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TECTONICS

Late Tectonic Vertical Movements of the Russian Far East

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Abstract—Morphostructural analysis of the stream network in the southern part of the Far East has been carried out. It has been established that the latest vertical movements in the region were manifested against the background of an older, partially eroded relief. Three stages of relief development are identified, reflecting neotectonic activity in the region: (a) pre–Oligocene, characterized by a more intense uplift of the Bureya Ridge, and less intense, the Sikhote-Alin Ridge; (b) Oligocene–Pliocene, characterized by the most intense vertical movements in the region during the period from the Late Eocene to the Holocene; and (c) the Pleistocene and the Holocene, during which a modern erosion-denudation relief was formed and no vertical movements of significant amplitude occurred. A map of the total amplitude of vertical neotectonic movements is constructed.

Keywords: latest tectonics, morphostructural analysis of the stream network, vertical movements, Russian Far East

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INTRODUCTION

The territory of the southern part of the Russian Far East is rather well provided with modern geological–geophysical and cartographic material in comparison with some other regions: (1) practically the entire territory of the southern part of the Russian Far East is covered by the State geological maps of scale 1 : 1000000 of the third generation, a distinctive feature of which from the maps of previous generations is the use of GIS-technologies, modern methods of absolute geochronology, deep geological–geophysical research, and space remote sensing data [9]; (2) the tectonic basis available for the territory was created according to the principles of terrane analysis, passed the test of time, and, importantly, is constantly being improved [1, 16]; (3) maps of the depths of the basement and roof of the magnetically active layer, Moho, 3D-density model [5, 4, 17]; (4) maps of fractal dimensions for the field of earthquake epicenters and parameters of their recurrence [20].

The study of neotectonic movements in the region presents a contrast in this respect. The last, and probably only, detailed neotectonic map of the south of the Russian Far East at a scale of 1 : 2500000 was published more than 23 years ago [2]. A significant drawback of the above-mentioned work was the absence of any description of the methodology used to construct this map, which makes it difficult to give an adequate assessment of the reliability of the data shown, in particular, vertical movements with an amplitude of 3.5 km, from –1 to +2.5 km. One should also mention the Neotectonic Map of Northern Eurasia [6], which shows the latest structure of the mainland and adjacent water areas in a single legend. The situation is different for this map in terms of the methodological support. Grachev [3] considered the methodological aspects of map construction in sufficient detail with a brief characterization of geodynamic processes determining the neotectonics of the regions. The range of vertical motions for Sikhote-Alin and adjacent territories according to the data of this map is ~2.2 km from –0.7 to +1.5 km. This differs significantly, by more than 1 km, from the data reported in [2]. The small scale of the map (1 : 5000000) [3, 6] does not allow for spatial correlation with more detailed geological and geophysical constructions for the Sikhote-Alin region made by us and other authors.

The Explanatory Notes to the State Maps of the third generation of the southern Russian Far East contain sections on the neotectonics of the corresponding sheets, but all of them are based on the materials of [2]. Therefore, several years ago we set the task of constructing a new neotectonic map for the southern part of the Russian Far East [11, 12] using a digital eleva-

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tion model and a stream network model built on its basis by calculating a number of structural and morphometric base surfaces.

This paper presents the methodology and actual materials used to construct base and difference surfaces with ages from the Holocene to the Eocene and the final map of vertical movements for this period. The calculated base and difference surfaces are presented in the supplementary materials.

CALCULATION METHODOLOGY AND ASSESSMENT OF THE INFLUENCE OF THE LITHOLOGIC COMPOSITION OF ROCKS ON THE TOPOGRAPHY

The amplitude and direction of the neotectonic movements could change in time, as the rate of uplift or subsidence in various areas and time intervals can be different, which has a determining influence on the topography in general and the hydrographic network, in particular. The structural morphometric method of constructing base surfaces based on the confluence points of watercourses of the same order [19, 14], developed by Filosofov [14, 15], not only identifies developing tectonic structures but also provides a means to assess their temporal evolution. Watercourses of higher orders develop, in general, over a longer time and reflect the sum of movements from the time of their emergence to the present day, while the development of watercourses of lower orders reflects neotectonic movements over a shorter and more recent period of time. Therefore, a comprehensive analysis of the base surfaces, constructed using thalwegs of watercourses of different orders, allows the evolutionary stages of both topography as a whole and of its individual recent structures to be traced. In this study, the model of the stream network and base surfaces was built using a method adapted for neotectonic studies by automatic calculation [10–12] using standard techniques [8].

The morphostructural analysis was based on the SRTM3 v.3 digital elevation model with a resolution of 3″ (Fig. 1), which was used to calculate the stream network preliminarily sorted into orders (Fig. 2). The stream order was increased only when streams of the same order merged [19, 14, 15]. All streams with a catchment area equal to $\sim 1.3 \times 10^5$ m^2 (200 DEM elementary cells) were considered. Such streams were assigned the first order. In total, ten stream orders were distinguished, with the tenth order assigned to the Amur River artificially as the largest and oldest stream with a catchment area exceeding the size of the study area (Fig. 2). Streams of the 8th and 9th orders are single, so they, as well as the tenth order stream, were excluded from further processing and analysis. We believe that this did not affect the final result of the assessment of the latest vertical movements.

A set of base and difference surfaces constructed for watercourses of orders 1–7, the number of which exceeded 250000 (Suppl. A1–A13), reflected the development of relief in the period between the inception of watercourses of different orders [15]. In order to exclude artifacts caused by the peculiarities of interpolation algorithms, the base surfaces were interpolated linearly with smoothing using the Average Nearest Neighbor algorithm [18].

To determine the influence of the lithological composition of rocks on the topography in two areas of the territory, the Sikhote-Alin ridges in the southeastern part and the Duse-Alin ridges in the northwestern part of the territory studied, within which there are outcrops of rocks with different resistance to weathering (Precambrian and Cretaceous granites, terrigenous rocks of different lithology and age), we analyzed the residual relief (difference surface between the modern relief and the base surface of the first order), on the one hand, and the slope steepness, on the other hand. It has been established that the lithology of rocks on the scale of the conducted research does not have a determining influence on the landforms, and this factor can be largely neglected. This can be due to the fact that the influence of the strength of the rocks composing the relief could be largely leveled out during the formation of ancient relief that has been developing for quite a long time. In addition, since the equilibrium profiles of watercourses older than the third order are mostly flattened and valley slopes do not exceed 3°, we believe that the presence of areas of high residual relief with steep slopes can also be explained by long-term erosion of the initially high ancient relief that has not yet reached equilibrium.

The calculation of neotectonic vertical movements was carried out only by mathematical processing of the digital elevation model without preliminary interpretation.

MORPHOSTRUCTURAL ANALYSIS

The shape of the most ancient terrain within the study area, which could be obtained by the method proposed, is shown in the base surface constructed along the valleys of watercourses of the seventh order (Suppl. A1). There are no reliable markers of its age; it can be assumed, however, that the terrain reflected in the surface that existed before large transit watercourses were formed within the Eocene rift troughs (such as the Amgun River flowing in the Upper Amgun intermountain trench); according to the model hydrographic network adopted in this study, these rivers are watercourses of the sixth order.

The base surface of the seventh order (Suppl. A1) suggests that the Eocene (pre-Oligocene) relief was rather high, asymmetric, with steep eastern and gentle western slopes, manifested in the Bureya Ridge in the

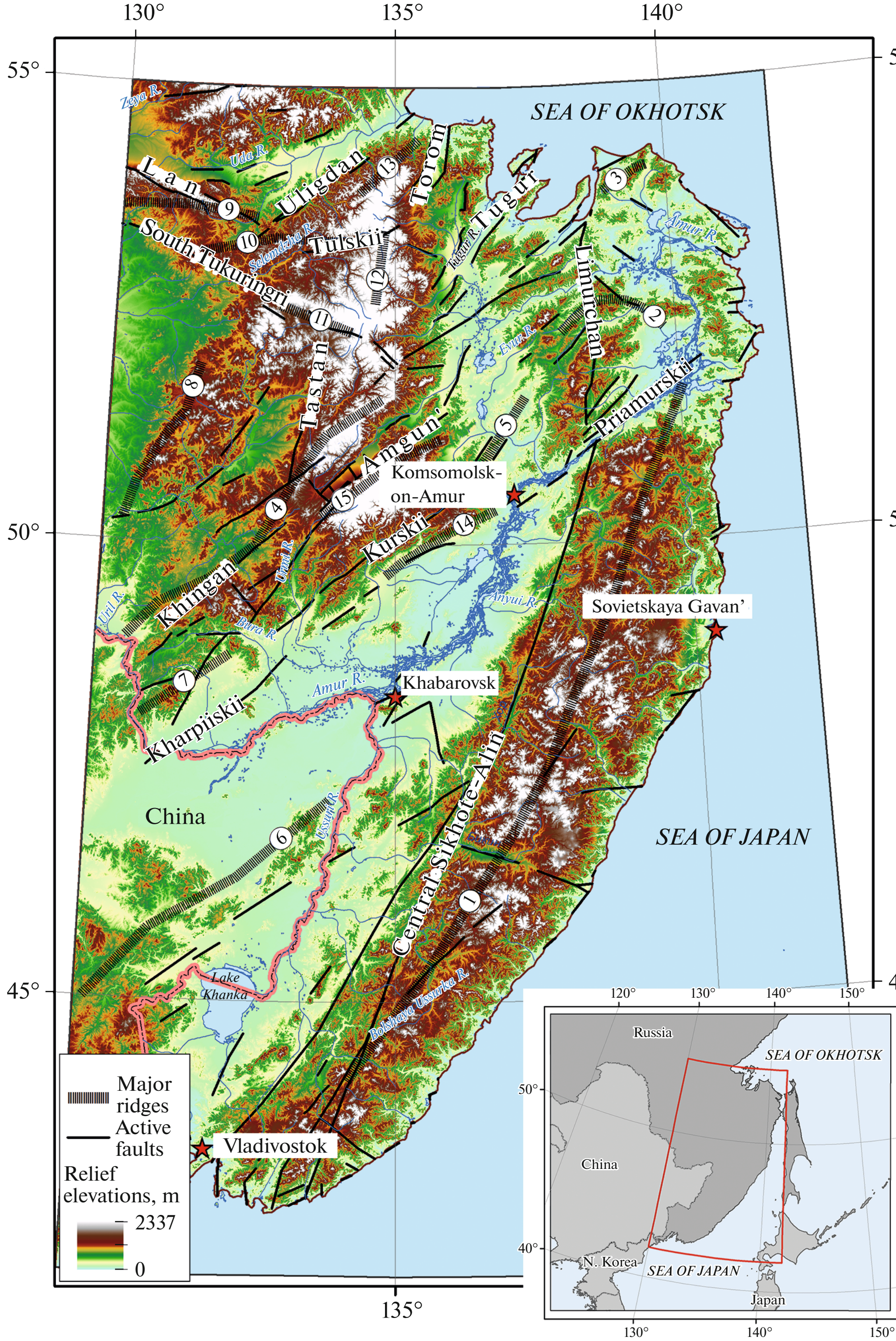

Fig. 1. Digital relief model of the southern part of the Russian Far East with indication of the main active faults and ridges, location of the work area (inset) on the geographical map of the eastern edge of Eurasia. Numbers indicate the ridges: 1, Sikhote-Alin; 2, Chayatyn; 3, Mevachan; 4, Bureya; 5, Myaochan; 6, Vandashan; 7, Kukan; 8, Turan; 9, Dzhagdy; 10, Selemdzha; 11, Ezop; 12, Yam-Alin; 13, Taikan; 14, Dzhaki–Unakhta–Yakbyyana; 15, Badzhal.

west and the lower Sikhote-Alin Ridge in the east. Moreover, there was probably no high relief east of the Evron-Chukchagir lowland and north of the modern Amur riverbed in its lower reaches.

The post-Eocene relief reflected in the sixth order base surface (Suppl. A2) was formed after large transit rivers such as the Amgun were formed within the Cenozoic rift troughs. The Bureya Ridge may have

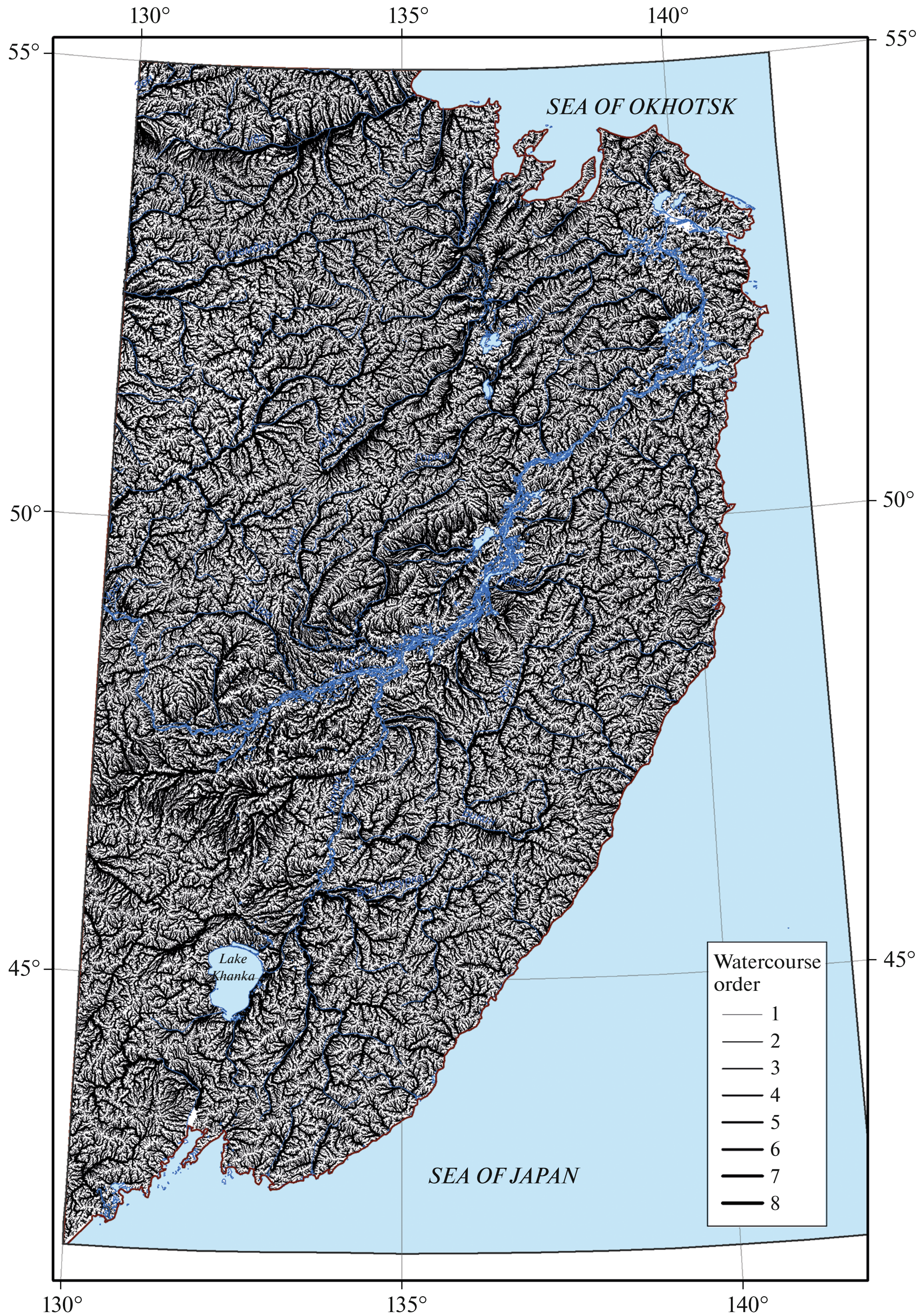

Fig. 2. Calculated model of the hydrographic network. Numbers indicate valley orders.

experienced uplift along with erosion at that time. The analysis of the difference surface between the base surfaces of the sixth and seventh orders shows that the greatest relief increment up to 400 m was in the southern part of the ridge; at the same time, there was significant erosion along the periphery of the ridge. The northern part of the Sikhote-Alin Ridge could also experience uplift, but less significantly: the maximum relief increment did not exceed ~280 m. It is also important that the uplift of the territory to the north of the modern Amur River bed in its lower reaches, the Khomi and Chayatyn ridges, though insignificant, began in that same (post-Eocene) period. The channel of the river system, which united the Sungari, Ussuri, Amur (north of Khabarovsk), Amgun, and other rivers, in the Oligocene (?) most likely passed through the Evron–Chukchagir lowlands northward toward the Sea of Okhotsk. Our assumption about the different position of the stream network based on the analysis of data on neotectonic vertical movements agrees with the assumption Melioranskii made almost a century ago: "The Amur River in this phase no longer flowed into the Sea of Japan due to a small tectonic uplift in the area of Kadi and Kizi lakes, which blocked access to this sea; instead, it found its way northward, using the lower part of the Amguni River valley for this purpose" (quoted from [7]).

In the southern part of the Bikin River, the highest elevations of this ancient relief were detected north of the Bolshaya Ussurka River, while the relief height in the southern part was insignificant. The topography reflected in the fifth order base surface (Suppl. A3) within Central Sikhote-Alin can be dated to the Oligocene, the time of formation of sandstones and conglomerates of the Uglovin Formation. Patches of sediments of this age were preserved in the valleys of large rivers of the Sikhote-Alin Range [12]. Analysis of this base surface, as well as the difference surface of orders 5 and 6 (Suppl. A12), suggests a major reorganization in the lower reaches of the Amur River. The Bureya Ridge continued to experience moderate growth. The uplift of the area to the north of the Priamurskii Fault became more intense. Most likely, the Evron–Chukchagyr lowland was also involved in this uplift. The modern antecedent valley of the Amur River began to form along the Priamurskii Fault roughly at the same time [12].

There was also a relatively uniform uplift of the entire Sikhote-Alin Ridge, somewhat more intense in the areas north of the Bolshaya Ussurka and Bikin rivers [11]. No significant vertical displacements were detected along the Central Sikhote-Alin Fault. It is important to note the rather intensive erosion of the ancient relief in the area between Khanka Lake and Peter the Great Gulf, which may indicate the southern direction of river runoff of the western slope of the southern part of the Sikhote-Alin Ridge. This agrees with the conclusions of Sorokin et al. [13], according to which, before the cardinal structural reorganization in the Neogene (?) time, the modern lower section of the Amur River (the river system that united the Sungari, Ussuri, Amgun, etc.) was not a continuation of its modern upper and middle sections (Amur, Zeya, Bureya, Liaohe, etc.). The outflow of the latter was directed southward to the Sunliao basin and further to the Bohaiwan Bay of the Yellow Sea.

Analysis of the base surface of the fourth order and the difference surface of the fourth and fifth orders (Suppl. A12) suggests that by the time of the beginning of the formation of the modern relief, the major faults, including the main structural suture of the Sikhote-Alin mountain system, the Central Sikhote-Alin Fault had been activated. The areas to the east of the fault experienced rather intense uplift, while the western areas of the positive relief increment were fragmentary and areas with zero relief elevation increment occupied large areas. Vertical movements during this period here were completely compensated by erosion and sedimentation. The intensity of uplift in the areas east of the Central Sikhote-Alin Fault generally exceeded the intensity of erosion [11]. At the same time, the older relief along the activated faults crossing large watercourses was subjected to intense erosion; vertical movements along these faults led to the formation of peculiar "scarps." The faults cutting the Sikhote-Alin Ridge in the latitudinal direction were also activated. The areas located between them experienced vertical movements of different intensity. The most significant uplift was in the area south of 44° N. It was probably at that time that the Amur River network acquired its present-day appearance, and the flow of rivers on the western slope of southern Sikhote-Alin was redirected from south to north to the present-day lower section of the Amur River basin. The antecedent valley of the Amgun River between the Omalskii and Omaldinskii ridges began to form. While the Sikhote-Alin Ridge was experiencing uplift, erosion and denudation processes were prevailing within the Bureya block. This activation of the neotectonic movements was presumably synchronous with the manifestation of Miocene–Pliocene basaltic volcanism [11, 12].

The analysis of base and difference surfaces of 3–1 order (Suppl. A5, A6, A7, A8, A9, A10) provides information on the development of the region during the Pleistocene–Holocene. At the beginning of the Pleistocene, the vertical tectonic movements were mainly stabilized. The relief increment over the whole area of the study area was approximately the same, and the intensity of incision (negative values of the difference surface) was rather high. The positive relief increment can largely be explained by erosion processes [11, 12]. It is important that erosion is more intense where the most intense uplift occurred at the previous stage of relief evolution. There are no signs of vertical intense movements along major faults. Areas of erosion of older relief in the valleys of large rivers were moving upstream relative to the erosion areas of the previous stage, indicating reversed erosion and the development of a new equilibrium profile of the rivers. Such a regime of relief development is typical, in general, for the entire Pleistocene–Holocene.

MAP OF NEOTECTONIC VERTICAL MOVEMENTS

At present, the lower boundary of the neotectonic movements in northern Eurasia is most often attributed to the Upper Oligocene–Lower Miocene in the Atlantic and Pliocene in the Pacific segments [3]. As shown above, we were able to trace the relief evolution of the southern Far East presumably from the Eocene, i.e., from some time earlier. The analysis of base surfaces and their differences showed that the neotectonic movements within the study area were manifested against the background of an older, partially eroded relief. The map of the neotectonic vertical movements in the southern part of the Russian Far East is presented in Fig. 3.

Neotectonic activity within the territory under consideration was manifested unevenly both in time and in space. The following three stages of relief evolution reflecting different intensities of neotectonic activity can be distinguished:

(1) pre-Oligocene, expressed in base surfaces of orders 5–7 and their differences, characterized by more intensive growth of the Bureya Ridge with positive amplitudes up to 700–800 m in its different parts, and more moderate growth of the Sikhote-Alin Ridge, with amplitudes up to 400 m in its northern part, up to 600 m in the central part, and up to 350 m in the southern part. This stage also saw a significant structural change in the lower reaches of the Amur River.

(2) Oligocene–Pliocene intensification, reflected in base surfaces of orders 5–4 and their difference (Suppl. A13), characterized by intense vertical movements. The range of positive vertical amplitudes at this stage was more than +550 m.

(3) Pleistocene–Holocene, expressed in base surfaces of orders 3–1 and their differences (Suppl. A8, A9, A10), during which no vertical movements of significant amplitude occurred. The range of vertical movements at this stage totaled up to 200 m. It was at this time that the modern erosion-denudation relief was formed; i.e., vertical movements in the area had an inherited character.

The seventh-order base surface (Suppl. A1), which reflects the pre-Eocene relief, does not show any details about significant parts of the study area, like the Southern Sikhote-Alin and the coast of the Sea of Okhotsk. Therefore, we took the sixth-order base surface as the initial surface for calculating the amplitude of the vertical movements. Consequently, the methods adopted in this study can be used to construct a map of vertical tectonic movements starting from the end of the Eocene. It should be noted that the sixth order base surface cannot be constructed along the ocean coast because the rivers flowing directly into the Sea of Okhotsk and Sea of Japan are of lower order; i.e., the coastal relief is younger. Therefore, it is impossible to sum up the total amplitude of vertical movements that occurred since the Eocene along the coast. This, however, only applies to the summarized map. The character of vertical movements in the coastal areas is reflected in the morphostructural analysis section.

Since neither the height of the initial relief nor the ratio between the rate of the latest uplift and the rate of erosional incision and denudation cannot be precisely determined, the difference between the fourth and sixth order base surfaces least affected and dissected by the modern erosion network, reflecting the uplift from the Late Eocene to the Pliocene, was taken as the value of the latest uplift. The median of the total erosional incision from the day surface to the fourth order base surface was adopted as the erosional incision synchronous with the uplift. Thus, the amplitude of vertical tectonic movements from the end of the Eocene to the end of the Pliocene are reflected in the sum of the difference surface of the fourth and sixth orders and the surface of the median of the total erosion incision of the relief (Suppl. A13).

It is noteworthy that the character of vertical movements of the Bureya and Sikhote-Alin ridges in the time interval from the Eocene to the Pliocene is significantly different. The Bureya Ridge experienced more intense asymmetric uplift than the Sikhote-Alin Ridge, with a gentler western and steeper eastern slope at the early stages. Moreover, the ridge itself was dissected by rift-like troughs initiated in the Oligocene.

The amplitude of vertical movements within the Sikhote-Alin Ridge at that time was much smaller and increased from south to north. The areas with higher rates of recent movements, located east of the Central Sikhote-Alin Fault, have the configuration of echeloned blocks.

As was noted above, intense vertical tectonic movements probably did not occur during the Pleistocene, and erosion and denudation processes mainly prevailed. Nevertheless, we made an attempt to analyze this denudation part of the relief. For this purpose, we analyzed watershed elevations of adjacent (headwaters separated by a common watershed) rivers. Such analysis was carried out separately for the relief above the base surfaces of watercourses of orders 3, 2, and 1 in order to emphasize the block tectonics in the Early and Middle Pleistocene and Upper Pleistocene–Holocene. Higher watersheds of adjacent rivers, completely surrounding the relief area under consideration, are believed to testify to the presence of a tectonic block and its more intensive uplift relative to the surrounding areas.

The analysis showed that the intensity of vertical movements of blocks at that time was low, with amplitudes rarely exceeding 100 m, and it was significantly higher within the Sikhote-Alin mountain system compared to the Bureya Ridge. It appears important that several echeloned blocks with the boundaries practically coinciding with the those identified for the Oligocene–Pliocene were distinguished within the former, south of the Bikin Fault (~46° N). More intense uplift of the central Sikhote-Alin Ridge is observed north of the Bikin Fault, while in its northern part the activity of vertical movements decreases.

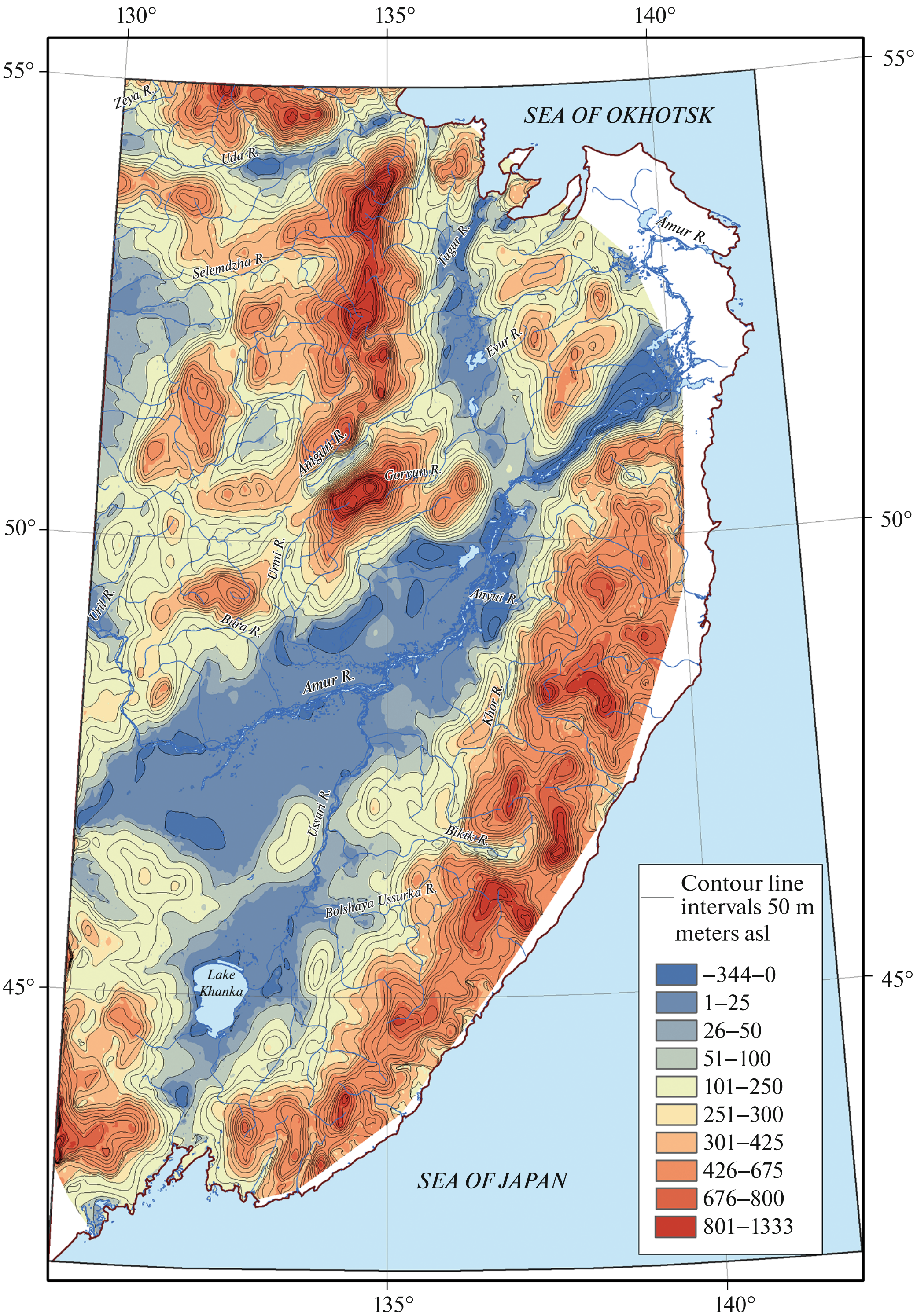

Fig. 3. Map of the neotectonic vertical movements in the southern part of the Russian Far East. Contour lines are drawn at 50 m intervals.

The general pattern of neotectonic movements in the Middle Pleistocene was essentially the same, but their amplitude became much smaller, and the boundaries of the distinguished blocks became less pronounced. By the end of the Pleistocene and beginning of the Holocene, the vertical movements had become of arched rather than block character; those were more intensely manifested in the north of the Bureya Ridge and in the central part of the Sikhote-Alin Ridge.

The map of vertical neotectonic movements (Fig. 3) is calculated as their sum from the end of the Oligocene to the Holocene, their span being 1540 m, and from –220 m in the area of the lower reaches of the Amur River along the Khomi Ridge to 1320 m within the Badzhal Range. Since the structural–morphometric method does not allow confident identification of regional negative movements and the analysis of boreholes and the sedimentary basin structure was not carried out within the framework of the present study, the negative values on the total map of vertical neotectonic movements in most cases indicate the intensity of erosional reworking of the pre-existing relief. Values close to zero are characteristic of areas within which subsidence was compensated by sedimentation. The total amplitude of vertical movements within the Bureya Ridge was higher than within the Sikhote-Alin mountain system. The most intense uplift of the Bureya Ridge, however, occurred before the Pleistocene, while the Sikhote-Alin Ridge was more active at later stages of development, including the Pleistocene. The map of the neotectonic vertical movements that we have constructed in general has qualitative similarity with the previously published maps of the late tectonics of the southern Far East [2, 3], but at the same time it has significant differences in estimating both the amplitudes of the latest movements and their age. We believe that our map more clearly reflects the structure geometry and block structure of the region.

It should be mentioned that all the maps presented in this study are constructed without taking into account the manifestations of post-Eocene volcanism, in the areas of which the amplitudes of vertical neotectonic movements may be overestimated. This applies mainly to the eastern slope of the Sikhote-Alin Ridge, its central and northern parts, as well as the eastern side of the Middle Amur sedimentary basin between 47° and 50° N. Determining the scale of this overestimation requires a separate study.

CONCLUSIONS

(1) Base surfaces reflecting the neotectonic evolution of the terrain and a map of the amplitude of vertical neotectonic movements were constructed, and the morphostructural analysis of the southern part of the Russian Far East was carried out using the digital elevation model and the hydrographic network model. The neotectonic vertical movements in the region were manifested against the background of older, partially eroded relief. Three stages of relief evolution reflecting neotectonic activity in the region were identified: (a) pre-Oligocene, characterized by more intense uplift of the Bureya Ridge and less intense uplift of the Sikhote-Alin Ridge; (b) Oligocene–Pliocene, characterized by the most intense vertical movements in the region during the period from the Late Eocene to the Holocene; (c) Pleistocene–Holocene, when the modern erosion-denudation relief was formed and there were no vertical movements of significant amplitude.

(2) The total amplitude of vertical movements in the northwestern part of the territory studied within the Bureya Province is higher than that in the east, within the Sikhote-Alin Province. The most intensive uplift of the Bureya Ridge took place before the Pleistocene, while the Sikhote-Alin Ridge was more active at later stages.

(3) The analysis of neotectonic vertical movements in the southern part of the Russian Far East indicated two major rearrangements in the river system: (a) the channel of the river system that united the Sungari, Ussuri, Amur (north of Khabarovsk), Amgun, and other rivers in the Oligocene (?) most likely passed through the Evron–Chukchagir lowland toward the Sea of Okhotsk rather than the Tatar Strait; (b) watercourses of the western slope of the southern Sikhote-Alin Range discharged into the basin of the Amur (middle and upper sections of the modern Amur), Zeya, Bureya, and Liaokhe rivers before the cardinal reorganization of the river network in the Neogene (?). The flow of this river network was directed southward toward the Sunliao basin and the Yellow Sea. The assumptions about the existence of these two rearrangements of the river network of the southern Far East were made earlier [7, 13] and were confirmed by our results.

SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at https://doi.org/10.1134/S1028334X24601615.

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CONFLICT OF INTEREST

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

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