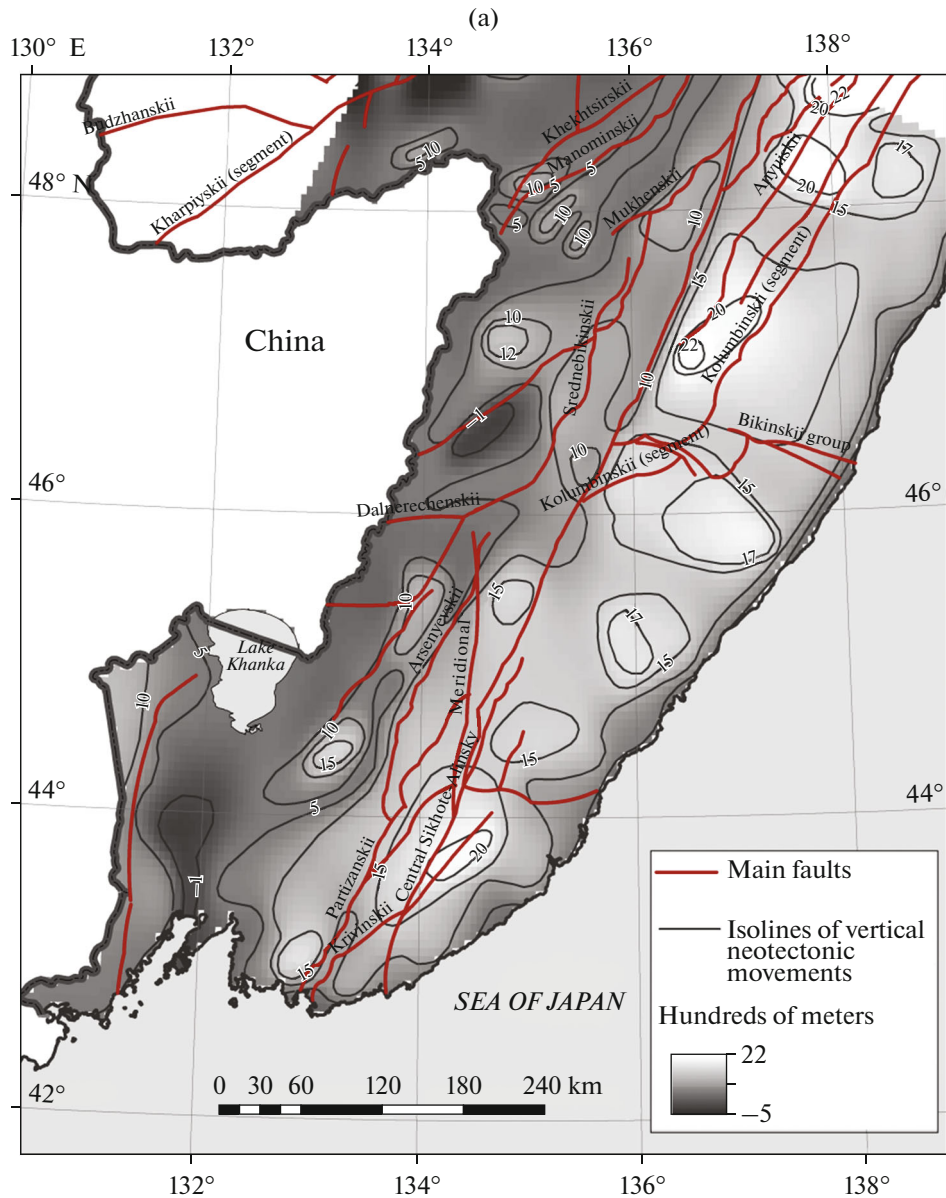


Fig. 6. A comparison of the complex self-similarity parameter of the river network in the south of the Russian Far East with the neotectonic data from [4] and [9]. (a) Fragment of a neotectonic map; isolines, vertical displacement (hundreds of meters). (b) Fragment of a neotectonic map of North Eurasia, isolines are the neotectonic movements, in km; (c) complex parameter of the river network self-similarity (PRNS) of southern Russian Far East, calculated in a sliding window of 40×40 km.

amplitudes of movements in total for the entire neotectonic stage.

Figure 6c shows, along with the PRNS map, the position of the epicenters of crustal seismic events in the region according to the earthquake data bank of the Laboratory of Seismology and Seismotectonics of the Institute of Tectonics and Geophysics FEB RAS (Khabarovsk), compiled from geohistorical materials and catalogs of the Geophysical Survey RAS up to 2015. As can be seen, the positions of most of the epicenters fall in the boundary zones between the relative maxima and minima of the PRNS areas, that is, the

seismic areas border the uplifts, which, as was mentioned earlier, is due to the block nature of neotectonic vertical movements [4].

RESULTS AND CONCLUSIONS

Research built on the morphostructural analysis showed that the evolution of the relief in the studied region during the neotectonic period has occurred in several stages; the most active uplift was proceeding by uneven intensity at the early stages. The total change in the topography from the Oligocene to the end of the

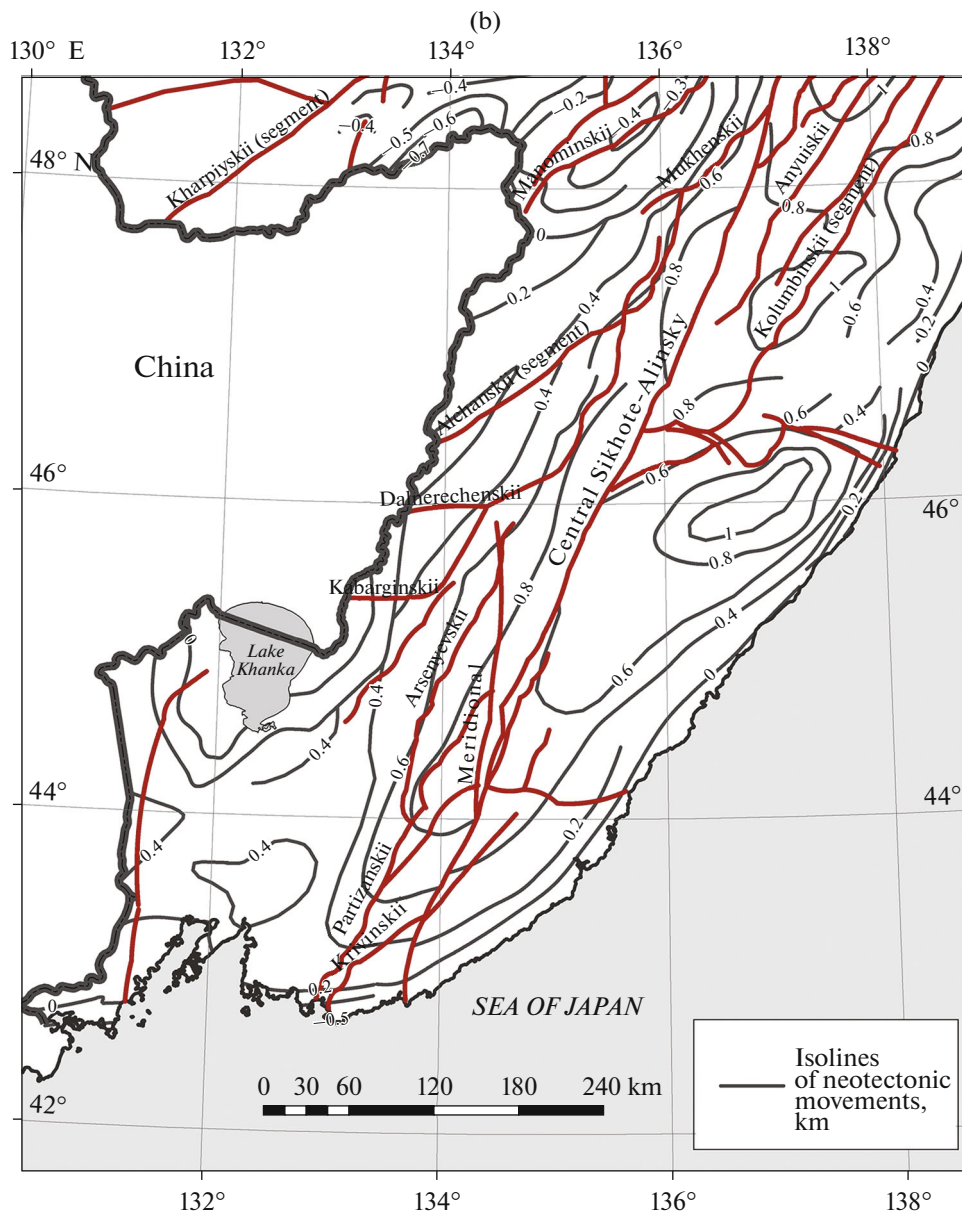


Fig. 6. (Contd.)

Pleistocene, which resulted from both vertical neotectonic movements and processes of erosion and denudation, is reflected in the difference surface from the first to sixth orders. It was shown that uplift prevailed during the entire neotectonic stage east of the Central Sikhote-Alin fault, while west of the fault, the most significant role from a certain point in time was played by the denudation and erosion of more ancient relief and subsidence of the land with sedimentation within the sedimentary basins. The uplift of the Sikhote-Alin east of the Central Sikhote-Alin fault was also uneven; it was more intense in the south and north of the studied area where erosion processes were also manifested along with uplift and less intense in the central part,

between the South Primorsk and Bikin fault zones, where denudation was more pronounced. It was revealed that the stepwise character of the neotectonic movements significantly affected the appearance of the modern river network pattern.

A new complex parameter, that is, PRNS, which characterizes the self-similarity of the of the river network pattern, was proposed to identify the latest tectonic movements. The parameter is a combination of exponents in the equations for the distribution of channels by length, the fractal dimension of channels, and the fractal dimension of points of change of the order of channels. In our opinion, this parameter is more accurate and descriptive in relation to the

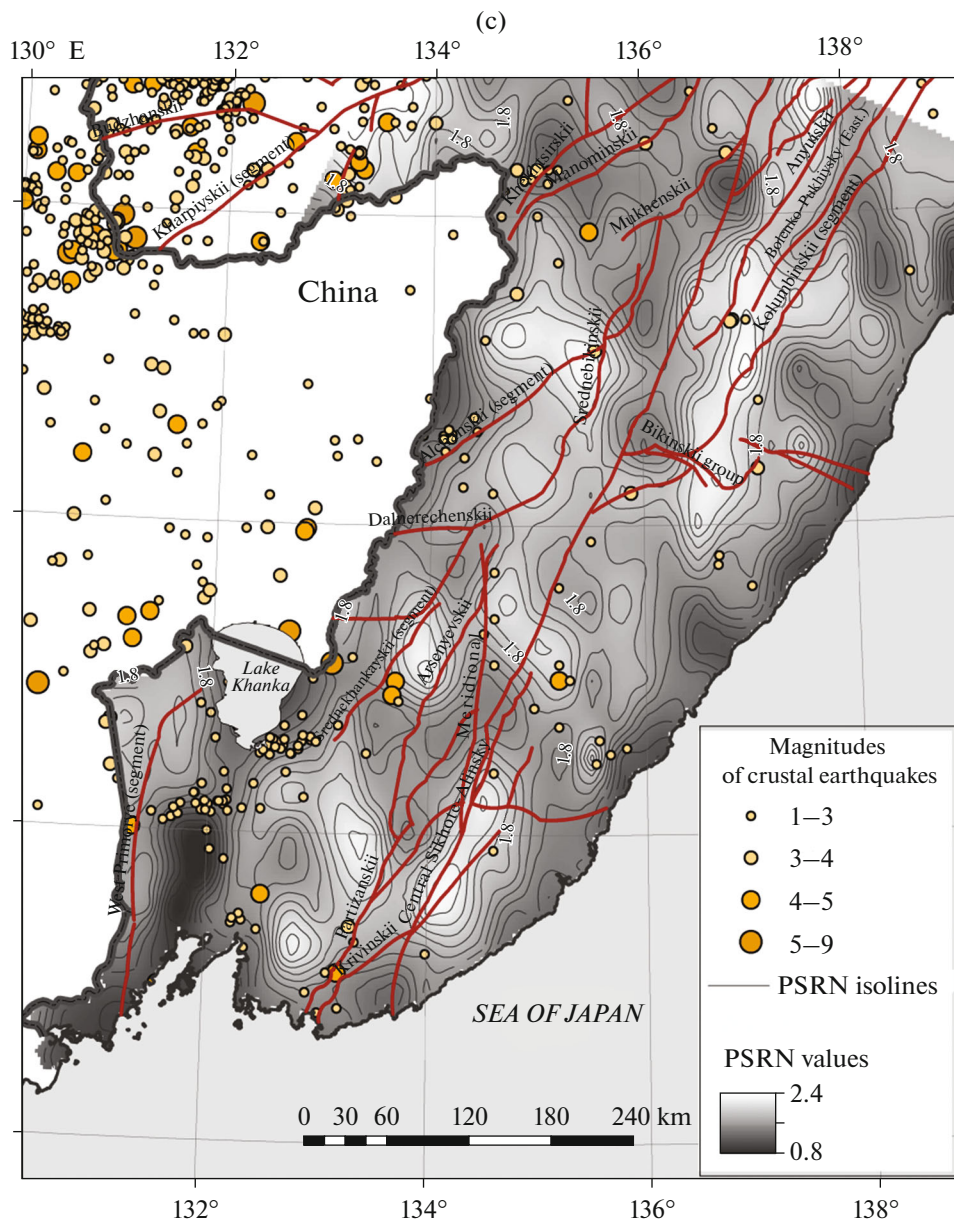


Fig. 6. (Contd.)

matching the self-similarity of the river network with the neotectonic movements.

Comparison of the results of morphostructural and fractal analyses showed a good correlation of these two methods. Areas of the PRNS relative maxima coincide with the areas of the largest ascending neotectonic movements, while the minima coincide either with the areas of the smallest relief increment or with the areas of the most significant erosion. As well, the most of the crustal earthquake epicenters are confined to the boundaries between the relative maxima and minima of the PRNS areas, that is, seismic areas border the

uplifts, which is associated with the block nature of neotectonic vertical movements.

A comprehensive analysis showed that in the areas with stepwise neotectonic movements, fractal analysis of the hydro-network aimed at identifying the direction of neotectonic movements encounters additional difficulties due to the peculiar evolution of the river network at each stage of development and the conserved pattern, reflecting the features of the development of the relief at different stages. Resolution of the contradictions and ambiguous data interpretation requires further more detailed methodological study.

ACKNOWLEDGMENTS

The authors are grateful to the reviewers A.V. Ivanov and V.I. Usikova for their comments, which significantly improved the manuscript, and to E.Yu. Didenko for help with the processing the article.

FUNDING

This study was supported by the Russian Science Foundation (project no. 16-17-00015). The work was carried out using the equipment of the Multiple Access Research Computing Center of the Moscow State University [2].

REFERENCES

- G. V. Bastrakov, "Erosion strength of rocks," *Geomorfologiya*, No. 2, 52–55 (1977).
- Vi. Voevodin, A. Antonov, D. Nikitenko, P. Shvets, S. Sobolev, I. Sidorov, K. Stefanov, Vad. Voevodin, and S. Zhumatiy, "Supercomputer Lomonosov-2: large scale, deep monitoring and fine analytics for the user community," *Supercomputing Frontiers and Innovations*, 6 (2), 4–11 (2019). <https://doi.org/10.14529/jsfi190201>
- Geodynamics, Magmatism, and Metallogeny of East Russia*, Ed. by A. I. Khanchuk (Dal'nauka, Vladivostok, 2006) [in Russian].
- S. V. Gorkusha, F. S. Onukhov, and F. G. Korchagin, "Seismicity and neotectonics of the Russian Far East," *Tikhookean. Geol.* **18** (5), 61–68 (1999).
- A. N. Didenko, V. G. Bykov, N. V. Shestakov, V. A. Bormotov, M. D. Gerasimenko, A. G. Kolomiets, N. F. Vasilenko, A. S. Prytkov, and A. A. Sorokin, "March 11, 2011, Tokhoku Earthquakes. Data on network of deformation and seismological observations of Far East Branch of the Russian Academy of Sciences," *Vestn. DVO RAN*, No. 3, 18–21 (2011).
- A. N. Didenko, V. S. Zakharov, G. Z. Gil'manova, T. V. Merkulova, M. V. Arkhipov, "Formalized analysis of crustal seismicity in the Sikhote Alin orogen and adjacent areas," *Russ. J. Pac. Geol.* **36** (2), 123–133 (2017).
- V. S. Zakharov, "Analysis of the characteristics of self-similarity of seismicity and the active fault network of Eurasia," *Moscow Univ. Geol. Bull.* **66** (6), 385–392 (2011).
- V. S. Zakharov, D. A. Simonov, G. V. Bryantseva, and N. I. Kosevich, "Characteristics of self-similarity of water stream system of the Kerch Peninsula and their comparison with results of structural—geomorphological analysis," *Geofiz. Prots. Biosf.*, **18** (1), 50–60 (2019). <https://doi.org/10.21455/GPB2019.1-5>
- Maps of the Youngest Tectonics of Northern Eurasia*, Ed. by A. F. Grachev (AOOT VNIIZarubezhgeologiya, 1997). <http://www.geokniga.org/maps/3465>.
- A. M. Korotkii, V. V. Korobov, and G. P. Skryl'nik, "Avalanches and landslides of the southern Russian Far East," *Geomorfologiya*, No. 2, 50–59 (2009).
- B. Mandel'brot, *Fractal Geometry of Nature* (Instl. Komp. Issled., Moscow-Izhevsk, 2002) [in Russian].
- M. A. Mel'nik and A. V. Pozdnyakov, "Fractal analysis of erosionally rugged topography: methodological approaches," *Vestn. Tomsk. Gos. Univ.* No. 301, 201–205 (2007) [in Russian].
- M. A. Mel'nik and A. V. Pozdnyakov, "Fractals in the erosional rugging of surface and autofluctuations in the dynamics of geomorphosystems," *Geomorfologiya* **3**, 86–95 (2008). <https://doi.org/10.15356/0435-4281-2008-3-86-95>
- I. I. Ngumanov, E. V. Ngumanova, and I. Yu. Chernova, *Principles of Morphometric Method of Searching for Neotectonic Structures* (Kazan. Univ., Kazan, 2016) [in Russian].
- F. S. Onukhov and T. V. Merkulova, "Rotation of crustal blocks between strike-slip zones of the Lower Amur region based on morphostructural data," *Geomorfologiya*, No. 4, 64–75 (2017).
- A. Yu. Sidorchuk, "Fractal geometry of riverine networks," *Geomorfologiya*, No. 1, 3–14 (2014). <https://doi.org/10.15356/0435-4281-2014-1-3-14>
- D. A. Simonov and G. V. Bryantseva, "Morphostructural analysis in neotectonic reconstructions of the Kerch Peninsula," *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.* **93** (3), 12–25 (2018).
- D. A. Simonov, V. S. Zakharov, and G. V. Bryantseva, "Complex geomorphological, morphological, and fractal analysis of the most recent vertical tectonic movements of the Kerch Peninsula," *Moscow Univ. Geol. Bull.* **74** (6), 549–558 (2019).
- D. A. Simonov, V. S. Zakharov, G. Z. Gil'manova, and A. N. Didenko, "Neotectonic vertical movements in the South Sikhote-Alin and characteristics of self-similarity of drainage network in the region," *Moscow Univ. Geol. Bull.* **75** (4), 330–341.
- V. Yu. Timofeev, D. G. Ardyukov, P. Yu. Gornov, A. V. Timofeev, M. G. Valitov, and E. V. Boiko, "Modern movements of the continental margin of the Russian Far East based on the GPS observations," *Vestn. SGUGiT* **22** (2), 88–102 (2017).
- Feder, E., *Fractals* (Plenum, New York, 1988).
- V. P. Filosofov, *Principles of Morphometric Method of Searching for Tectonic Structures* (Izd-vo Saratov. un-ta, Saratov, 1975) [in Russian].
- S. A. Chupikova, Extended Abstract of Candidate's Dissertation in Geography (Tomsk, 2010).
- E. Dombradi, G. Timar, G. Bada, S. Cloetingh, and F. Horvath, "Fractal dimension estimations of drainage network in the Carpathian—Pannonian system," *Global Planet. Change* **58**, 197–213 (2007). <https://doi.org/10.1016/j.gloplacha.2007.02.011>
- C. Donadio, F. Magdaleno, A. Mazzarella, and G. M. Kondolf, "Fractal dimension of the hydrographic pattern of three large rivers in the Mediterranean morphoclimatic system: geomorphologic interpretation of Russian (USA), Ebro (Spain) and Volturno (Italy) fluvial geometry," *Pure Appl. Geophys.* **172**, 1975–1984 (2014). <https://doi.org/10.1007/s00024-014-0910-z>
- S. K. Jenson and J. O. Domingue, "Extracting topographic structure from digital elevation data for geographic information system analysis," *Photogrammet-*

- ric Engineering and Remote Sensing **54** (11), 1593–1600 (1988).
27. M. G. Kogan, N. F. Vasilenko, D. I. Frolov, J. T. Freymueller, G. M. Steblov, A. S. Prytkov, and G. Ekstrom, “Rapid postseismic relaxation after the Great 2006–2007 Kuril earthquakes from GPS observations in 2007–2011,” *J. Geophys. Res.* **118** (7), 3691–3706 (2013).
28. J. D. Pelletier, “Self-organization and scaling relationships of evolving river networks,” *J. Geophys. Res.* **104** (B4), 7359–7375 (1999).
29. Search Earthquake Catalog: U.S. Geological Survey, 2019. Available from: <https://earthquake.usgs.gov/earthquakes/search>.
30. A. N. Strahler, “Quantitative analysis of watershed geomorphology,” *Trans. Am. Geophys. Union* **38** (6), 913–920 (1957).
31. D. L. Turcotte, *Fractals and Chaos in Geology and Geophysics*, 2nd ed. (Cambridge Univ. Press, Cambridge, 1997).
32. USGS Earth resources observation and science (EROS) Center. www.usgs.gov/centers/eros. (accessed date of December 1, 2019).
33. V. S. Zakharov, A. N. Didenko, G. Z. Gil’manova, and T. V. Merkulova, “Characteristics of self-similarity of seismicity and the fault network of the Sikhote Alin orogenic belt and the adjacent areas,” *Geodynam. & Tectonophys.* **10** (2), 541–669 (2019). <https://doi.org/10.5800/GT-2019-10-2-0425>

Recommended for publishing by A.I. Khanchuk