

# Neotectonic Vertical Movements in the South Sikhote-Alin and Characteristics of Self-Similarity of the Stream Network in the Region

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**Abstract**—A morphostructural analysis of the relief and fractal analysis of the stream network of the South Sikhote-Alin orogenic belt were carried out. The formation of the relief at the neotectonic period occurred in several stages, which was reflected in the stream network pattern: (1) during pre-Oligocene time there was a general uplift of Sikhote-Alin; (2) activation of vertical neotectonic movements occurred in the Pliocene, which were most intense to the East of the Central Sikhote-Alin Fault and were synchronous with basaltic volcanism; (3) in the Pleistocene, vertical movements of significant amplitude did not occur; at this time, the modern erosion–denudation relief typical of the studied region was formed; and (4) at the end of the Pleistocene and in the Holocene a slight activation of vertical neotectonic movements to the East of the Central Sikhote-Alin Fault occurred, which was reflected in the residual relief peculiarities. Comparison of the morphostructural and fractal analyses showed that the maxima of the PRNS complex parameter of self-similarity are consistent with the areas of greatest increments in elevation and the minima are consistent with the areas of the smallest increment of relief or with the areas of most significant erosion. In the regions with a stage character of neotectonic evolution, the fractal analysis of the stream network should involve additional factors controlled by the peculiarities of the stream network evolution at each stage of the evolution, as well as by the conservative nature of its pattern, which reflect the features of the evolution of the relief at different stages.

**Keywords:** neotectonics, relief, stream network, morphostructural and fractal analysis, self-similarity

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## INTRODUCTION

The relation of neotectonics to the formation of relief is well known and has been studied by various methods of structural geomorphology (Nikolaev, 1988; Trifonov, 2017); the stream network pattern is among the important indicators of the direction of neotectonic movements. The disadvantages of many known techniques include the fact that most of the structural–geomorphological and neotectonic maps compiled with their use reflect the amplitude and direction of tectonic movements over the entire neotectonic stage, while it is difficult to distinguish movements related to different stages in the formation of neotectonic structures. At the same time, neotectonic structures can develop not only at different periods, but unevenly as well. The amplitude and direction of the neotectonic movements may change over time and the rate of uplift in different areas and at different time

intervals can differ, which affects both the relief and the stream network pattern. The structural–morphometric method suggested by Filosofov (1975) allows identification of changing tectonic structures, as well as consideration of their evolution over time. The stages of neotectonic movements can be distinguished on the basis of the assumption that higher-order watercourses develop for a long time and reflect the algebraic total of movements for the interval from their inception to the present time, while lower-order watercourses reflect neotectonic movements in a shorter period of time and have a younger age. Thus, the comprehensive analysis of monobasis surfaces (Filosofov, 1975) of watercourses of different orders makes it possible to distinguish the stages in the evolution of the relief, which, in turn, reflects the evolution of the growth of neotectonic structures expressed in the relief; in our opinion, this allows us determine the

relationships of the neotectonic movements and structures with a stream network pattern more accurately. In this regard, we have chosen the method of structural–morphometric analysis adapted for neotectonic studies as a basis for the study of the latest vertical tectonic movements (Simonov and Bryantseva, 2018).

As has been shown in many studies (Feder, 1991; Pelletier, 1999; Turcotte, 1997), the stream network pattern has a pronounced property of self-similarity (fractality) in a quite wide range of scales. This allows us to consider the stream network pattern as a qualitative, as well as a quantitative parameter for assessing neotectonic vertical movements and fractal analysis of a stream network as one of the methods for such an assessment, which may provide significant help in the study of large territories using huge data volumes.

The relationship between the indicators of self-similarity (fractal dimension, etc.) and the density of the river network was studied in (Mel'nik and Pozdnyakov, 2008; Sidorchuk, 2014). A tendency towards a general increase in fractal dimension with the relief height (Sidorchuk, 2014), as well as a certain correlation with the direction of vertical movements (Donadio et al., 2014; Mel'nik and Pozdnyakov, 2008; Simonov et al., 2019; Zakharov et al., 2019) were revealed. Despite the significant number of studies devoted to this topic, there are still a number of uncertainties for this type of analysis, including the methodological aspect. The issues of the correct choice of scale and selection of the parameters for fractal analysis and comparison of the results of fractal analysis of stream networks with the results of neotectonic analysis remain insufficiently studied. This makes a research in such direction very relevant.

A significant part of the eastern margin of Eurasia is formed by the fold–nappe systems of the Cretaceous Sikhote-Alin–North Sakhalin orogenic belt, which is divided by the rift structure of the Tatar Strait of the Miocene age into the Sikhote-Alin and Hokkaido–Sakhalin branches. These previously constituted a single structure (Parfenov, 1984; *Geodinamika...*, 2006). The structures of the continental Sikhote-Alin branch occupy a significant part of the territory of Russia from the coast of the Sea of Japan in the south to the coast of the Sea of Okhotsk in the north (Fig. 1, inset). In the west, the continental branch of the belt borders with the Early Paleozoic Bureya–Khankai orogenic belt.

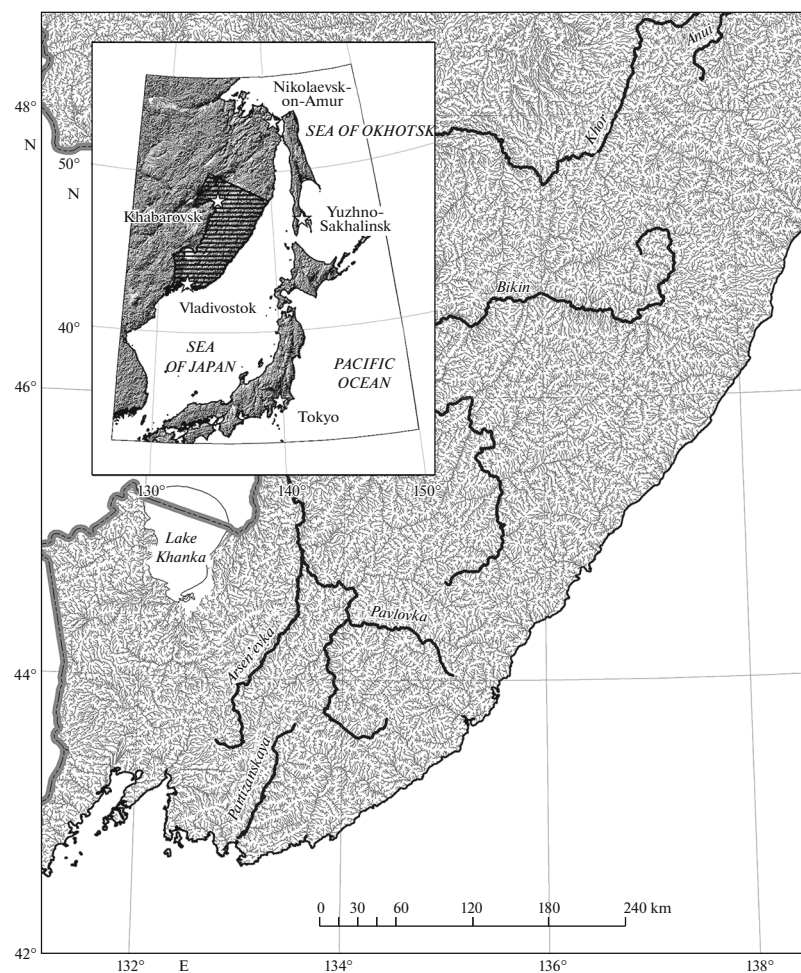
In the modern relief, the Sikhote-Alin orogenic belt is a large mountain system (Sikhote-Alin Ridge) with a length of more than 1000 and a width of up to 250 km with an average height of 800–1000 m (a maximum height of 2090 m, Tordoki-Yani Mt) and a general northeastern orientation of the main mountain range and individual ridges. The sublatitudinal Omi Ridge in the north and the Przhhevskii Mountains in the south are exceptions. The Sikhote-Alin Ridge in its middle part is divided by the transverse Bikin depression–block zone. The eastern slope of the Sikhote-

Alin Ridge drops abruptly to the sea, and the wide western slope is gentle. The axial zone of the Sikhote-Alin Ridge (Central Sikhote-Alin Fault) is characterized by linearly elongated or isolated dome–vaulted forms, as well as by the narrow graben- and horst-like structures.

Our study is aimed at detailed analysis of the neotectonic evolution of the Southern Sikhote-Alin and comparison of the results with the characteristics of the self-similarity of the stream network.

## MATERIALS AND METHODS

**The morphostructural analysis** was carried out using the method suggested by Filosofov (1975) and adapted for calculation on a computer. The (DEM) SRTM v.3 digital elevation model with a resolution of 90 m was used as the initial data for both morphostructural and fractal analyses. To obtain the most accurate synchronization of the stream network and DEM, the watercourse network was simulated using the algorithms applied in most of the modern geoinformatic systems (Jenson and Domingue, 1988). In our case, ArcMap GIS was used. The watercourses calculated in this way (Fig. 1) were classified into orders according to the algorithm, in which the order of the valley increases only when two watercourses merge, have a lower order of magnitude by 1, and the intersection of two watercourses of different orders does not result in an increase in the order (Strahler, 1957; Filosofov, 1975). In the analysis, we considered all watercourses with a drainage basin of at least 1300–1400 thousand m<sup>2</sup> (200 elementary cells of the DEM SRTM). The first order was assigned to such watercourses. A total of ten orders of watercourses were identified at the given parameters within the studied area. Since the Ussuri River has the largest drainage basin within the studied area in the basin, this river is the ninth-order watercourse with the given parameters; the tenth order was assigned to the Amur River without analysis, as a watercourse of a clearly higher order. To identify the true order of the Amur River with the given calculation parameters, it is necessary to construct a stream network within the entire drainage basin of the Amur River, i.e., for an area several times larger than the area of the study, which was not part of our research task. This assumption does not affect the result in any way, since the tenth-order watercourse is the only such watercourse and is not included in further processing and analysis. The watercourses of the first order are the most widespread, their portion exceeds 50%; the number of watercourses of the second order is ~23%; of the third order, <12%; of the fourth order, ~6%. There are very few watercourses with orders of higher than fifth (in total, 9%, of which the fifth order is ~3%, and the sixth order is ~1.5%). These are mainly transit watercourses with a developed equilibrium profile. In further analysis, we limited ourselves to the first–sixth orders.



**Fig. 1.** The stream network model for the studied area calculated by the DEM SRTM.

Based on the initial data available for the streams of six selected orders, a set of monobasis surfaces was calculated. These are interpolated surfaces constructed from the thalwegs of streams of each order that to some extent reflect the remnants of the ancient relief of the time of occurrence of streams of these orders, as well as different surfaces that reflect the evolution of the relief in the period between the formation of water-courses of different orders (Filosofov, 1975). Since the distribution of streams, especially of higher orders, is not uniform, the monobasis surfaces were interpolated linearly with smoothing by the nearest environment method in order to exclude artifacts caused by the peculiarities of the interpolation algorithms.

The structural and geomorphological studies, including the morphostructural analysis, should involve the erosion resistance of relief-forming rocks as a significant factor. The material composition of rocks is heterogeneous within the studied region. Hard igneous and metamorphic rocks, as well as sedimentary rocks with a noticeably lower hardness, mainly terrigenous, are widespread. Within our study, the

actual erosional strength of rocks, determined by Bastrakov (1971) as the ratio of the power of the erosion flow to the erosion rate cannot be calculated without an additional research. Therefore, we used an indicator proposed by Rzhevskii and Novik (1984) as a coefficient characterizing erosion resistance, which characterizes the difficulty of rock destruction, a generalized and more universal characteristic than the compressive strength coefficient, which is widely applied to assess the strength of rocks. A direct relationship between the erosional hardness and compressive strength for different lithological types of rocks was shown by Bastrakov (1971).

The correlation between the compressive strength and the index of the difficulty of destruction, as well as the correspondence of these coefficients to different types of rocks, was adopted according to published tables (Gornaya..., 1987). To evaluate the influence of lithological heterogeneity on the formation of the relief and subsequent comprehensive analysis, we used the State Geological Map of the Russian Federation with a scale of 1 : 1000000 (Gosudarstvennaya..., 2011)

and compiled a map of the difficulty of rock destruction. In accordance with the above-described correlation between the difficulty of destruction and erosion resistance this map can be used as an analogue of the erosion resistance map. In addition, in order to reveal the influence of the lithological composition of rocks on the morphology of the relief the steepness of the slopes was calculated as well.

**Study of the self-similarity patterns of the stream network.** As mentioned above, in addition to many different factors, including climatic and hydrological ones, the patterns of the geological structure, and the lithological composition of rocks and fracturing, the formation of the stream network pattern is significantly influenced by the latest and modern vertical tectonic movements. This makes its pattern one of the most sensitive markers of these processes.

Feder (1991), Pelletier (1999), and Turcotte (1997) considered the basic relationships between the key parameters of drainage basins, which have a power-law nature and can be used to describe the stream network patterns quantitatively using the approaches of fractal geometry.

It is known that the stream network pattern changes with different directions of neotectonic vertical movements. Thus, a relatively large number of short channels with a frequent change in orders may indicate a local uplift regime, while elongated streams of the same order with a relatively rare change in orders may indicate a local regime of subsidence (Filosofov, 1975). The exponential indicator of the distribution of streams by the length can serve as a quantitative expression of this dependence:

$$N \sim L^{-\alpha}, \quad (1)$$

where  $N$  is the number of streams of a specific order (or range of orders) and  $L$  is their length. This parameter makes it possible to characterize the ratio of channel lengths: the greater the relative share of short channels is, the higher  $\alpha$  is.

Usually, fractal analysis calculates the fractal dimension  $D$ , which is an indicator in a power law like

$$N \sim \delta^{-D}, \quad (2)$$

where  $\delta$  is the considered scale and  $N$  is the number of elements of a given scale. We used the box dimension method (Feder, 1991; Turcotte, 1997) to calculate  $D$ . This characteristic can be applied for the numerical analysis of the density of streams and the frequency of order changes.

We describe the density of watercourses by the fractal dimension of the stream network pattern and denote it as  $D_r$ . The higher values of the fractal dimension  $D_r$  correspond to both the areas of the winding channels and the zones with frequent branching of the stream network; therefore, using this parameter alone

it is not possible to distinguish between the tectonic regimes of uplifts and subsidence reliably.

To characterize the degree of branching of the stream network, the fractal dimension of the set of points at which the order changes was calculated; we denote it by  $D_{oc}$ . The higher values of this parameter will occur in the areas where frequent branching (change of order) of channels occurs, which corresponds to uplifts.

The self-similarity analysis of the hydraulic network was carried out in a sliding window using the author's modernized FrAnGeo v.3.3 software. We analyzed all three characteristics of the self-similarity of the stream network and selected the parameters of the windows and the scale taking the following circumstances into account: the scale range for any type of self-similarity analysis for reliable determination of its parameters must be no less than the first order; the lower boundary of the scales must be such that it belongs to the scaling region, i.e., the validity of relations (1) and (2). The upper boundary of the scales should be such that the analytical window fits into the size of the region a sufficient number of times to compile a detailed pattern of the spatial variations of the analyzed characteristics.

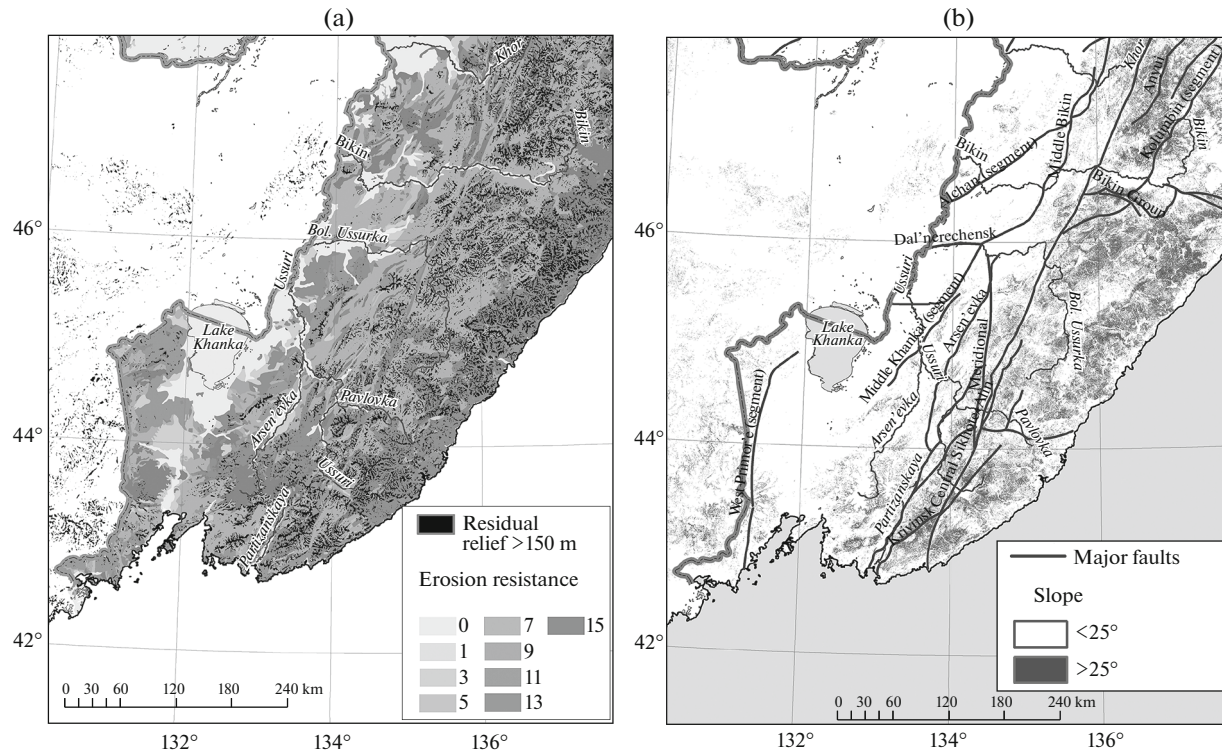
As a result of test calculations, the following window parameters were selected: the window size was  $0.5 \times 0.5^\circ$  ( $\sim 40 \times 40$  km at a given latitude); the overlap was  $0.25^\circ$  ( $\sim 20$  km); and the range of cell sizes that were used in the calculation was from  $0.5$  to  $0.05^\circ$  ( $\sim 40$ – $4$  km).

**The complex self-similarity parameter.** The parameters described above that characterize the stream network are usually used separately during fractal analysis. Although all of them, to one degree or another, reflect vertical movements of different directions, individually they do not allow comparison with neotectonic movements and distinguishing the conditions of uplift and subsidence. A dense network with relatively large orders corresponds to subsidence, while that with relatively short orders indicates uplift. In order to improve the methodology, we propose to use a *complex* (combined) self-similarity parameter that combines several characteristics of the stream network pattern.

The following combination is proposed as such a PRNS (Parameter of River Network Self-similarity) parameter:

$$\text{PSRN} = \langle D_r \rangle + \langle D_{oc} \rangle + \langle \alpha \rangle, \quad (3)$$

where the excess over the minimum value for each parameter, normalized to the range of variations in angle brackets, is given in angle brackets. Normalization is necessary to bring the variations of each parameter to the same range (from 0 to 1). Such a combination is necessary for more correct reflection of tectonic movements of the sign in the resulting values of the PRNS parameter. The proposed parameter is new;



**Fig. 2.** A comparison of the map of erosion resistance and residual relief with a height of less than 150 m (a) and the distribution of relief with a slope steepness of more than 25° within the studied region (b).

we tested the probability and efficiency of its application in comparison with the results of morphostructural analysis. This work continues our research on the development of a methodology that provides identification of the neotectonic movements using fractal analysis techniques.

## RESULTS AND DISCUSSION

**Morphostructural analysis.** The studied area is composed of rocks that differ significantly in strength. At the same time, the relief of this area is ancient and developed over a long time, which can neutralize the influence of the strength of rocks that form the relief. In order to assess the influence of rock strength on the formation of the relief, we compared the residual relief and the map of rock strength (Fig. 2a). It was shown that the residual relief with a height of more than 150 m is estimated somewhat better in the areas where the stronger rocks are exposed on the day surface. However, it cannot be argued that the strength of rocks is a key factor, since the high residual relief within the Central Sikhote-Alin in the areas of distribution of significantly less strong rocks is quite widespread as well. In addition, it is important to note that the high residual relief is distributed to a much greater extent to the east from the Central Sikhote-Alin Fault (Fig. 2a). It is significant that slopes with a steepness of more than 25° are registered almost exclusively to the east from

the Central Sikhote-Alin and Partizanskii faults (Fig. 2b) and their distribution correlates well with a high residual relief (Fig. 2). It can be assumed that the high residual relief is most likely due to more intense upward movements to the east from the Central Sikhote-Alin Fault at the last stages in the evolution of the Sikhote-Alin. In this regard, in further constructions, we proceeded from the fact that the factor of the erosional stability of rocks in the studied region is not decisive in the formation of the relief and can be largely neglected.

The configuration of the most ancient relief of the Sikhote-Alin within the Primorsky Region, which can be analyzed by the proposed method, is reflected in the monobasic surface plotted along the valleys of the sixth-order streams (Fig. 3a). There are no reliable markers of the age of this relief. It can be noted that the highest values of the height of this ancient relief are registered to the north from the B. Ussurka River, while the height of the relief in the south was insignificant. Apparently, the valleys of the Bikin, B. Ussurka, and Pavlovka rivers already existed at that time and crossed the Sikhote-Alin in a sublatitudinal direction.

The younger relief, reflected in the monobasic surface of the fifth order (Fig. 3b), can be presumably dated as the Oligocene, which is the time of the formation of the sandstone and conglomerate of the Uglovinskaya Formation of the Oligocene. The frag-

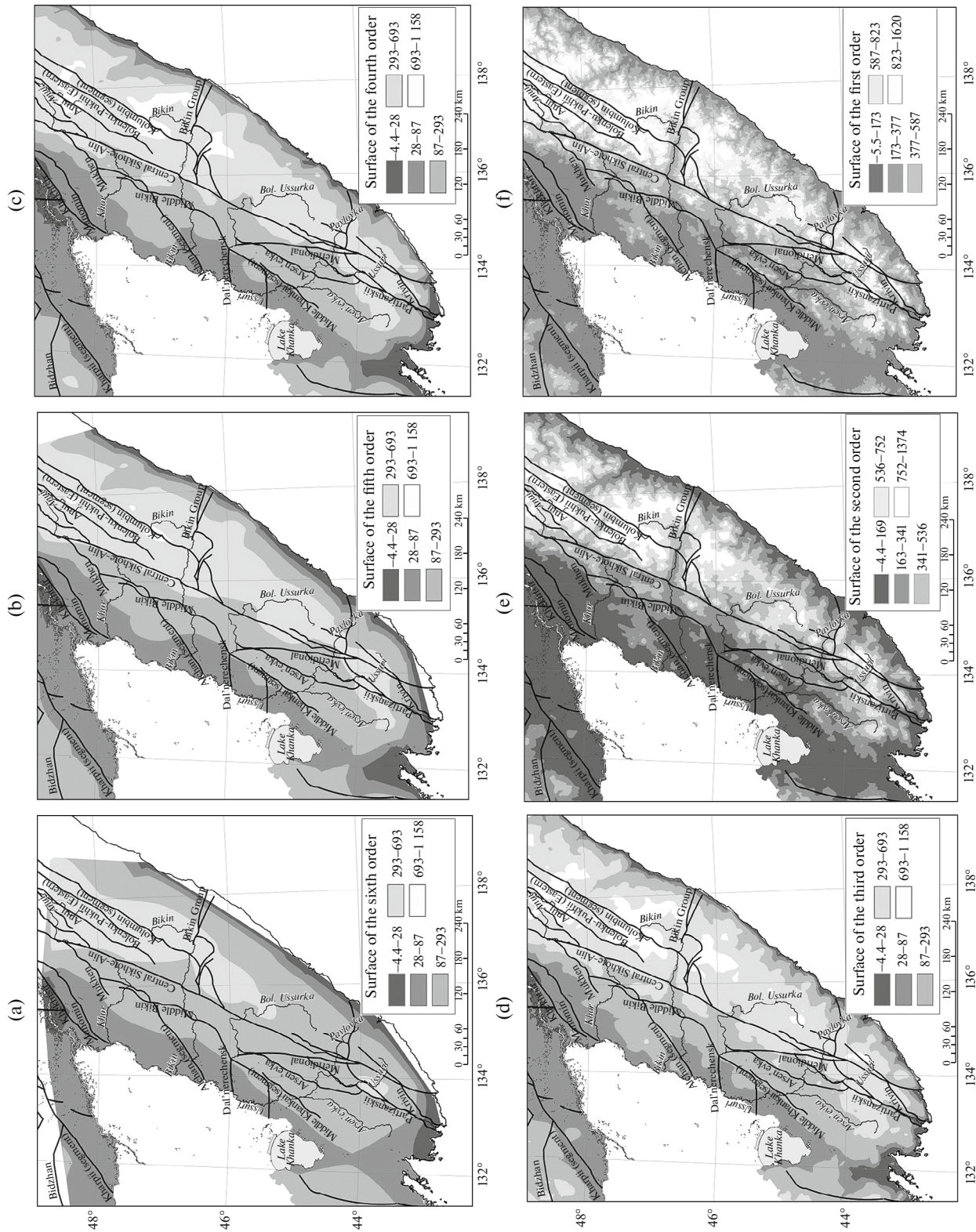


Fig. 3. Monobasis surfaces plotted along watercourses of different orders. (a) Sixth order; (b) fifth order; (c) fourth order; (d) third order; (e) second order; (f) first order.

ments of deposits of this age have been preserved in the valleys of large rivers. The most significant areas of deposits of the Ugolinskaya Formation within the Central Sikhote-Alin are detected in the middle course of the Bikin River, within the depression found in the fifth-order monobasis surface. As is evident from the analysis of the differential surface of the fifth and sixth orders (Fig. 4a), there was a relatively uniform uplift of the entire Sikhote-Alin up to the Oligocene, which was somewhat more intense in the regions to the north from the B. Ussurka and Bikin rivers.

This uplift on the eastern slope was compensated by the erosion of large rivers, which is expressed in close to zero or even negative values of the differential surface in the middle and lower reaches of the B. Ussurka, Arsen'evka, and Pavlovka rivers, as well as in the upper reaches of the modern Ussuri River. It is interesting that uplift was compensated by erosion, not completely, but to a large extent, in the upper reaches of the Bikin River, within the Central Sikhote-Alin, while this is not observed in the middle reaches. It is unlikely that significant vertical displacements occurred along the Central Sikhote-Alin Fault at that time. It is important to emphasize the rather intense erosion of the more ancient relief between Lake Khanka and the Gulf of Peter the Great. Based on this, we may assume that in the Paleogene the flow of the rivers of the western slope of the Sikhote-Alin was directed to the south, to the Gulf of Peter the Great, and not to the north, to the Amur, as it is at present. According to the analysis of the monobasic surface of the fourth order (Fig. 3c), it can be assumed that by the time of the formation of modern watercourses of the fourth order, the valleys of the largest rivers in the region acquired their modern outlines. The relief of the southern end of the Sikhote-Alin became higher.

The most interesting conclusions can be drawn from analysis of the differential surfaces of the fourth and fifth orders (Fig. 4b). Based on the analysis of this surface, it can be assumed that by the time of the formation of the relief, whose configuration is reflected in the monobasis surface of the fourth order, the activation of large faults, including the main structural suture of the Sikhote-Alin–Central Sikhote-Alin Fault, took place. It is clearly evident that the areas to the east from the Central Sikhote-Alin, Partizanskii, and Izvilistyi faults experienced quite intense uplift, while to the west, the areas of positive relief increment are fragmentary, and a large area is occupied by areas with zero values. This may indicate that the vertical movements were completely compensated by erosion and sedimentation during this period.

In the areas to the east from the Central Sikhote-Alin Fault, zero values of the differential surface were registered along the valleys of the largest rivers higher than the fourth order only. This indicates that, in general, the uplift rate of this area during the formation of

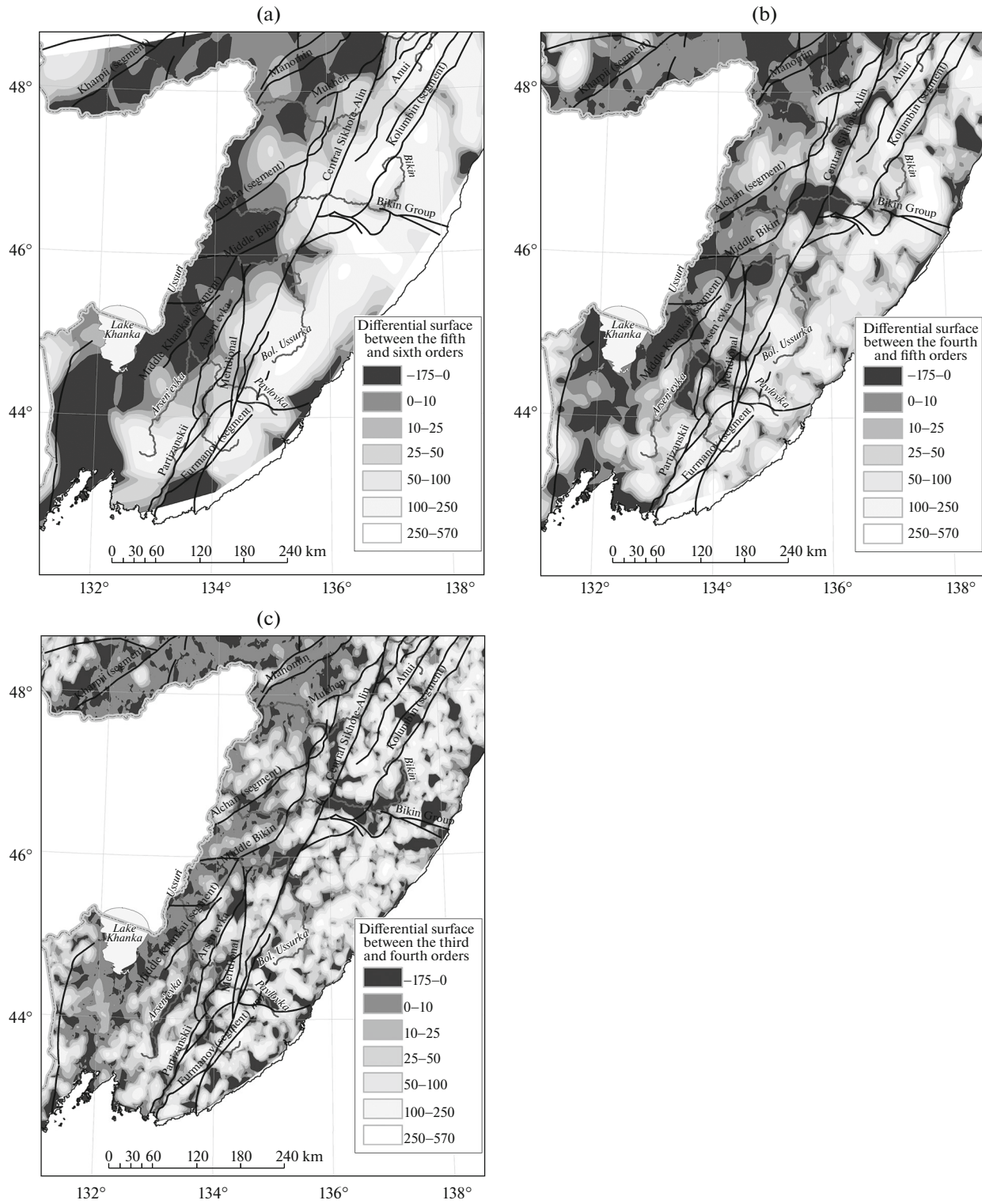
fourth-order rivers exceeded the intensity of erosion, and, if it was compensated, it was only for the large rivers.

At the same time, it is necessary to emphasize the intensive erosion of the more ancient relief by the rivers along the activated faults and crossing them, which may indicate the formation of a type of “ledge” formed due to the vertical movements along these faults. The erosion of the more ancient relief of the Bikin River at its intersection with the Central Sikhote-Alin Fault is the most striking example. The faults that cut the Sikhote-Alin in the latitudinal direction, namely the Bikin and South Primor'e zones of the Izvilistyi Fault, became more active at that time. The areas located to the south from the South Primor'e Zone and to the north from the Bikin Fault experienced a more intense uplift than the segment enclosed between these faults and the block located to the southeast from the Izvilistyi Fault and the Primor'e Zone experienced an uplift with the highest amplitude.

In addition, we note that significant uplift at this time was experienced by the entire region to the south of 44° N. Intensive erosion of the area between Lake Khanka and the Gulf of Peter the Great, which we noted at the previous stage of the evolution of the relief, was no longer occurring this stage. It can be assumed that the river flow from the western slope of the Sikhote-Alin was redirected to the Amur at this time. Most likely, the described activation of the neotectonic movements was synchronous to the Pliocene basaltic volcanism, and the most significant increment of relief in the upper reaches of the Bikin River, noted on the differential surface, is due to the eruptions of basalt and the formation of the largest Zevin basaltic plateau.

The monobasis surfaces of the third, second, and first orders (Figs. 3d–3f) reflect the evolution of the relief in the Pleistocene. The most useful information about the evolution of the relief at the considered stage can be obtained from the analysis of the corresponding differential surfaces.

Thus, analysis of the differential surface of the third and fourth orders (Fig. 4c) shows that stabilization of vertical tectonic movements occurred at the beginning of the Pleistocene. The increment in the relief height over the entire area of studied territory is almost the same, with a slight predominance in the north. The increment of the relief is combined with erosion of the more ancient relief (as is evident from the negative values of the differential surface) and the erosion is more intense in the places where the most intense uplift took place at the previous stage of the evolution of the relief. It is noteworthy that no signs of vertical movements along the large faults were noted. The areas of more ancient relief erosion in the valleys of large rivers move upstream in relation to the areas of erosion that were noted at the previous stage, i.e., backward erosion occurs and new profiles of these rivers were developed.



**Fig. 4.** Differential surfaces between the monobasis surfaces of the fifth and sixth orders (a), the fourth and fifth orders (b), and the third and fourth orders (c).

This indicates the stability of the region and the formation of the relief mainly due to the erosion. The western slope of the Zevin basaltic plateau is being

actively eroded. Less intense erosion and a smaller relief increment are characteristic of the segment between the Bikin Fault and the South Primor'e Zone



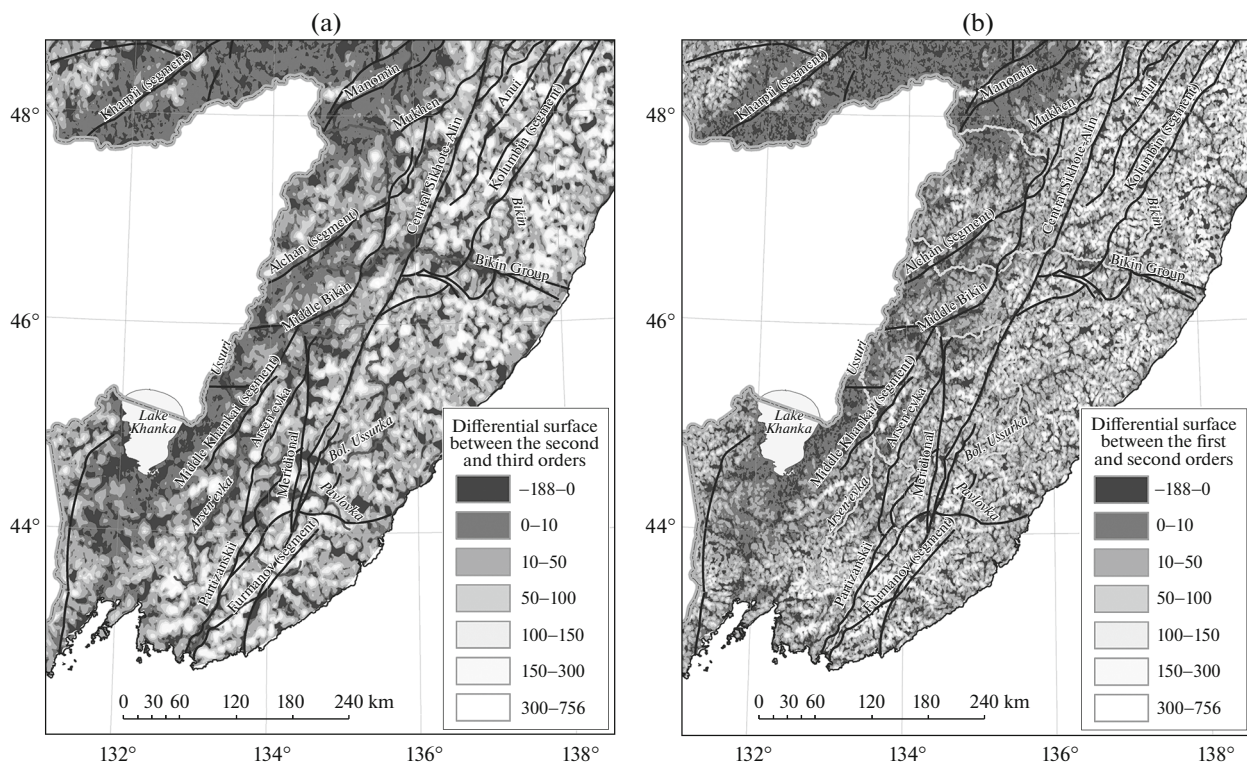


Fig. 5. The differential surface between monobasis surfaces of the second and third orders (a), first and second orders (b).

of the Izvilystyi Fault, which can be explained by the fact that the amplitude of the neotectonic uplifts at the previous stage was lower.

Analysis of the differential surface of the second and third orders (Fig. 5a) shows that the situation did not change at this stage. There is no evidence for intense vertical movements; gradual erosion of the previously formed relief continued.

The differential surface between the first and second orders (Fig. 5b) indicates that the situation did not change fundamentally at the end of the Pleistocene. No evidence of pronounced vertical movements was detected.

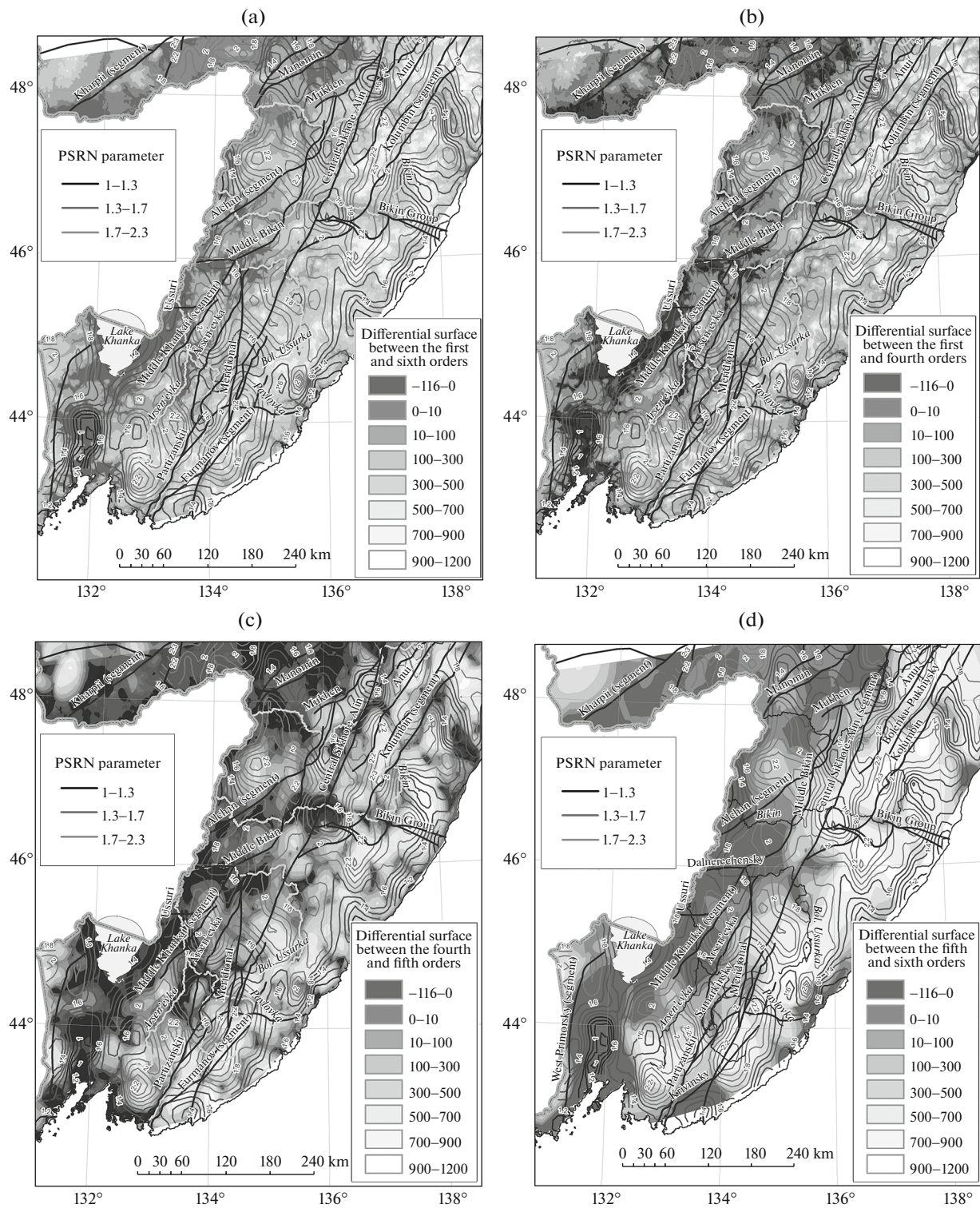
Most likely, an insignificant activation of the Central Sikhote-Alin Fault occurred again in the Holocene. This is reflected in the fact that the high residual relief and the steepness of the slopes of the modern relief are manifested almost exclusively to the east from it (Fig. 2). However, we can assume that this activation was extremely insignificant, since a key role is played in the formation of a high residual relief by the fact that the relief was subjected to erosion that was initially higher than that developed to the west from the Central Sikhote-Alin Fault.

Thus, using the structural–morphometric method, we may trace the evolution of the Sikhote-Alin relief starting from the Oligocene. Three stages of the evolution of the relief, reflecting the neotectonic activity can be distinguished: the pre-Oligocene stage of the

evolution of the Sikhote-Alin; the stage of the Oligocene–Pliocene activation characterized by rather intense vertical movements and a well-pronounced activation of the Central Sikhote-Alin Fault; and the Pleistocene stage, during which significant vertical movements did not occur and the modern erosion–denudation character of the relief was formed.

**Comparison of the results of morphostructural analysis with the results of fractal analysis of the stream network.** The stream network pattern was formed throughout the neotectonic stage of the evolution. In this regard, the most justified aspect is the comparison of our proposed PRNS parameter of fractal dimension with a differential surface of first–sixth orders, reflecting the total change in the topography from the Oligocene to the end of the Pleistocene, which occurred both as a result of vertical neotectonic movements and as a result of erosion and denudation. This differential surface reflects the total trend of vertical movements for the neotectonic stage, without division into sub-stages.

Comparison of the differential surfaces of the first and sixth orders with the spatial distribution of the complex PRNS parameter of the stream network (Fig. 6a) shows that, in general, the maxima of the PRNS parameter coincide with the regions of the highest relief increase, while the minima coincide with the regions of the lowest relief increase or with areas of the most significant erosion. However, such a coincidence is not observed everywhere; areas with an inverse cor-



**Fig. 6.** A comparison of the complex self-similarity parameter PRNS with the differential surface between the monobasis surfaces of the first and sixth orders (a), first and fourth orders (b), fourth and fifth orders (c), fifth and sixth orders (d).

relation occur. In our opinion, this is due to the previously described stages in the evolution of the relief, as well as due to the inversion of vertical movements on the same territory at different stages. The younger

stream network formed a pattern characteristic of younger movements, but at the same time, the older and more developed stream network were conserved and reflected the direction of the movements that

occurred at the previous stage of the evolution of the relief, which is evident from the results of fractal analysis.

As was noted above, the largest number (>90%) of watercourses are those of the first to fourth orders; they make the greatest contribution to the calculation of the fractal characteristics of the stream network. Based on this, we should assume that the fractal characteristics of the stream network mostly reflect the total evolution of the relief for the period from the inception of the fourth-order streams to the inception of the first-order streams. For the studied region, this is the period from the end of the Pliocene to the end of the Pleistocene. As a result of the structural-morphometric analysis, this time interval was mostly characterized by the erosion–denudation processes, which are reflected in the total differential surface between the first and fourth orders.

Comparison of the results of fractal analysis with this differential surface demonstrates (Fig. 6b) that some minima superimposed on areas with a significant increase in the relief over the entire neotectonic stage can be explained by the most intense erosion of the relief formed at the previous stages during the final the Pleistocene stage. Some maxima are explained by the dissection of the relief into isolated ridges during intense erosion rather than by the neotectonic uplift itself. Comparison of the results of fractal analysis with differential surfaces reflecting the evolution of the relief at the previous stages (Figs. 6c and 6d) shows the coincidence of individual minima and maxima of the *PRNS* parameter as well, which could not be explained in the previous analysis.

## CONCLUSIONS

A morphostructural analysis of the relief and a comprehensive analysis of the self-similarity of the Sikhote-Alin stream network within the Primorsky Region were carried out; a series of monobasic and differential surfaces were constructed, which allowed us to trace the neotectonic evolution of the studied region from the Oligocene.

It was shown that the relief was formed in several steps at the neotectonic stage, which was reflected in the features of the stream network pattern. Before the Oligocene, the Sikhote-Alin uplift was approximately uniform. The activation of vertical neotectonic movements was most likely synchronous to the Pliocene basaltic volcanism; they were most intense to the east from the Central Sikhote-Alin Fault. Vertical movements of significant amplitude most likely did not occur during the Pleistocene; at that time, the modern erosion–denudation relief typical of the studied region was formed. At the end of the Pleistocene–Holocene, there was probably a minor activation of recent vertical movements to the east from the Central

Sikhote-Alin Fault, which was reflected in the features of the residual relief development.

The results of morphostructural and fractal analyzes have been compared. As a whole, the results showed satisfactory correlation: the maxima of the complex self-similarity parameter *PRNS* coincide with the regions of the greatest relief increment, while the minima coincide with the regions with the smallest relief increment, or with the regions of the most significant erosion.

In regions with a staged nature of their neotectonic evolution it is necessary to take additional factors into account when carrying out fractal analysis of a stream network due to both the characteristics of the stream network at each stage of the evolution and the conservation of its pattern.

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