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Geodynamic Characteristics of Neotectonic Structures in the Olenek and Vilyui Areas of the Yakutian Kimberlite Province

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Abstract—The first comprehensive seismotectonic study was performed in the Olenek and Vilyui areas of the Yakutian kimberlite province, which was aimed at elucidating the geodynamic activity of neotectonic structures of the Siberian craton and assessing the environmental hazard of groups of kimberlite fields. Based on the degree of activity and trend of geodynamic processes, we have developed regional principles for the classification of neotectonic structures of the Siberian craton and its fold-thrust framing with the rationale for their differentiation into classes. The active segments of the Verkhoyansk and Baikal–Patom fold–thrust belts are analyzed, which have a dynamic effect on the mode of tectonic deformations of the adjacent sections of the Siberian Platform, where groups of kimberlite fields are localized. The revealed patterns of seismotectonic destruction processes made it possible to establish the intensity and types of the Earth's crust stresses and strains in the reactivation zones of the marginal sutures of the Siberian craton. Applying mathematical statistics methods permitted a quantitative analysis of the geodynamic parameters of the geologic environment in the Olenek and Vilyui areas of the Yakutian kimberlite province, based on the significant factors responsible for activation of the recent structures as manifestations of a single stress accumulation/discharge process in the Earth's crust. Using the set of seismotectonic data, we have differentiated the activation zones according to the stress–strain intensity in the Earth's crust and have assessed the potential environmental hazard of groups of kimberlite fields in the Yakutian diamondiferous province.

Keywords: Kimberlite province; kimberlite fields; active faults; kinematic types; geodynamic characteristics; earthquake mechanism; seismotectonic deformations; potential seismicity; environmental hazard

INTRODUCTION

The creation of the scientific foundations of safe and effective technologies for the exploitation of diamond deposits is based on multiscale seismotectonic analysis, the data of which take into account the time factor and reflect the calculated intensity of seismic tremors uniform for a specific risk level. The geodynamic processes occurring in the Earth's crust are complex and depend on many factors, the effects of which in different tectonic structures are manifested differentially. The problem of seismotectonic activation of the structures of Precambrian cratons, which are traditionally considered tectonically stable regions, has recently been revised (Artyushkov et al., 2018). As it has been noted earlier (Imaeva et al., 2018), a number of earthquake epicenters were recorded on the territory of the Siberian craton by instrumental seismological observations with M_w = 4.0–5.7 and high gradient deformation zones of the newest and modern vertical tectonic movements.

The studies presented in this article are aimed at establishing the degree of geodynamic activity of the newest structures of the Siberian craton and assessing the environmental hazard of groups of kimberlite fields in the Olenek and Vilyui areas of the Yakutsk diamondiferous province. The groups of kimberlite fields of these regions are located in different tectonic structures, and some of them are close to the zones of dynamic influence of the marginal sutures of the Siberian Platform. Using an example of an integral seismotectonic study, it is shown that a medium-scale analysis of geodynamic parameters by significant factors of activation of the newest structures allows us to differentiate the contact zones of marginal sutures by the degree of intensity of the stress-strain state of the Earth's crust, as well as to assess the ecological situation of the groups of kimberlite fields of the Olenek and Vilyui areas of the Yakutsk diamondiferous provinces.

During the research the following scientific tasks were solved:

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– analysis of the published structural tectonic, geological and geophysical, geodesic and seismological data;

– development of regional principles for the classification of neotectonic structures of the Siberian craton with the rationale for their differentiation into classes;

– identification of active segments of the Verkhoyansk and Baikal-Patom fold-thrust belts, which have a dynamic effect on the style of tectonic deformations of kimberlite fields of adjacent sections of the Siberian Platform;

– establishment of the intensity and types of stress-strain state of the Earth's crust of the reactivation zones of the Siberian craton's marginal suture zones;

– quantitative analysis of the geodynamic characteristics of the geological environment for significant indicators of factor analysis;

– assessment of the potential environmental risk of kimberlite field groups of the Olenek and Vilyui areas of the Yakutsk diamondiferous province.

The research is based on regional material from case studies of authors. The information on geology, tectonics, geophysics, seismogeology and other related disciplines obtained by other industrial and research organizations has also been used.

METHODS OF RESEARCH

To solve the tasks we used a new set of studies aimed at identifying the degree of geodynamic activity of the newest structures of the Olenek and Vilyui areas of the Yakutsk kimberlite province and determining the parameters of their seismotectonic deformations. According to the degree of activity and orientation of geodynamic processes for the entire territory of the Siberian craton, regional principles for the classification of neotectonic structures were developed with the rationale for their differentiation into classes (Gusev et al., 2015, 2016; Imaeva and Kolodeznikov, 2017; Imaeva et al., 2017). We consider the newest geodynamic areal taxon of a territorial rank as a spatially localized integral object with multifactorial interaction of its main components in the section of the Earth's crust. Here we use the terms "domain" and "newest structure" as synonyms, and the term "segment" unites a number of domains (newest structures), which in their development are subject to uniform geodynamic conditions.

The classification of domains is a multi-level system consisting of eight activity classes of modern geodynamic formation processes of neotectonic structures. Each activity class is characterized by its characteristic set and the optimal number of features. Among them, the following factors are considered: tectonic (geodynamic setting); material, geophysical (the magnitude of the heat current, anomalies in the field of gravity, the thickness of the Earth's crust); morphostructural (elevation of the relief, its contrast, the speed of vertical and horizontal movement of the Earth's surface). In addition, the inheritance of the dynamics of neotectonic structures depending on the formation conditions in the previous stages of the domain development, as well as deformation signs and GPS data, were considered. The determination of the geodynamic activity of neotectonic structures and the establishment of a specific class was carried out by interpreting both primary and additional characteristics. By the degree of activity of the latest tectonic movements, the domain classes are grouped into three groups: low (classes 1–2), moderate (classes 3–5) and high (classes 6–8). The zonality of the geodynamic processes' activity of the Siberian Platform neotectonic structures of its fold-thrust framing is shown in Fig. 1.

Geodynamic indicators of the geological environment deformation that can cause environmental consequences are primarily associated with the intensity of the stress-strain state of the Earth's crust manifestations, allowing to assess the degree of its destruction. Such data may include: seismicity; newest and modern tectonic movements; propagation features of tectonic fracturing and a network of discontinuous faults, etc. A set of geodynamic indicators of the geological environment for platform and orogenic structures characterized by different types of stress-strain state of the Earth's crust is significantly different. This factor must be considered by other researchers. To assess the significance of the geodynamic characteristics of the Olenek and Vilyui areas of the Yakutsk kimberlite province, we applied a methodology (*R*-modification) of factor analysis, which is multidimensional-statistical and distinguishes the contributions of individual factors (Gzovskii, 1975; Nikolaev, 1980). We used this technique for the first time in seismotectonic analysis of the collision zones active structures of the Arctic-Asian and Baikal-Stanovoy seismic belts, where the density characteristics and the classification of the activity of modern geodynamic processes are described in detail (Imaev et al., 2000; Imaeva et al., 2005). The following factors were taken into account: fault density (P), gradients of the newest vertical tectonic movements (Grad V), amplitude of the newest tectonic movements (A), density of earthquake epicenters (S), geophysical data characterizing gravity field anomalies (G).

The considered matrices of correlation relationships of areal factor analysis showed the presence of positive significant relationships between individual variables. The most stable are the associations of the following elements: fault density – density of epicenters – geophysical data ($r = 0.6$); fault density – gradient of the newest tectonic movements – amplitude of the newest tectonic movements ($r = 0.3$). One of the forms of recording the obtained values of the compared parameters is factor equations, which are the product of factors arranged in a sequential order as the corresponding correlation coefficient decreases. According to the results of the analysis, the equation of the geodynamic process can be written as follows: $F = P_{0.8} \times A_{0.6} \times \text{Grad } V_{0.6} \times S_{0.5} \times G_{0.4.}$ More over, the first three factors (indicators) are the most significant and in total reach 80% effect: fault density, amplitude of the newest tectonic movements and the gradient of

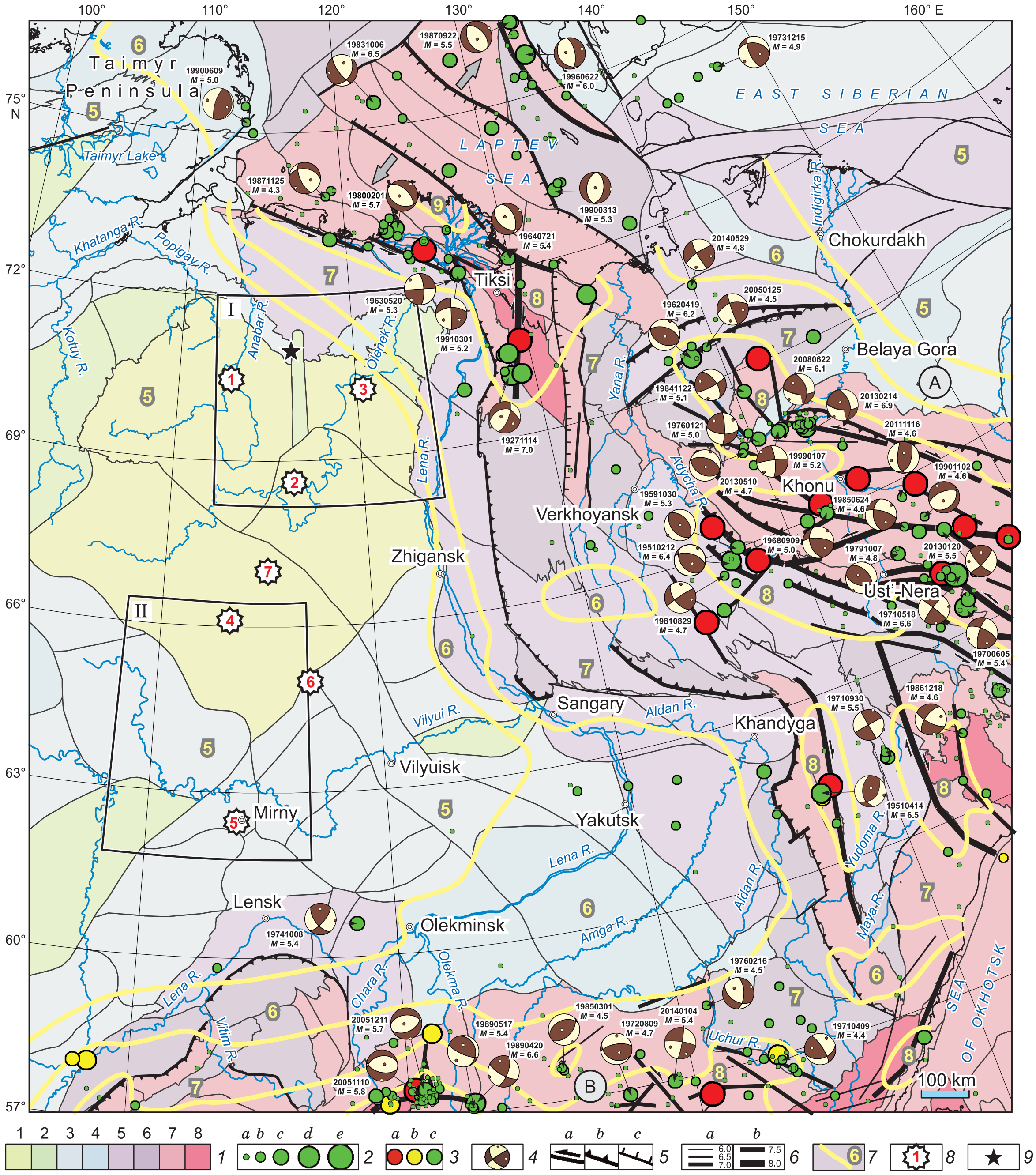


Fig. 1. The scheme of seismotectonics of the Siberian craton and its fold-thrust framing (modified after (Gusev et al., 2015)). Seismic belts: Arctic-Asian (A), Baikal-Stanovoy (B). The kimberlite regions are marked with a framework: Olenek (I), Vilyui (II). *1*, classes of geodynamic activity: 1–2, low, 3–5, moderate, 6–8, high; *2*, epicenters of earthquakes with magnitude (M_w), respectively: ≤4.0, 4.1–5.0, 5.1–6.0, 6.1–7.0, ≥7.0 (Gusev et al., 2015); *3*, earthquake calendar dates: *a*, to 1700 yr., *b*, 1700–1900 yr., *c*, 1900–2015 yr.; *4*, focal mechanisms of earthquakes: the date of occurrence of the event and magnitude (lower hemisphere), the outputs of the axes of the main compressive stresses (black dots) and extensions (white dots); *5*, kinematics of active faults: *a*, strike-slips, *b,* thrust faults, *c,* normal faults; *6*, magnitude potential of active faults; *7*, intensity isolines in points on a scale MSK-64 (Gusev et al., 2015); *8*, groups of kimberlite fields: 1, Kuonap, 2, Middle Olenek, 3, Lower Olenek, 4, Daldyn-Alakit, 5, Malo-Botuobin (Mirny), 6, Nakyn, 7, Upper Mun; *9*, Tomtor deposits of rare Earth elements.

the newest vertical tectonic movements. When assessing the potential environmental risk of groups of kimberlite fields in the Olenek and Vilyui areas, we used the most significant indicators of factor analysis (fault density and gradients of the newest vertical tectonic movements). Other geodynamic factors: heat current, velocity of modern vertical tectonic movements, seismic activity, were taken into account in the form of absolute values when determining the class of geodynamic activity of neotectonic structures and the final environmental risk assessment of kimberlite fields' groups.

RESEARCH RESULTS

Activation of tectonic structures of the Siberian craton. The main part of the Siberian craton is occupied by a platform formed by complexly deformed metamorphic rocks of the basement, which are overlain by flat-lying sedimentary and volcanic sediments of the cover (Mokshantsev et al., 1975; Gusev et al., 1985; Prokopiev et al., 2001). The Verkhoyansk and Baikal-Patom fold-thrust belts are its eastern and southern boundaries (Fig. 2). The Verkhoyansk fold-

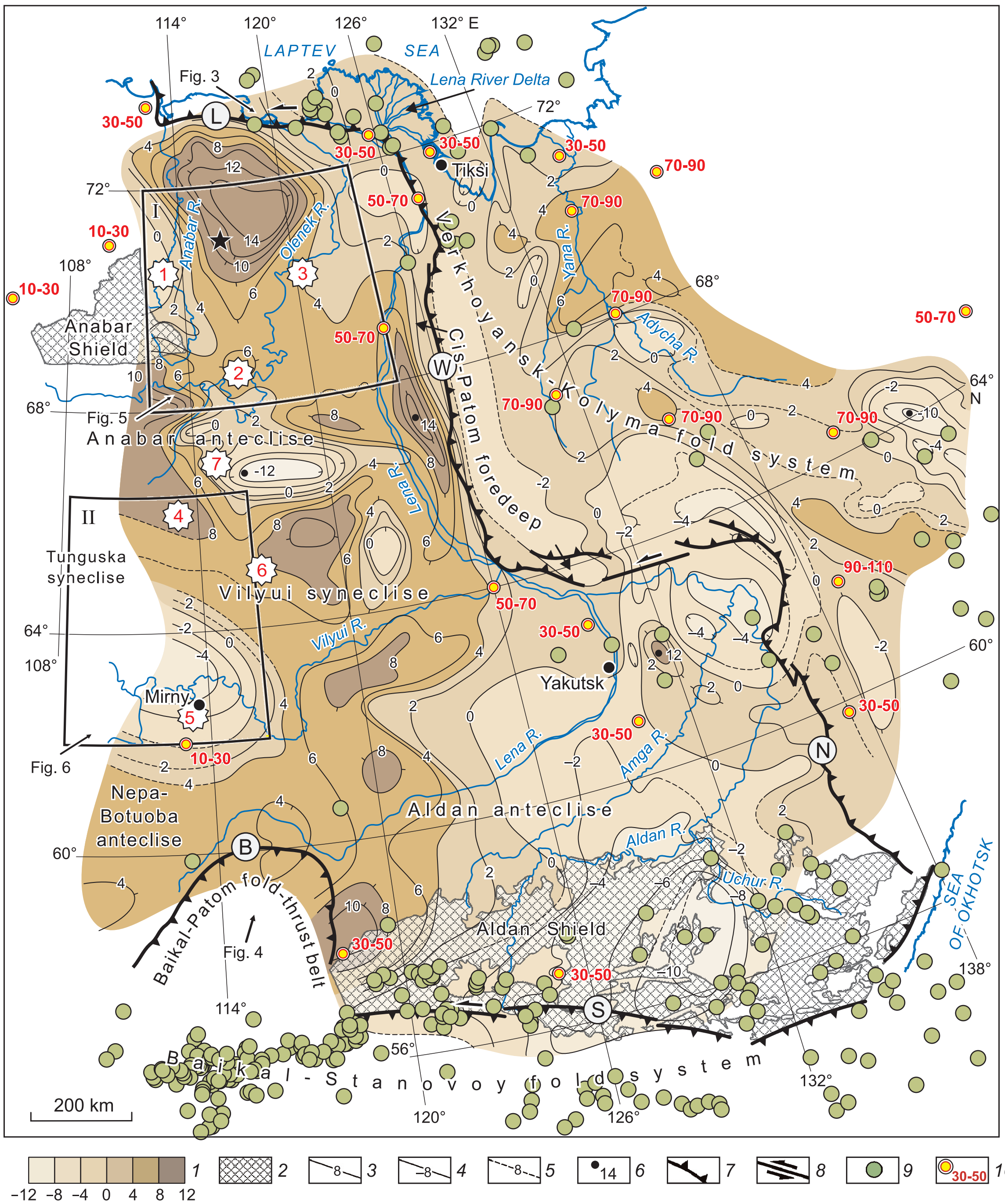


Fig. 2. Tectonic structure of the Siberian craton (modified after (Parfenov et al., 2001)). Marginal thrusts: L, Lena-Anabar, W, West Verkhoyansk, N, Nel'kan-Kyllakh, S, Stanovoy, B, Baikal-Patom. The kimberlite regions are marked with a frame: Olenek (I), Vilyui (II). *1*, the scale of velocities of modern vertical tectonic movements (mm/yr); *2*, areas of the rock outcrops of crystalline basement on the surface; *3–5,* velocity isolines of modern vertical tectonic movements (mm/yr) (Bocharov et al., 1982): *3*, positive, *4*, negative, *5*, estimated; *6*, maximum values of speeds; *7–8,* kinematics of active faults: *7*, thrust faults, *8*, strike-slips; *9*, earthquakes epicenters with $M_w \geq 4.1$ (Gusev et al., 2015); *10*, values of the heat current (mW/m^2) (Duchkov et al., 2015); *11*, groups of kimberlite fields: 1, Kuonap, 2, Middle Olenek, 3, Lower Olenek, 4, Daldyn-Alakit, 5, Malo-Botuobin (Mirny), 6, Nakyn, 7, Upper Mun; *12*, Tomtor deposits of rare Earth elements.

thrust belt is formed by a thick (up to 15 km) wedge of deformed rocks of Carboniferous, Permian, Triassic and Jurassic, which are typical accumulations of a passive continental margin (Gusev et al., 1985; Prokopiev and Deikunenko, 2001). The Baikal-Patom fold-thrust belt is an undifferentiated zone composed of lower and upper Archean heterogeneous complexes. Starting from the early Proterozoic further, it developed as a structure of the dome-block type, constantly experiencing the uplift, erosion and introduction of intrusions of different age and composition (Gusev et al., 1985; Smelov et al., 2001).

For the newest stage of tectonic development of the Siberian craton structure, relatively differentiated uplifts were experienced, the values of which range from 100 to 1500 m. An important feature of the neotectonic structure is the high density of linear tectonic faults (Gusev et al., 1985). The boundaries of neotectonic structures coincide with the activated faults of various rank, age and depth. This indicates that the newest movements are mainly block in nature and reflect the general tendency of the tectonic development of the territory (Imaeva et al., 2018). The degree of geodynamic activity of the newest structures of the Siberian craton (Fig. 1) and the planned distribution of elements (Fig. 2) show that the highest geodynamic activity indicators are characteristic of regional strike-slip zones and marginal foreland thrusts, separating the Siberian Platform from the Verkhoyansk-Kolyma and Baikal-Stanovoy fold-thrust systems. The central regions of the Siberian Platform are characterized by low and moderate values of the geodynamic activity characteristics of neotectonic structures (Fig. 1).

It is noteworthy that the weakly activated platform structures are distinguished by a differentiated velocity field of modern vertical tectonic movements and their high values (Fig. 2). High-gradient zones of deformations of modern movements are recorded on the northern side of the Anabar anteclise. Their planned pattern is typical for the peripheral zones of glacioisostatic elevations of other platforms. The speed of vertical movements in similar structures reaches tens of centimeters per year, which is 1–2 times higher than their values outside the glacial zones, which is comparable with the geodetic parameters of the Anabar anteclise (Nikonov, 1977). Another factor in the activation of the tectonic structures of Precambrian cratons in the Pliocene-Quaternary is probably the influx of large volumes of fluids into the lithosphere over the past several million years (Trifonov, 1999; Artyushkov, 2003; Trifonov et al., 2008; Artyushkov et al., 2018). Indicators of their impact on the geological environment are considered fluid genesis deposits, including kimberlites (Letnikov, 2006). An example of the activation of this type is the Olenek kimberlite region, where extensive high-gradient deformation zones are formed with the maximum values of the velocities of the newest and modern vertical tectonic movements (Fig. 2).

The geodynamic factors of activation of the newest structures platform and reactivation of its marginal sutures, in addition to structural and dynamic characteristics, include heat current data (Fig. 2). The Siberian Platform is characterized by a predominance of low values, which average 20–35 mW/m^2 (Duchkov and Sokolova, 1997; Duchkov et al., 2015). Above this level (up to 50–70 mW/m^2), values are noted in the region of the dynamic influence of marginal sutures, which is possibly associated with heat generation during collision processes at the boundary of lithospheric plates. Anomalously low heat current (20–30 mW/m^2) was recorded within the kimberlite province of the Siberian craton at the maximum thickness of the cryolithozone. A cryolithozone of this thickness could only be formed if there were low heat currents of 20–15 kyr (Balobaev, 1991). In similar kimberlite provinces of the American and African Platforms, the average geothermal heat current is almost the same and varies between 46–54 mW/m^2. Therefore, the thermal anomalies of the Yakutsk kimberlite province are probably “superficial” and do not reflect the temperature conditions in the deep layers of the Earth’s crust.

Seismotectonics. This subsection analyzes the active segments of the Verkhoyansk and Baikal-Patom fold-thrust belts, which have a dynamic effect on the tectonic deformation style of adjacent sections of the Siberian Platform, where groups of kimberlite fields of the Olenek and Vilyui areas of the Yakutsk kimberlite province are localized. The marginal suture zones of the Siberian craton are spatially close to the main seismic generating structures of the Verkhoyansk and Baikal-Stanovoy fold systems and are associated with them according to a certain kinematic type (Figs. 1, 2). In these zones, the main epicentral fields are shown, the seismological parameters of which fully reflect the style of tectonic deformations of the joined fault systems. Activation of marginal suture zones has a dynamic effect on the occurrence of local seismicity in the contact structures of the Siberian Platform.

In the Olenek kimberlite region, mainly located in the gradient zone of moderate geodynamic activity indexes, single local seismic events have been recorded of medium intensity with M_w = 4.0–5.5. The main zone of local seismicity manifestation is within the Lena-Anabar marginal thrust, the tectonic structures of which separate the seismically active region of the shelf of the Laptev Sea from the less active and passive structures of the northern and central parts of the Siberian Platform (Figs. 1, 2). The tectonic structures of the Lena-Anabar thrust zone are clearly decrypted in aerial photographs and space photographs, and are also reflected in geophysical fields (Prokopiev et al., 2001). The main tectonic elements here are the Anabar-Khatanga saddle, the Olenek sector of the Verkhoyansk fold-thrust belt, the Lena-Anabar trough, and the Olenek uplift (Fig. 3). The most active is the Olenek sector, the frontal zone of which, with a width of up to 70 km, stretches for 500 km in the latitudinal direction from the estuary of the Lena River to the Khatanga Bay. The tectonic structures of the sector are represented by a series of west-north-western strike folds formed in the Mesozoic under the influence of sublatitudinal left strike-slip movements along the north-

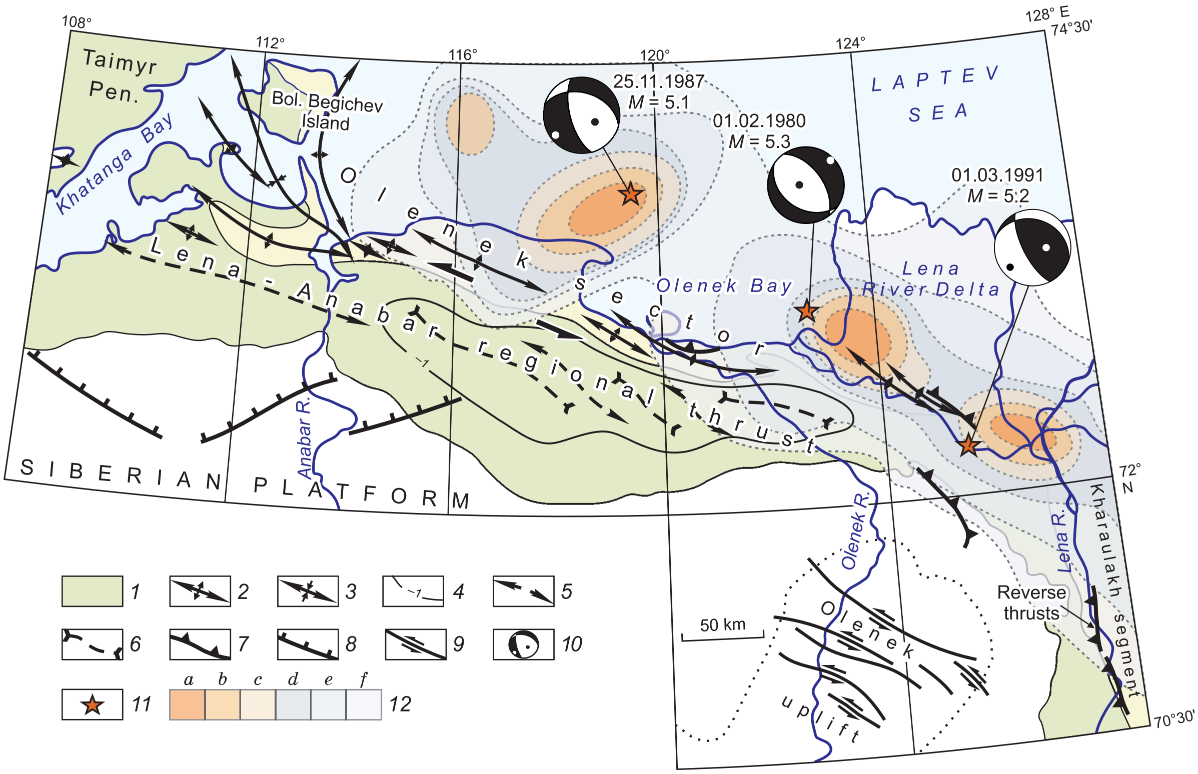


Fig. 3. Seismoectonic scheme of the Olenek sector of the Lena-Anabar segment (modified after (Imaeva et al., 2016)). *1*, continental Lower Cretaceous deposits; *2*, axis of anticlines; *3*, axis of synclines; *4*, isohypses of the Lower Cretaceous bottom; *5*, axis of syndepositional shafts; *6*, axes of syndepositional troughs; *7–9,* kinematics of active faults: *7*, thrusts, *8*, normal faults, *9*, strike-slips; *10*, focal mechanisms of earthquakes: the date of occurrence of the event and magnitude (lower hemisphere), the outputs of the axes of the main compressive stresses (black dots) and extensions (white dots); *11*, earthquake epicenter location; *12*, earthquake epicenters density (number of events 1º×1º): *a*, 26–30, *b*, 21–25, *c*, 16–20, *d*, 11–15, *e,* 6–10, *f*, 1–5. Big arrows show a relative movement of the Earth crust blocks.

ern margin of the Siberian Platform. This is indicated by the en-echelon orientation of the folds, as well as a sharp turn of the structures on the flank of the northern wing and oblique discharges in the West of the southern wing of this strike-slip zone. It can be assumed that the Olenek sector in terrestrial terms defines the front of the large late Mesozoic Verkhoyansk fold-thrust system. In the vicinity of the Lena River delta, the deformation zone changes near-latitudinal to sub-latitudinal strike and can be traced under the thick cover of the South Laptev rift trough to its interface with the South Taimyr folded zone (Imaeva and Kolodeznikov, 2017).

The activated structures of the Olenek sector in seismic terms are confined to the Lena-Taimyr zone of earthquake epicenters (Fig. 1). Over the period of instrumental observations, about 400 local earthquakes occurred within the crust at depths of 10–30 km. Within the zone, several maxima of seismic activity are distinguished (Fig. 3), which correlate with a sublatitudinal system of gravitational anomalies of various intensities. The seismic process in the Lena–Taimyr epicenter zone develops both under extension (the Lena River delta, the coast of the Olenek and Anabar Bays), and compression conditions (Taimyr Peninsula). Such a variety of solutions of focal mechanisms explains the presence of a different kinematic spectrum of discontinuous faults (thrust-faults, strike-slips, and their modifications). According to the calculations of seismotectonic deformations within the Lena-Anabar marginal thrust, the mode of extension of the Earth's crust with a small strike-slip component is predominant. The action azimuth of tensile stresses, when compared with similar ones in the Laptev Sea rift zone, is distinguished by its orientation. The directions of the main stress axes indicate the location of their transverse strike of the main tectonic elements and at shallow dip angles they have a northeast – southwest direction (Imaeva et al., 2016).

The Vilyui kimberlite region is located in the zone of dynamic influence of seismic generating structures of the western flank of the Baikal-Stanovoy seismic belt (Figs. 1, 2). Here, the southeastern part of the Cis-Patom foredeep is most active, expressed as a complexly constructed synclinal structure, which can be considered as a long-term developing Cis-Patom marginal foredeep (Gusev et al., 1985; Prokopiev and Deikunenko, 2001). The tectonic structures of the foredeep are marginal and are activated in seismotectonic terms by the active processes of both the Baikal Rift Zone and the Stanovoy fold system. The southeastern part of the Cis-Patom foredeep is composed of thick late Precam-

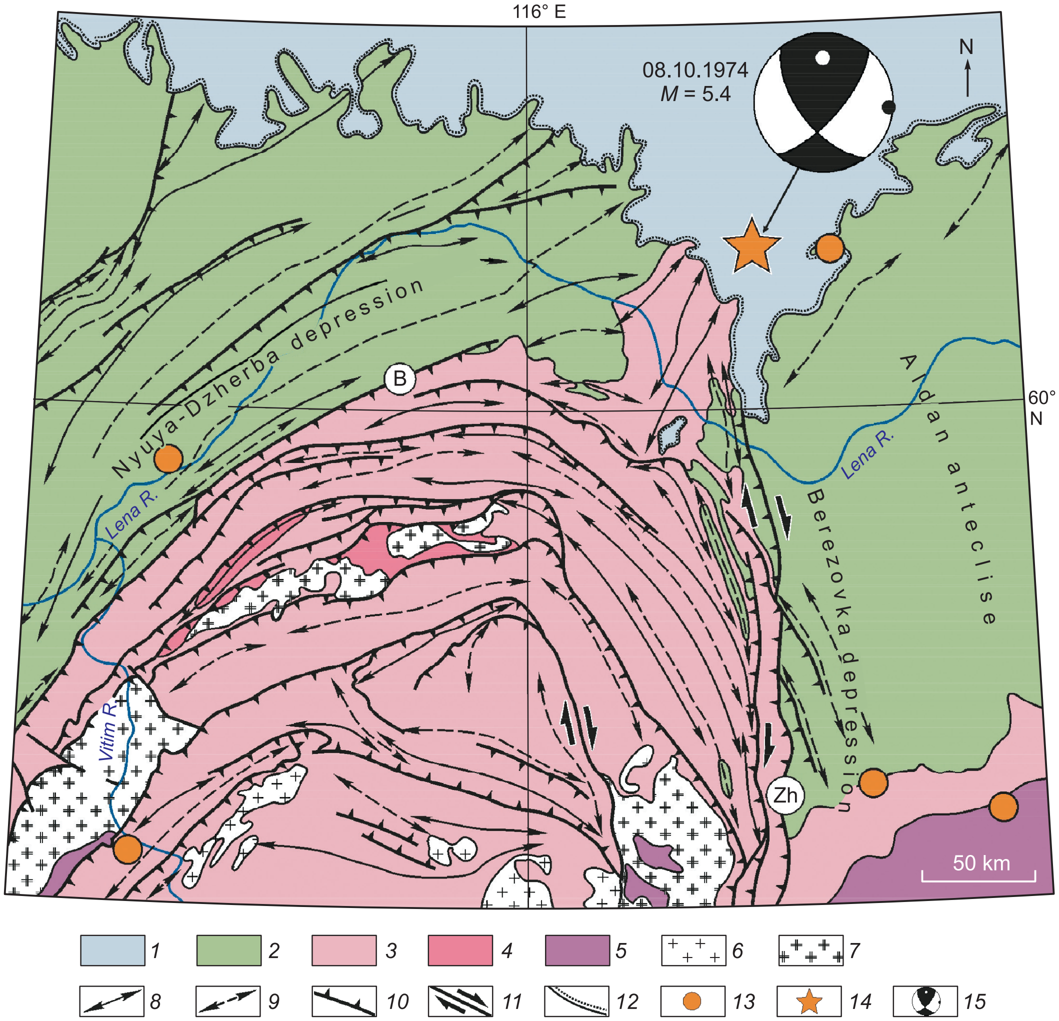


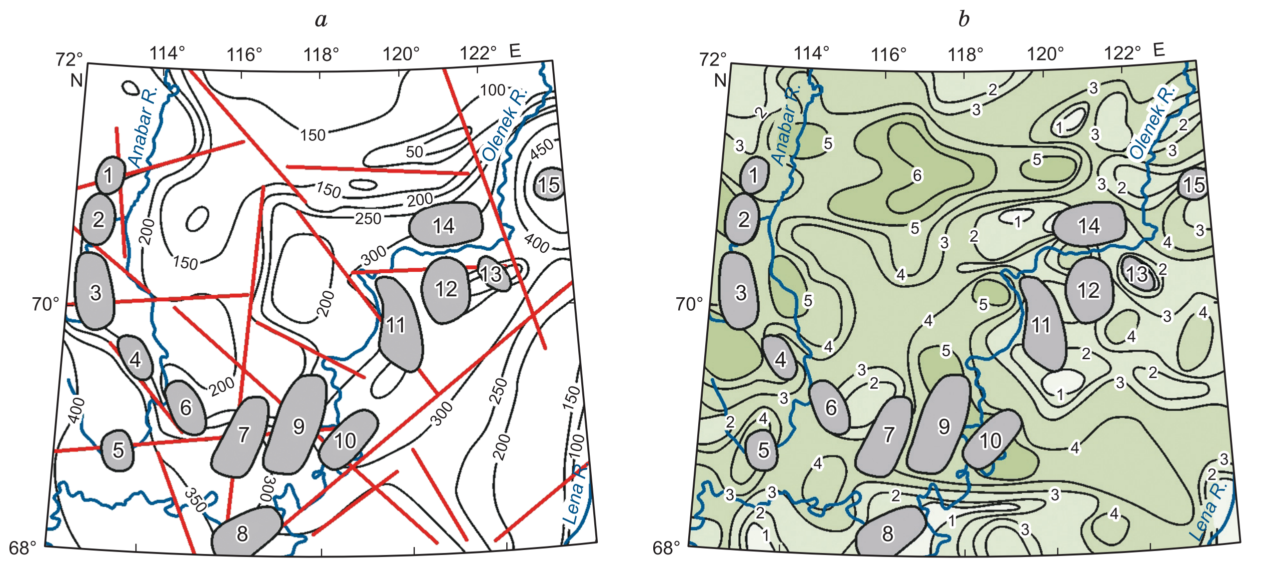
Fig. 4. Geological-structural scheme of the Baikal-Patom fold and thrust belt (modified after (Prokopiev and Deikunenko, 2001)). The faults are marked: B, Baikal-Patom, Zh, Zhuya. *1–5,* deposits: *1*, Jurassic, *2*, lower-middle Paleozoic, *3*, Riphean-Vendian, *4*, Lower Proterozoic, *5*, Archean; *6–7*, granitoids: *6*, Paleozoic, *7*, Proterozoic; *8–9,* axes: *8*, anticlines, *9*, syncline; *10,* thrusts; *11*, strike-slips; *12,* angular unconformity; *13*, earthquakes epicenters with $M_w \geq 4.0$–5.0 (Gusev et al., 2015); *14*, epicenter of the Middle Lena earthquake; *15*, focal mechanisms of earthquakes: the date of occurrence of the event and magnitude (lower hemisphere), the outputs of the axes of the main compressive stresses (black dots) and extensions (white dots).

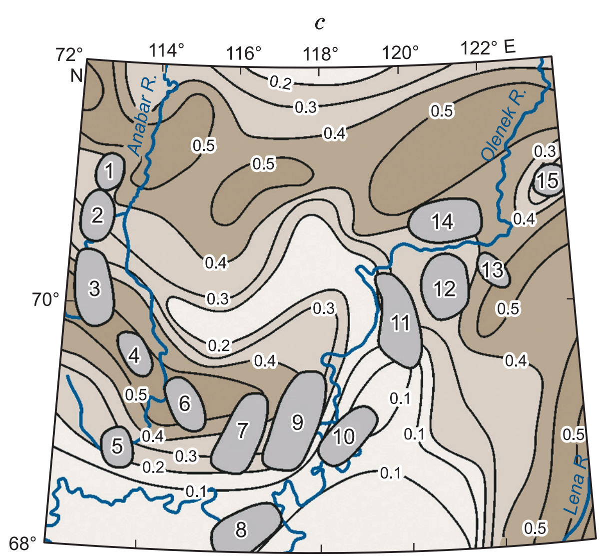
brian sediments, the total thickness of which in its central part reaches 12–14 km, and decreases to 4–5 km to the periphery. The outer Prilensky and inner Bodaibo subzones are distinguished, which significantly differ in their structure (Fig. 4).

In the outer subzone of the Patom marginal thrust linear asymmetric folds developed, often overturned towards the platform, the intensity of which decreases northward. The most complex structure is characterized by folds stretching along the northeastern flank of the Cis-Patom zone near its border with the Berezovka depression, characterized by steep wings (30–70°) and narrow arches. On the northwestern flank of the zone, less abrupt, sometimes brachyform folds are developed, complicated by large-amplitude faults. According to deep drilling and seismic surveys, the internal structure of the trough has been deciphered (Prokopiev and Deikunenko, 2001). It has been stated that the mapped linear folds and anticlinal zones are a reflection of a complex deep thrust structure, which is a combination of various types of duplexes, ramp anticlines, and sheeted fans. The basal disruption of the thrust zone sequentially moves to higher stratigraphic levels when moving towards the Siberian Platform. The total horizontal tectonic shortening is 10–15 km. In the rear part of the zone, the Riphean deposits of the Patom synclinorium over the Baikal-Patom thrust system thrust over the formations of the Nyuya-Dzherba depression. The nuclei of large anticlinal zones are represented by duplexes, more rarely, single ramp anticlines (Prokopiev and Deikunenko, 2001). The western side of the Berezovka depression is disturbed by the frontal thrusts of the Zhuya system, along which the Riphean sequence overlay the Cambrian deposits of the western slope of the Aldan anteclise. In the rear part of the zone, west of the Zhuya thrusts, imbricate-oriented linear folds are mapped, and the faults themselves have a combined thrust fault right strike-slips kinematics.

Seismotectonic studies of this area show that the formation of extensive dome elevations continues within it. In a number of cases, current movements of the Earth's crust acquire a contrasting character, which leads to the activation of marginal sutures and regional faults. Such tectonic movements can be accompanied by seismic activity. A direct confirmation of the possibility of seismic events is a number of local earthquakes recorded in 1957–2018 years (Figs. 1, 3). The seismicity zone is manifested as single earthquakes, which are noted on the left bank of the Lena River (between Peleduy and Olekminsk), as well as in the north of the Patom highland. In the Berezovka foredeep, the Middle Lena (Melichan) earthquake was noted with M_w = 5.5–5.7, the epicenter of which is located in the basin of the Biryuk River, the left estuary of the Lena River (Imaeva et al., 2018). Its mechanism (the right thrust fault-strike slip along the sub-longitudinal plane) fully reflects the style of tectonic deformations in the contact zone (along the Zhuya fault) of the structures of the Cis-Patom foredeep and the Aldan anteclise, as well as the direction of seismotectonic activation from the structures of the Baikal-Patom fold-thrust belt to the Siberian Platform.

Geodynamic characteristics of factor analysis of the Olenek and Vilyui areas of the Yakutsk kimberlite province. When assessing the geodynamic indicators of factor analysis for individual groups of kimberlite fields, we used the most significant of them: fault density and gradients of the latest vertical tectonic movements (Figs. 5, 6). The am-





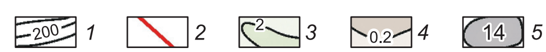


Fig. 5. Geodynamic characteristics of the geological environment of the Olenek (I) kimberlite region. *1*, isohypsobasites of the top surface; *2*, activated faults; *3*, faults density values: maximum (≥5), high (4), average (3–2), minimum (≤1); *4*, velocity gradients of the latest vertical tectonic movements (in the text, the gradient values will be given without its constant factor (10^{-8} year^{-1})): maximum (≥0.5), high (0.5–0.4), average (0.3–0.2), minimum (≤0.1); *5*, separate kimberlite fields (Brachfogel et al., 1997): Kuonap group (1): 1, Starorechin, 2, Ary-Mastakh, 3, Dyuken, 4, Luchakan, 5, Ogoner-Yuryakh, 6, Kuranakh; Middle Olenek group (2): 7, West Ukukit, 8, Mun, 9, Chomurdakh, 10, East Ukukit; Lower Olenek group (3): 11, Orto-Yargih, 12, Merchimden, 13, Molodin, 14, Toluok, 15, Kuoyk.

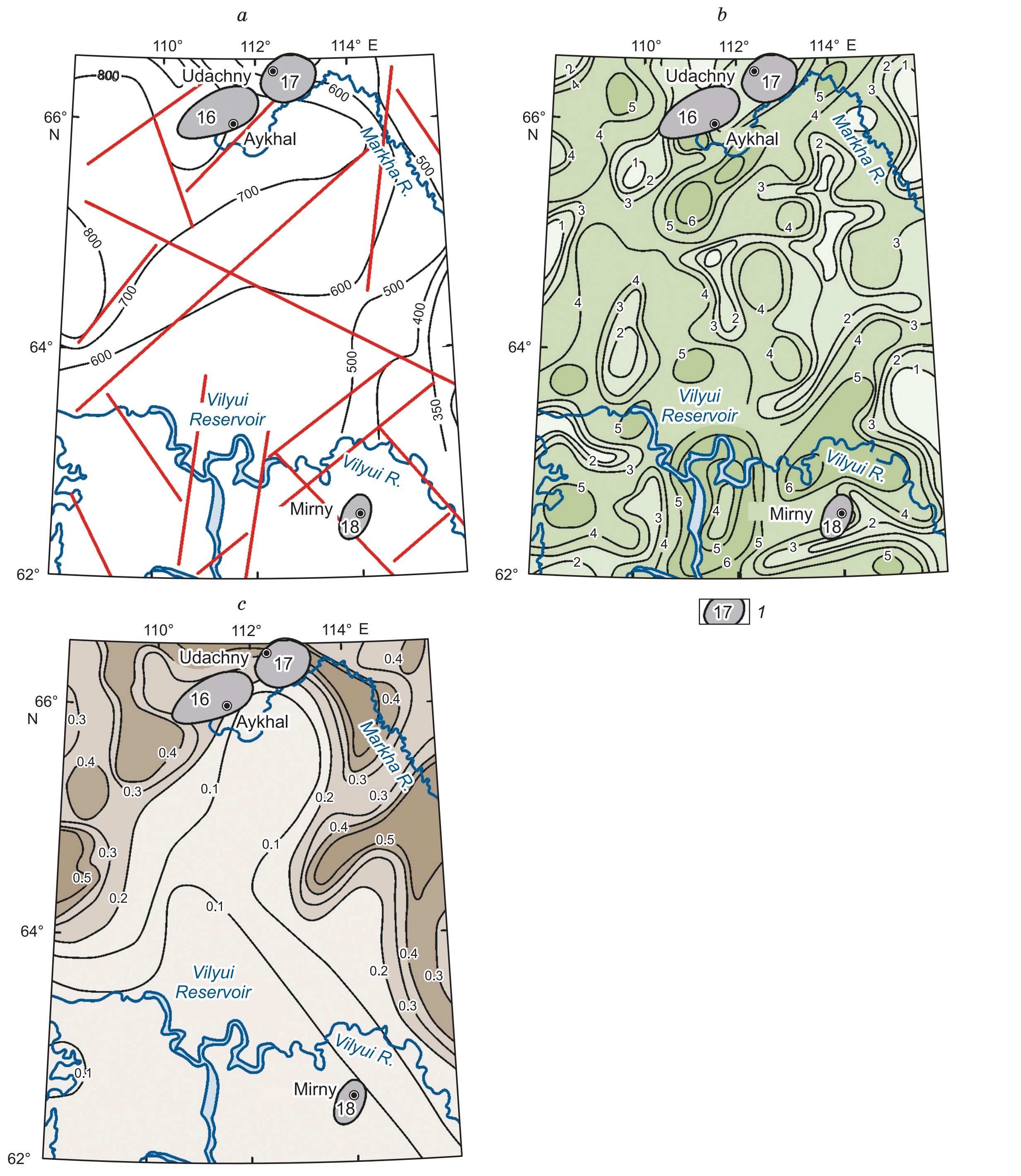


Fig. 6. Geodynamic characteristics of the geological environment of the Vilyui (II) kimberlite region. *1*, isohypsobasites of the top surface; *2*, activated faults; *3*, faults density values: maximum (≥5), high (4), average (3–2), minimum (≤1); *4*, velocity gradients of the latest vertical tectonic movements (in the text, the gradient values will be given without its constant factor (10^{-8} year^{-1})): maximum (≥0.5), high (0.5–0.4), average (0.3–0.2), minimum (≤0.1); *5*, separate kimberlite fields (Brachfogel et al., 1997): Daldyn-Alakit group (4): 16, Alakit, 17, Daldyn; Malo-Botuobin (Mirny) group (5): 18, Malo-Botuobin (Mirny).

plitude diagrams of the newest vertical tectonic movements with marked active faults lines (Figs. 5*a*, 6*a*) were calculated for the above two factors.

The *Olenek* region, which combines the Kuonap (1–6), Middle Olenek (7–10) and Lower Olenek (11–15) groups of kimberlite fields, is characterized by the coincidence of the strike of the isolines of the fault density and the main kimberlite control zones (Fig. 5*b*). The maximum fault density (≥5) was noted for single kimberlite fields of the Kuonap and Middle Olenek groups. In other cases, this value of the density of faults is confined to the areas of joint regional faults (in the North of the site) or to zones of their dynamic influence (in the South). The Lower Olenek group of kimberlite fields is characterized by a homogeneous field of average density values, only the central part of the Toluok field is in the zone of minimum values. The Kuonap group of kimberlite fields is characterized by a higher level of tectonic fracturing. Basically, its fields tend toward regions of high values of fault density with a transition to average values (Dyuken, Luchakan, Ogoner-Yuryakh and Kuranakh fields). The exception is Starorechin and a part of the Ary-Mastakh kimberlite field, where the maximum density of faults is recorded. The Middle Olenek group is located in the zone of high density values (East Ukukit and Chomurdakh fields) with their variable going up (West Ukukit field) and lower fault density values (Mun field).

Significant areas spread within the Olenek kimberlite region, occupied by zones of maximum and high values of the velocity gradient of the newest vertical tectonic movements (Fig. 5*c*). They are confined to areas of sharply dissected relief, where a network of active breaking fractures is developed (Fig. 5*a*). The orientation of the velocity gradient zones corresponds to the strike of the main morphostructural elements of the site. The areas of minimum gradient values are located mainly in the South and contour the aligned watershed surfaces. The Lower Olenek group of the kimberlite fields is characterized by gradient zones with a significant dispersion of their values: from high in the North and West to minimal in the South. For the Kuonap group of kimberlite fields, a predominance of high and maximum values of gradient zones has been noted. So, the Luchakan, Dyuken and Kuranakh fields are in homogeneous areas of maximum values. The Ary-Mastakh field in the South is characterized by maximum values of the gradient, the magnitude of which decreases to the average values to the North. Ogoner-Yuryakh and Starorechin kimberlite fields are located in zones of high and medium gradient values. In the Middle Olenek group, the West Ukukit field are characterized by sharp changes in the values of the gradient zones from minimum and average to maximum values. Mun and East Ukukit kimberlite fields are located in the zone of minimum values of the velocity gradient of the newest vertical tectonic movements.

The *Vilyui* region, which unites the Daldyn-Alakit (16–17), Malo-Botuobin (Mirny) (18) groups of kimberlite fields, is characterized by a higher degree of fault density (Fig. 6*b*). The zones of maximum and high values cover a large area here, located in the fields of the dynamic influence of regional faults. The Malo-Botuobin (Mirny) kimberlite group is contoured by an isometric sub-longitude maximum of high fault density values in the center and in the West. The kimberlite fields of the Daldyn-Alakit group are characterized by a significant scatter in density values. The Malo-Botuobin field in the North has a zone of high values of fault density, and to the South their values decrease. In the South of the Alakit kimberlite field, the density maximum is recorded, which decreases to the average to the North. The homogeneity of the tectonic fracture is characterized by the Daldyn field, which is characterized by a predominance of average density values with a slight increase in the density of faults to the East. The Nakyn group of kimberlite fields (No. 6 in Figs. 1, 2) is characterized by similar characteristics with the kimberlite fields of the Daldyn-Alakit group.

The Vilyui kimberlite region sharply differs from the Olenek region in the low degree of contrast of neotectonic movements (Fig. 6*c*). Zones of minimum and average values of the velocity gradient of the newest vertical tectonic movements prevail, and zones with maximum and high indexes are localized in the North, West, and East. The Malo-Botuobin (Mirny) field is completely located within the region of the minimum values of the gradients, which is consistent with the weak dissection of the relief. The territory of the kimberlite fields of the Daldyn-Alakit group is characterized by gradient zones with different intensities. The Malo-Botuobin field is homogeneous and is located in the region of minimum gradient values. Alakit and Daldyn kimberlite fields are more differentiated in the gradient relation. The values of the velocity gradient here increase from South to North from minimum to maximum values. The Nakyn group of kimberlite fields is characterized by maximum values of the velocity gradient of the newest vertical tectonic movements.

DISCUSSION OF THE RESEARCH RESULTS

In assessing the potential environmental hazard of the kimberlite field groups of the Olenek and Vilyui areas, we used the calculated indicators, both factor analysis (fault density and gradients of the newest vertical tectonic movements (Figs. 5, 6)), and absolute values of other geodynamic characteristics of the newest structures activation (geodynamic activity, speed of modern vertical tectonic movements, intensity of seismic activity in points (Figs. 1, 2)). Depending on the obtained values of geodynamic parameters of the geological environment, we estimated the degree of environmental hazard of certain groups of kimberlite fields, according to the criteria for assessing the environmental situation of territories to identify areas of ecological emergency and ecological disaster zones of the Natural Resources Ministry of the Russian Federation dated November 30, 1992 (http://docs.cntd.ru/document/901797511). This manual states that "the geodynamic indicators of the geological environment deformation with ecological consequences can be presented in the form of intensity and scale of the current stress-strain state manifestation of the lithosphere upper parts. These indicators are determined by the parameters of the critical strain rates and the scale of the expected seismic effect". The document developed a scale for assessing the ecological situation of the territories (relatively satisfactory, intense, critical, catastrophic (or environmental disaster area)), which we used. We have compiled the resulting table "Geodynamic characteristics of the new-

Table 1. Geodynamic characteristics of the newest structures Olenek and Vilyui regions Yakutsk kimberlite province

№	Kimberlite fields	*P*	*Grad V*	v_m	*C*	*J*	*Ecological setting*
Olenek kimberlite region (I)							
	Kuonap group (1)	2–5	0.1– ≥ 0.5	0–7	1	o	Relatively satisfactory
1	Starorechin	4	0.3–0.4	0–2	1	5	
2	Ary-Mastakh	4–5	0.2–0.4	0	1	5	
3	Dyuken	4	0.2–0.5	0–2	1	5	
4	Luchakan	3–4	≥ 0.5	2	1	5	
5	Ogoner-Yuryakh	3–4	0.1–0.4	4	1	5	
6	Kuranakh	2–4	0.4–0.5	6–7	1	5	
	Middle Olenek group (2)	1–5	≤ 0.1–0.5	2–6	1	5	Relatively satisfactory
7	West Ukukit	2–4	0.2–0.5	4–6	1	5	
8	Mun	1–2	≤ 0.1	2–4	1	5	
9	Chomurdakh	4–5	0.1–0.4	4–6	1	5	
10	East Ukukit	4–5	≤ 0.1	4	1	5	
	Lower Olenek group (3)	1–4	0.1–0.5	0–6	1–3	5–7	Tense
11	Orto-Yargih	2–4	0.1–0.3	4–6	1	5	
12	Merchimden	2–3	0.3–0.4	2–4	1	5–6	
13	Molodin	1–2	0.4–0.5	2–4	2	6–7	
14	Toluok	1–4	0.3–0.4	2–6	2–3	6–7	
15	Kuoyk	2–4	0.2–0.3	0–2	2	7	
Vilyui kimberlite region (II)							
	Daldyn-Alakit group (4)	2–5	0.1–0.5	6–8	1	5	Relatively satisfactory
16	Alakit	2–5	0.1–0.3	6–8	1	5	
17	Daldyn	2–4	0.1–0.5	8	1	5	
	Malo-Botuobin (Mirny) group (5)	3–5	≤ 0.1	0…–4	3	5	Tense
18	Mirny	3–5	≤ 0.1	0…–4	3	5	

Note. *P*, faults density, *Grad V*, velocity gradients of the latest vertical tectonic movements (10^{-8} year^{-1}), v_m, velocities of the modern vertical tectonic movements (mm/yr), *C*, class of geodynamic activity, *J*, intensity of tremors in points on a scale MSK-64 (Gusev et al., 2015). The numbering of areas and groups of kimberlite fields corresponds to Figs. 1, 2. The numbering of separate kimberlite fields corresponds to Figs. 5, 6.

est structures of the Olenek and Vilyui areas of the Yakutsk kimberlite province", which reflects all the analyzed factors of the newest structures activation and assessed the degree of environmental hazard (Table 1).

The *Olenek* region is located in the contact zone of the Anabar shield tectonic structures and the anteclise of the same name. It is located in a differentiated field of general indicators of the geodynamic activity of the latest structures (Table 1). Almost all kimberlite fields are located in zones with a significant spread in fault density, velocity gradients of modern and newest vertical tectonic movements (Figs. 2, 5) and low and moderate values of geodynamic activity (Fig. 1). Within it, the territories of the Kuonap and Middle Olenek kimberlite groups can be assessed by a relatively satisfactory ecological situation. By the rank of neotectonic zoning, the kimberlite fields of these groups are located in morphostructural regions with insignificant amplitudes of positive neotectonic movements (Fig. 5*a*). A part of the kimberlite fields of the Kuonap and Middle Olenek kimberlite groups located in the zones of maximum and average values of the geodynamic characteristics of factor analysis (Fig. 5*b, c*), as well as located in the high-gradient velocity zones of present-day vertical tectonic movements (Fig. 2), can be assigned to regions of structural-dynamic instability.

The Lower Olenek group of kimberlite rocks in this region is close to the zones of dynamic influence of regional faults of the marginal sutures of the Siberian Platform, which are characterized by an increased degree of tectonic fracturing and seismic activity (Figs. 1, 2). Here high heat currents and a number of weak and medium level earthquakes are recorded (M_w = 4.0–5.7). Seismotectonic reactivation of the marginal sutures of the Verkhoyansk fold-thrust belt can have a dynamic effect on adjacent sections of the Siberian Platform, where kimberlite fields of Lower Olenek group are located. With this in mind, the ecological situation is assessed here as tense. The Tomtor deposit of rare-earth elements, which is located between the Kuonap and Lower Olenek groups of kimberlite rocks, is characterized by increased values of the geodynamic activity of the newest structures (Figs. 1, 2) and a similar degree of ecological hazard.

The Vilyui region is almost completely located in the zones of low or moderate geodynamic activity of the newest structures (Fig. 1). Along the perimeter, it is outlined by isometric lines of maximum and high values of fault density (Fig. 6*a*). Given this factor, its structural-dynamic setting is generally assessed as tense. According to the second factor (the velocity gradient of the newest vertical tectonic movements), the Daldyn-Alakit group of kimberlite fields is in the high-gradient zone of transition from minimum to maximum values, and the Malo-Botuobin group is confined to the zone of minimum gradient values (Fig. 6*b*). It is necessary to take into account the fact that the northern section of the region (Daldyn-Alakit group) is located in the zone of high speeds of modern vertical tectonic movements, and the southern (Malo-Botuobin group) in the zone of negative values (Fig. 2). A joint consideration of these measures allows us to give a general ecological assessment of this region as relatively satisfactory with a possible transition to tense (Malo-Botuobin group), which is due to the proximity of the southern kimberlite group to the seismically active structures of the peripheral zone of the Baikal-Stanovoy seismic belt.

On the "Map of Seismotectonics of Eastern Siberia" the territory of the Yakutsk kimberlite province is assigned to a seismically dangerous area with a tremor intensity of 5–7 points (Gusev et al., 2015). The deformation fields of seismotectonic zones on the territory of kimberlite regions are formed in accordance with the dynamics of the front blocks of the collision zones: Lena-Taimyr in the North (Olenek kimberlite region) and Baikal-Stanovoy in the South (Vilyui kimberlite region). Besides local seismic events (M_w = 4.0–5.7), this region may also experience transit effects from strong earthquakes from neighboring seismic zones. In addition, in the area of the Vilyui reservoir, the occurrence of "induced seismicity" is not ruled out, when pressure on the underlying rocks can increase under the influence of the reservoir's water lens. In such cases, the equilibrium tectonic balance changes with the response of the geological environment in the form of underground tremors, which increases the level of seismic hazard by an order of magnitude. Similar phenomena have been recorded in the world practice of hydraulic structures. The occurrence of even moderate intensity earthquakes in this region (6–7 points) can lead to significant environmental consequences of significant scale. Mining operations, accompanied by large-scale explosions in diamond mining quarries, can also affect the level of seismic activity. The assessment of the geodynamic characteristics of the geological environment by certain factors for groups of kimberlite rocks of the Olenek and Vilyui areas of the Yakutsk kimberlite province gives only approximate results. It is necessary to analyze long-term instrumental observations of the seismic situation of these objects and conduct large-scale geodynamic research.

CONCLUSIONS

Seismotectonic studies aimed at establishing the degree of geodynamic activity of the newest structures of the Siberian craton and assessing the ecological situation of the Olenek and Vilyui areas of the Yakutsk diamondiferous province allowed to make the following conclusions:

1. A quantitative analysis of the geodynamic characteristics of the geological environment, carried out for individual kimberlite fields of the Olenek and Vilyui areas, substantiated the significance of the parameters used as manifestations of a single process of accumulation and discharge of stresses in the Earth's crust.

2. The marginal thrust reactivation zones and the frontal segments of the Verkhoyansk and Baikal-Patom fold-thrust belts have a dynamic effect on the style of tectonic deformations and seismic activation of adjacent sections of the Yakutsk kimberlite province of the Siberian Platform.

3. The conducted studies allowed us to differentiate separate groups of kimberlite fields of the Olenek and Vilyui areas according to the degree of potential seismic hazard and ecological risk.

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