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Seismotectonics of the northern sector of the Verkhoyansk fold system (north-east of the Russian Arctic)

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Abstract. *In the northern sector of the Verkhoyansk fold system, tectonic structures are separated by crustal geoblocks of different ages, which belong to the Siberian platform and the Mesozoic Laptev Sea plate. These geoblocks are key objects of studies aimed at clarifying the evolution of the transitional 'continent-shelf' zone of the Arctic boundary between the Eurasian and North American lithospheric plates. Our study focused on the northern sector of the Verkhoyansk fold system and aimed to clarify regularities of seismotectonic destruction of the crust. We analyzed the seismotectonic data on neotectonic structures located in the Kharaulakh segment and the Lena River Delta, geological and geophysical structural features, active faults, modern structural plans, and the dynamic characteristics of the present-day terrain. Based on the comprehensive analysis of the study results, we identified for the first time a system of conjugated active strike-slip faults that reflect the structural plan of the northern sector of the Verkhoyansk fold system. In the sublongitudinal direction along the Ust-Lena right-lateral strike-slip fault, a structural boundary is traced as a major element of the kinematic plan of the modern structures, which predetermines the seismotectonic parameters of the zones of increased seismic activity. In small-scale geological and tectonic maps, as well as in satellite images, the Ust-Lena fault is structurally manifested from the Lena River Delta to the Orulgan segment of the Verkhoyansk fold system. The Bulun fields of earthquake epicenters (M_w = 6.8–7.0) and a wide zone of seismic dislocations varying in genesis are located at the southeastern termination of this fault. We analyzed the state of crustal stress across the study area using the tectonophysical data on the Late Cenozoic rupturing and folding deformations along with seismological data, and conclude that this is a unique transitional region wherein the mid-oceanic and continental crustal structures are conjugated, and the tectonic stress field changes from extension to compression. This study clarifies the kinematic plan of the modern structures in the shelf-continent transition zone of the Arctic boundary between the Eurasian and North American lithospheric plates. The study results can be useful for Arctic shelf development projects of Russian and foreign companies.*

Key words: Arctic segment of the boundary between the Eurasian and North American lithospheric plates, northern sector of the Verkhoyansk fold system, continent-shelf zone, modern structures, active faults, kinematic types, earthquake focal mechanism, seismotectonic deformations, tectonic stress types, dynamic model of modern structures.

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Introduction

The Arctic boundary between the Eurasian and North American lithospheric plates has been explored, but modern structures of the shelf-continent transition zone remain the least studied. Most studies of this region are devoted to the Laptev Sea riftogenesis [1–4 et al.] and the dynamics of seismogenerating structures in the adjacent segments of the continental Arctic-Asian seismic belt [5–7 et al.]. Many publications state that in the Kharaulakh seg-

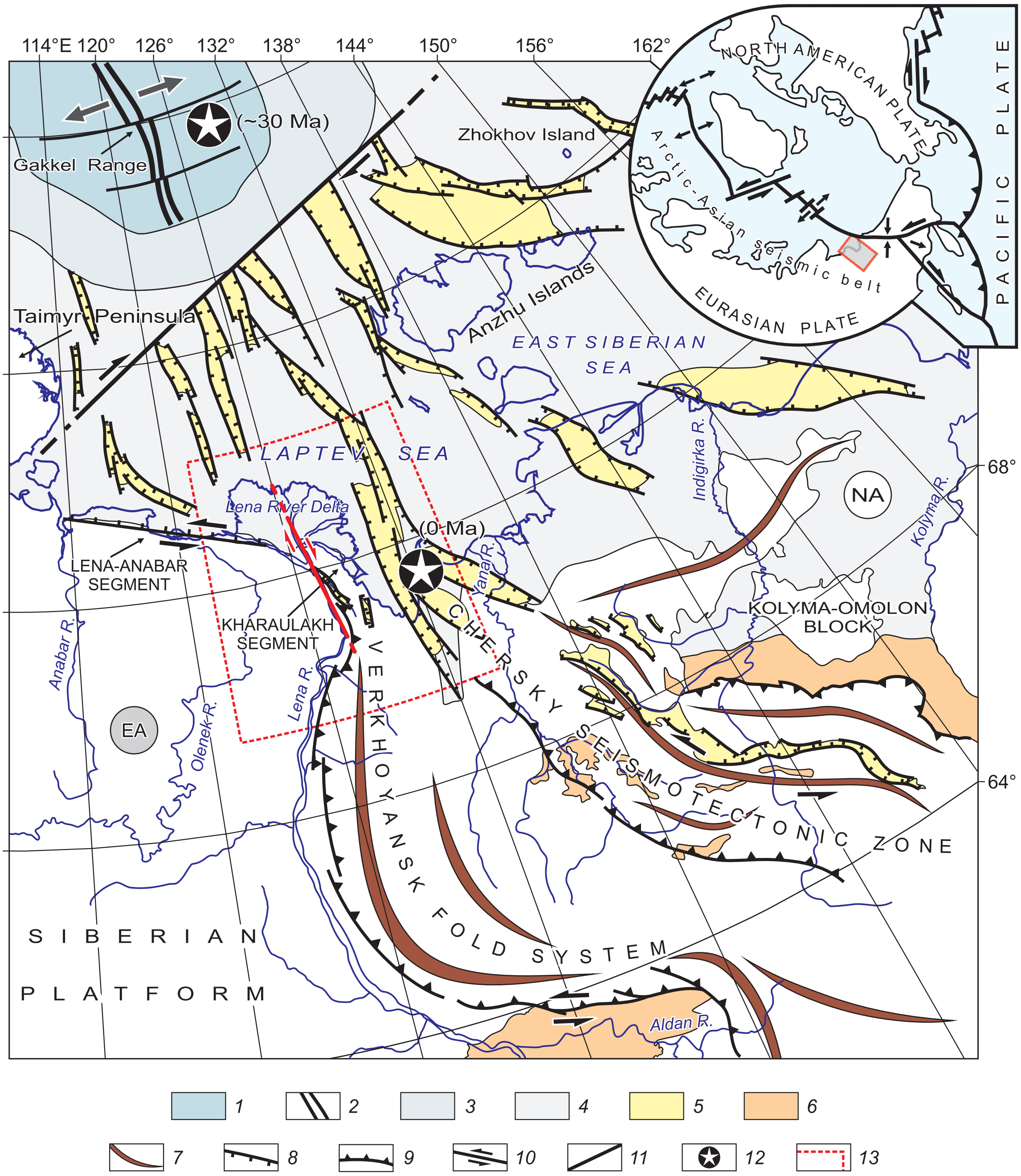

Fig. 1. Cenozoic tectonics of the Arctic sector of the Eurasian-North American lithospheric plate boundary (modified after [30]).
Lithospheric plates: EA– Eurasian; NA– North American.
Inset: notation of study area.
1 – Eurasian Basin; *2* – Gakkel spreading ridge; *3* – continental slope; *4* – cover of Pliocene–Quaternary deposits; *5* – rift basins; *6* – Cenozoic depressions (piedmont and intermontane troughs); *7* – mountain ranges; *8* – normal faults; *9* – reverse and thrust faults; *10* – strike-slip faults (red – Ust-Lena fault); *11* – transform fault; *12* – locations of rotation poles for the Eurasian and North American plates in different time intervals (after [31]); *13* – study area.

ment of the Verkhoyansk fold system and the Lena River Delta, extensional zones and seismic activity of neotectonic structures developed under the influence of rifting in the Laptev Sea shelf (Fig. 1).

Our study focused on the northern sector of the Verkhoyansk fold system, which is a unique geodynamic polygon. Field seismotectonic surveys and studies of the Late Cenozoic tectonic stress field of the study area were complemented by investigations of paleoearthquake traces in the zones influenced by large active faults. We investigated the interactions of seismogenerating structures that developed in the zone of transition from the rift depressions extending from the mid-Arctic Gakkel ridge to the Laptev Sea shelf and further into the Chersky seismotectonic zone of the Eurasian continent. Based on our research algorithm, we identified zones with different tectonic regimes of the stress-strain state of the crust and constructed a regional structural-dynamic model of the main seismogenerating structures of the study area.

The research objectives were as follows:

• Analyze earthquake epicenter distribution patterns based on records of both stationary and temporary networks of field seismic stations;

• Determine the kinematic type of seismotectonic deformations in focal areas of earthquakes with $M_w = 4.3–5.5$;

• Consolidate a unified catalog of earthquake source parameters;

• Identify the zones of active fracturing that influence the stress-strain state of the crust of conjugated blocks and segmentation of modern structures;

• Identify uniformly deformed dynamic segments within the modern structures of the Kharaulakh segment of the Verkhoyansk fold system and the Lena River Delta and clarify their genesis; and

• Determine the structural-kinematic plan of the junction of the main geostructures in the shelf-continent transition zone of the Arctic boundary between the Eurasian and North American lithospheric plates.

Our comprehensive study used data from new regional case studies implemented by the authors and data on the geology, tectonics, geophysics, seismogeology, and hydrogeology of the study area from publications by industrial and research organizations.

Research methods

Our seismotectonic studies are based on the concept envisaging the structural and dynamic uniformity of the geophysical medium and specific regularities of seismogeodynamic processes taking place in this medium. The research methodology was developed by the Institute of Physics of the Earth RAS [8, 9] and supplemented as described in [7, 10, 11]. The research algorithm starts with establishing the general trends in the neotectonic development of the study area. Modern (Late Cenozoic) structures in the study area were analyzed considering the recent tectonics as a structural framework comprising active faults and other features demonstrating the present-day tectonic activity related to the regional seismicity. Neotectonic structures of the Russian Arctic are ranked by degree of activity according to the regional principles of the classification described in [7, 10, 11].

In our study, a domain is a neotectonic geodynamic taxon of the territorial rank, which is considered as a spatially-localized integral object with multifactor interactions between its main components. The classification of domains is a multi-level system including eight classes of activity of modern geodynamic processes that lead to the formation of neotectonic structures. Each activity class is characterized by its specific and optimal set of features pertaining to tectonics (geodynamic setting), geophysics (heat flow, gravity field anomalies, and crustal thickness), morphostructure (elevation, difference between the highest and lowest elevations, and rates of vertical and horizontal movement of the ground surface), material, deformation features, and GPS measurements. Additionally, the inherited dynamics of the neotectonic structures were considered with respect to conditions in previous stages of domain development. To assess the modern geodynamic activity and specify the class of each domain, we interpreted both its primary and additional features. Three groups of activity classes were distinguished as follows: low activity (classes 1–2), moderate activity (classes 3–5), and high activity (classes 6–8). The characteristics for the domains specified in the northern sector of the Verkhoyansk fold system are shown in Fig. 2.

The next stage of the study aimed to identify the most probable areas of recent activity for a more detailed investigation and search for reference objects. Large-scale morphostructural and structural-dynamic mapping was carried out to provide the two components of morphotectonic analysis. The main concept for this analysis is consistency between terrain features and corresponding rates and types of endogenous processes. Relative movements of crustal blocks during neotectonic activity

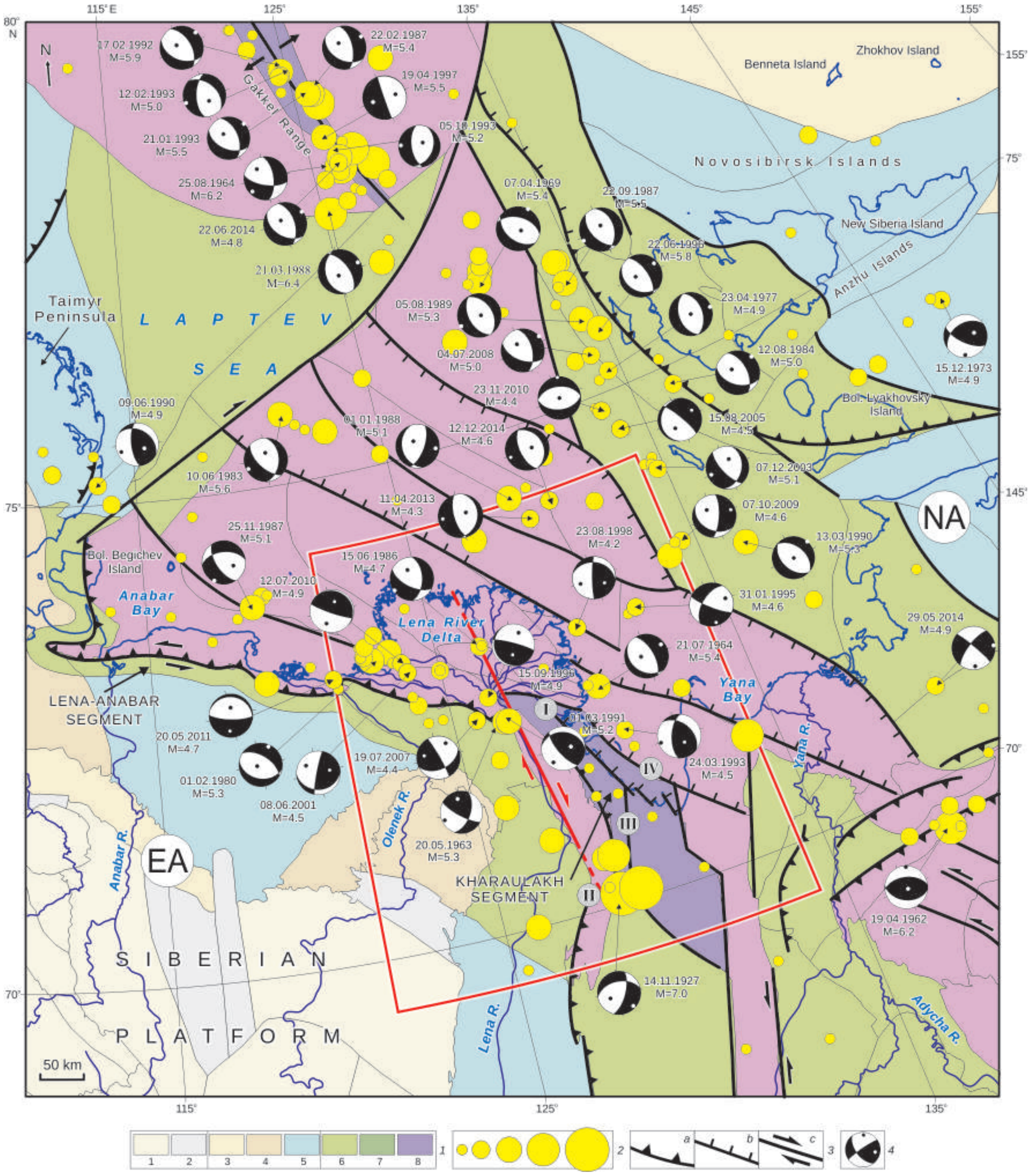

Fig. 2. Geodynamic activity of neotectonic structures in the Arctic sector of the Eurasian-North American lithospheric plate boundary (modified after [6]). Lithospheric plates: EA– Eurasian; NA– North American.
Active fault systems: I – Primorsky, II – Verkhoyansk, III – Kharaulakh, IV – Buor-Khaya.
1 – classes of geodynamic activity: low (1–2), moderate (3–5), high (6–8); *2* –earthquake epicenters (M_w): ≤ 4.0, 4.1–5.0, 5.1–6.0, 6.1–7.0, and ≥ 7.0 (data from [6]); *3* – kinematics of active faults: thrusts (*a*), normal faults (*b*), strike-slip faults (red – Ust-Lena fault) (*c*); *4* – earthquake focal mechanisms: date and magnitude (lower hemisphere), emergence of the main compression and extension stress axes (black and white dots, respectively).

cycles create the main features of the terrain – morphostructures bordered by active faults. The types of endogenous geodynamics are reflected in the features of modern geodynamic activity within the blocks of various ranks, as well as in the linear fault zones separating the blocks.

The data base, including geological, geophysical, and seismological data from the study area, provides the basis for investigating the structural-dynamic features of the main fields of earthquake epicenters characterized by a maximum seismic potential. To this end, large-scale remote images and laser-scanning images of the pleistoseist areas of strong earthquakes were deciphered which allowed preliminary mapping of active faults, diagnostics of fault kinematics, and selection of sites for detailed field surveys. Attention was given to additional indicators of recent fault activity, such as displacements identified by repeated geodetic surveys; earthquake epicenters confined to the zones of dynamic influence of faults; focal mechanisms of earthquakes as indicators of the dynamics; directions of crustal movements; geothermal and gas-hydrochemical anomalies (evidence of increased crustal permeability); and seismic profiling, seismic survey, gravimetric, and electrical survey data. Field studies were carried out to collect and clarify the information on deformation and displacements of young terrain elements and sediments, determine their ages, and discover evidence of strong paleo- and modern earthquakes. Trenching was performed on seismogenic deformation sites. Based on the field database, it was possible to clarify the kinematic types of the Late Cenozoic folds and faults and the structural parageneses of active faults. The kinematic types of the contact zones of the main seismogenerating structures were determined, and models showing the regional structures and dynamics were created. The experience of Russian and international joint research projects shows that the sequence of data collection and processing described above ensures that the resultant datasets provide for a comprehensive and reliable investigation of modern seismogeodynamic processes.

Seismotectonics of the Kharaulakh segment

Geological and tectonic structure. The Kharaulakh segment of the northern sector of the Verkhoyansk fold system includes the southern termination of the rift depressions in the Laptev Sea shelf and the coastal conjugated structures that belong to the Chersky seismotectonic zone (Fig. 1, 2). The sediments observed in this area cover a wide age range, from the Upper Proterozoic to the Cenozoic inclusively (Fig. 3). In terms of tectonics, the Kharaulakh segment is a frontal zone of the Verkhoyansk fold system that formed mainly in the Early Cretaceous [12, 13]. This segment began to form in the Riphean at the Siberian platform margin and developed as an extensive passive continental margin in the course of its long-term evolution, which is manifest in its structure and types of dislocations observed. Based on the structural and geometrical analyses of the structure-forming zones of the Kharaulakh segment, it is possible to distinguish two phases of Mesozoic folding. In the first phase, folding occurred in the eastern part of the segment, as evidenced by the northeast-striking folds and faults. In the second phase, sublongitudinal folds deviating to the northwest were formed. It is probable that the second phase included the formation of the main thrust structures and the knee bend of the Kharaulakh segment, which strikes along the left bank of the Lena River Delta to the fold zone of the Olenek sector of the Lena-Anabar segment (Fig. 1, 2).

Cenozoic events in the study area were related to the interaction of the North American and Eurasian lithospheric plates in northeastern Asia. At the beginning of the Cenozoic, this territory was involved in intensive tectonic processes associated with rifting along the continental continuation of the Gakkel spreading ridge. The continental crust was partially destructed over vast areas, including the northern sector of the Verkhoyansk fold system [2, 5, 14]. The Cenozoic megacomplex contains mainly Paleocene–Eocene continental sediments observed with a sharp angle discordance at different horizons of the dislocated Precambrian–Mesozoic megacomplex. The sediments fill a series of sublongitudinal depressions formed during the earliest phase of rifting in the continental continuation of the Gakkel spreading ridge. At some locations, the Paleogene sediments are folded and disturbed by thrusts and reverse faults. At the eastern sides of the Kengdei, Naiba, and other small depressions, local thrusts are confirmed by direct structural observations and exploratory drilling materials.

In the field study of the Kengdei River, we observed a gently dipping thrust and a contact of essentially sandy and mainly coal-bearing beds of Lower Eocene age (Fig. 4). The footwall of the thrust is an aleurite-sandy bed containing abundant relics of freshwater mollusk fauna. In the hanging wing, there are three layers of coal separated by aleurites and variegated sandstones with numerous casts of leaves. The thrust is marked by the displacements of the lower coal layer. The fault plane is subhorizontal in the southern part of the outcrop and dips at 30–35° in the frontal part where micro-thrusts are observed.

The thrust fault is accompanied by tectonic fractures clearly observed in the lithified interlayers of

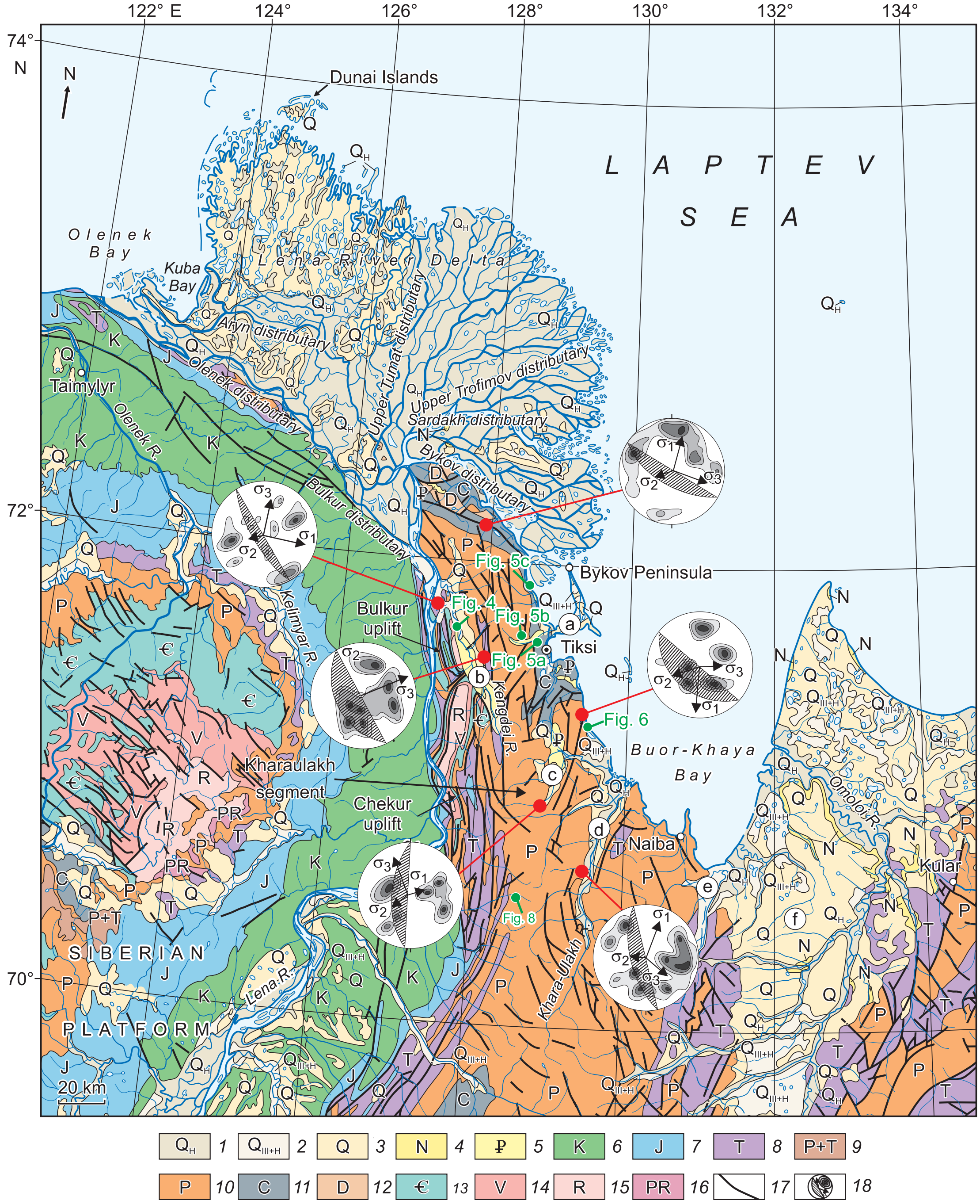

Fig. 3. Fragment of the geological map of the northeastern sector of the Verkhoyansk fold system (scale 1:1,500,000) (from [22]). Cenozoic basins: Khorogor (*a*), Kengdei (*b*), Kunga (*c*), Kharaulakh (*d*), Naiba (*e*), Omoloi (*f*).
1–3 – Quaternary system: *1* – Holocene; *2* – Neopleistocene and Holocene; *3* – Neopleistocene; *4* – Neogene system, Pliocene; *5* – Paleogene system; *6* – Cretaceous system, lower series; *7* – Jurassic system, upper series; *8* – Triassic system; *9* – Permian system, upper series, Triassic system*;* *10* – Permian system, upper and lower series; *11* – Carboniferous, upper and lower series; *12* – Devonian system; *13* – Cambrian system; *14* – Vendian system; *15* – Riphean system; *16* – Lower Proterozoic; *17* – faults differing in kinematics; *18* – rock fracturing diagrams, positions of vectors of the principal stress axes: extension (σ_1), intermediate (σ_2), compression (σ_3), and fault planes. Green dots – positions of the figures.

sands and aleurites. The circle diagram shows several maximum values grouped in the sublongitudinal and northeastern belts (Fig. 4). Their spatial positions relative to the working plane of the fault indicate the major thrust displacement. At the same time, the southeastern hanging wing shifted both to

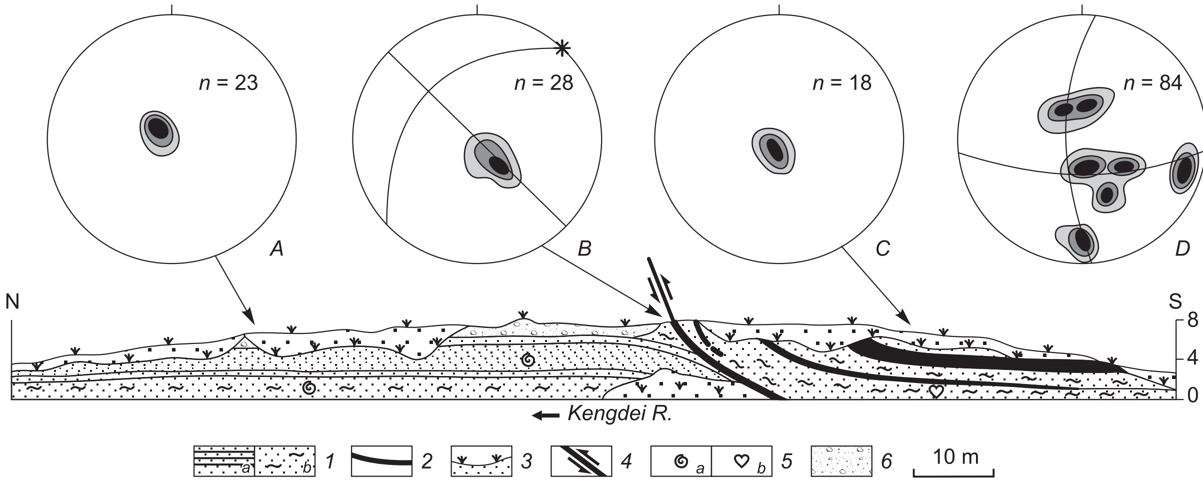

Fig. 4. Knyazyuregin thrust in the Kengdey depression.
1 – sandstones (*a*) and aleurite-sandy deposits (*b*); *2* – coal seams; *3* – scree and soddy areas; *4* – thrust plane; *5* – paleontological remains: freshwater mollusks (*a*) and casts of leaves (*b*); *6* – sand-gravel-pebble deposits. *A–D* – fracture diagrams (*n* – number of measurements).

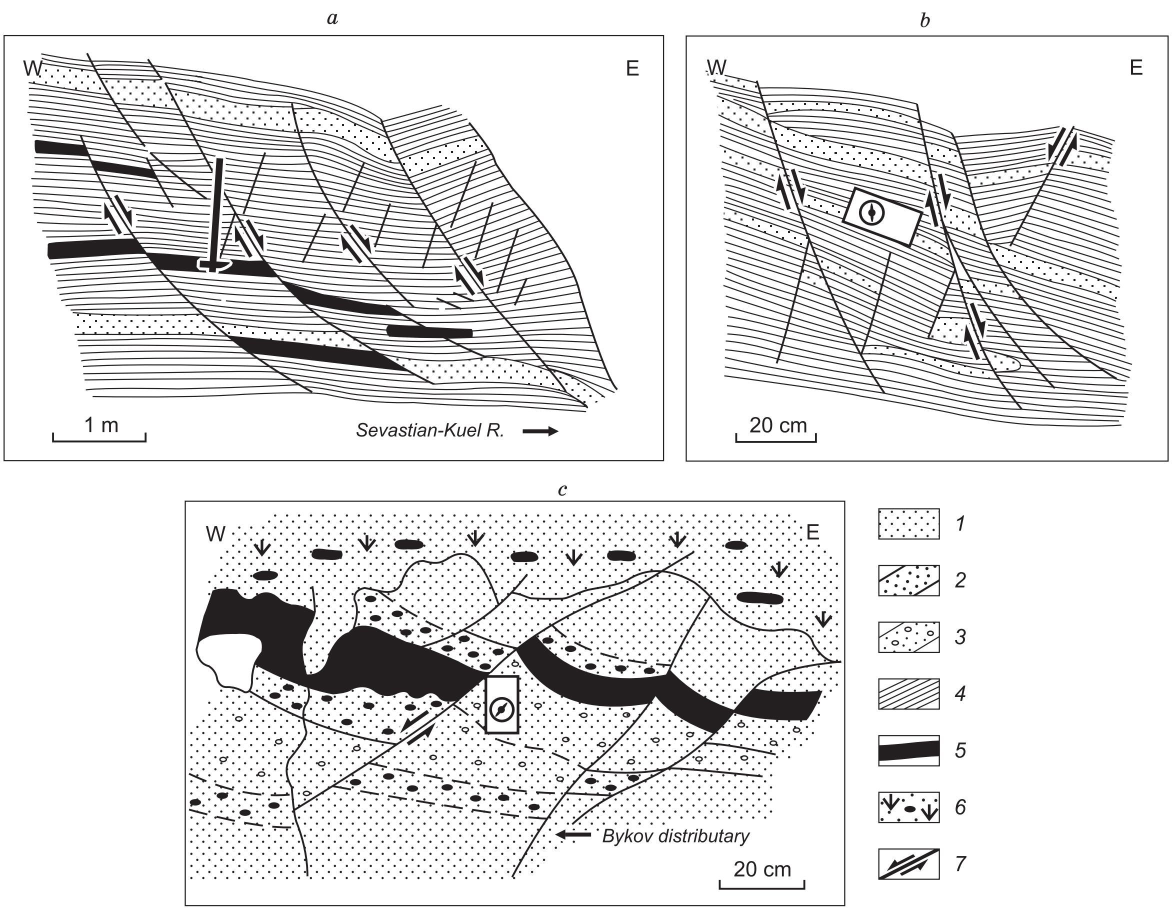

Fig. 5. Normal faults in stratigraphically different heterochronous rocks of the Laptev Sea coast (data from [5]).
a – Carboniferous deposits of the Sevastian-Kuel River; *b* – Permian deposits of the Khorogor River; *c* – Eocene deposits of the Bykov distributary. *1* – sandstones; *2* – sands with pebbles of various sizes; *3* – gravelites; *4* – shale; *5* – coal (*a*) and lignite (*c*); *6* – vegetation and silt soil; *7* – normal faults.

the north and northwest. The thrust is oriented across the strike of the Kengdei depression, which is also indicative of northwestern displacement. All of the above-mentioned observations suggest compression in the Cenozoic. The structural study results show that the compression axis was oriented sublatitudinally. According to the analysis of the Cenozoic cross-sections of the Kharaulakh segment and adjacent territories, compression took place in the Middle Miocene [5, 14, 15].

The next phase of the Cenozoic history was extension in the Pliocene–Quaternary. The axis of extension was oriented sublatitudinally and to the northeast. Normal fault displacements are observed in the rocks of the Laptev Sea, which are stratigraphically different in age (Fig. 5). Such displacements are manifest in the irregular shapes of the modern terrain features, including chopped forms and sharp ledges. Their working planes are identified in the Carboniferous sandstones and aleurites with intense cleavage and are accompanied by bands of crushed rocks, gouge, and numerous slickensides. Displacement amplitudes vary from several dozens of centimeters to a few meters. With depth, the faults are less-steeply dipping and can be classified as listric faults.

An example of a listric fault is a fault in the coastal outcrop of the 8–10 m marine terrace of the Buor-Khaya Bay near the place where the Yt-Yurege River reaches the sea (Fig. 6). Here, about 50 km south of Tiksi Settlement (600 m northwest of the Yt-Yurege River mouth), there is a contact zone of carbonaceous schists and Pliocene weathering crust represented by kaolinite clays developed on the schists. The zone is classified as a listric normal fault with a flattening plane (the dip angle reduces from 55° in the upper part to 30–35° in the lower part of the outcrop). The fault strike is parallel to the seashore, and the dip is to the northeast (dip azimuth of 50°). Bedrock with numerous normal fault slickensides and 20–25 cm beds of mylonite can be observed in this zone.

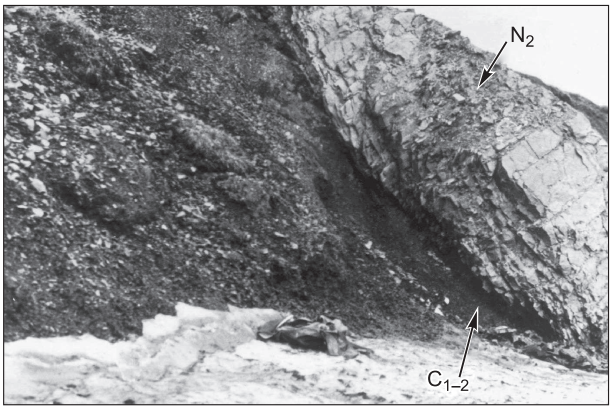

Fig. 6. Listric normal fault at the Yt-Yurege River mouth, Laptev Sea coast.
Outcrops: dark – Tiksi formation (C_{1-2}), light – Pliocene (N_2) weathering crust. Photograph by V.S. Imaev.

Normal faults are also observed in the Cenozoic depressions (Fig. 3). The fault kinematics is clearly confirmed by fracture diagrams. The Kharaulakh depression sides are steeply-dipping (up to 70–75°) normal faults. The normal fault planes are cut into separate segments by strike-slip faults. The strike-slip fault kinematics is confirmed by their positions relative to the displaced normal faults. Normal faults were also detected by structural observations in the field on the western side of the Kengdei depression and confirmed by geophysical data [14].

In the dynamic setting of the Cenozoic, faults of two directions were active. Reverse faults with a strike-slip component, and normal faults with a strike-slip component developed mainly in the sublongitudinal direction. The sublatitudinal faults showed more complex kinematics, and multidirectional strike-slip faults with a normal component were dominant (Fig. 2, 3). The systems of regional and local faults active in the Cenozoic are revealed on the basis of geological and geophysical datasets, and their kinematics are confirmed by fracture diagrams and focal mechanisms of earthquake sources [5, 11, 14]. Considering the fault locations, lengths, and kinematics, four main fault systems are distinguished: I – Primorsky (strike-slip faults with a normal component), II – West Verkhoyansk (thrusts), III – Kharaulakh (strike-slip faults with a normal component), and IV – Buor-Khaya (normal faults).

The Primorsky system of strike-slip faults with a normal component (I) is located in the northern part of the Kharaulakh segment of the northern sector of the Verkhoyansk fold system. The Primorsky normal fault system, with a small left-lateral strike-slip component, strikes west-northwest for about 50 km. It is subparallel to the Bykov distributary from the Lena River Delta to Buor-Khaya Bay. Along the western coast of the Buor-Khaya Bay, the Primorsky normal fault system continues as a series of sublongitudinal (north-northwest-striking) faults with a total length of 160 km, which are cut by northeast-striking faults. The highest activity is observed in the central part of the Primorsky system, that is, the area from the Khorogorsky to the Kharaulakh depression.

The West Verkhoyansk system (II) extends to the right bank of the lower reaches of the Lena River. It separates the Verkhoyansk fold-thrust belt from the Siberian platform. Near the Chekurovka area, thrusts are also traced on the left bank of the Lena River, where the Cambrian strata of the footwall and the Vendian formations of the hanging wing are in contact along the inclined zone of crushed rocks. Fracture diagrams and focal mechanisms of earthquake sources confirm the kinematic type, strike, and dip of the West Verkhoyansk thrusts (Fig. 2, 3). Despite its ancient age, this fault system was recently active, as evidenced by the clearly morphologically-manifest frontal part and the epicenters of weak earthquakes confined to the zone of its dynamic influence.

The Kharaulakh system of sublongitudinal faults (III) is located in the central part of the study area (Fig. 2, 3). It is a 6–7 km wide and almost 200 km long zone of closely-spaced subparallel faults consisting of two rectilinear echeloned segments connected by a diagonal link (3 km wide, 20–25 km long). The fault system is active, as evidenced by clear morphological features in aerial photographs and features observed in the field (numerous ravines, gullies, rock collapse, and landslides), as well as local earthquakes, including the 1927–1928 Bulun events (M_w = 8–9).

The Buor-Khaya fault system (IV) includes normal faults located along the western coast of Buor-Khaya Bay (Fig. 2, 3). The faults cut the basement of the riftogenic structure, and most of them penetrate into the upper horizons of the sedimentary cover, which suggests their young (Pliocene–Quaternary?) age. The age assumption is based on geological and geomorphological field observations [16] and multichannel seismic profiling data [17]. Sublongitudinal faults belonging to this system are traced from the coastal areas into Buor-Khaya Bay where they can be clearly detected in the seafloor relief. These faults are further confirmed by earthquake focal mechanism solutions.

Seismicity and seismotectonic deformations. The Kharaulakh segment is located within the continental part of the northwest flank of the Arctic-Asian seismic belt (Fig. 1, 2). The first instrumental data on its seismicity were obtained in 1909, when an earthquake (M_w = 6.8) in the Laptev Sea near the delta of the Lena River was recorded by the global network of seismic stations (Fig. 2, 7). Earthquakes of M_w = 5.5–6.0 with epicenters in the Laptev Sea area were recorded in 1914–1926. The epicenters of five Bulun earthquakes (M_w = 5.8–6.8) recorded in 1927–1928 were located 140–160 km south of the Tiksi settlement. Analysis of the locations of the local earthquake sources (Fig. 7) in relation to the tectonic features of the Kharaulakh segment (Fig. 3) shows that the epicenters are mostly confined to the systems of large faults and thus confirm their current activity. It should be noted that most earthquakes in this area occurred in the crust at depths up to 35 km (94 % of the total number for the specified depth); only 6 % were recorded in the depth range of 36–55 km, while the most frequent local seismic events occurred at a depth of 15 km.

The field of tectonic stresses is inhomogeneous in the seismically-active Kharaulakh zone, as revealed from earthquake focal mechanism solutions (Fig. 7, Table 1). The major stresses acting in the earthquake sources have different azimuths and dip angles ranging from horizontal to subvertical. This suggests that the seismic process in this zone developed under both extension and compression. The seismically-active Buor-Khaya and Primorsky zones are currently subject to extension across the strike of the regional structures. This assumption is supported by earthquake focal mechanism solutions showing normal faulting. Further westwards to the Lena River, extension is replaced with compression. In this area, strike-slip faults, normal faults with a strike-slip component, and thrusts are revealed from the local earthquake focal mechanism solutions. Normal faults with a strike-slip component are shown by earthquake focal mechanisms for the Bulun events in the seismically-active Kharaulakh zone.

Based on the analysis of the state of crustal stresses from north to south, another transitional area is revealed wherein extension (sea shocks in Buor-Khaya Bay) is replaced by compression, as evidenced by thrusts in the Naiba depression. Southeast of the Chersky seismotectonic zone, the field of tectonic compression stress is stable, and the earthquake focal mechanism solutions show strike-slip, thrust, and reverse faults. The seismological data are consistent with the geostructural observations and confirm a wide range of faults (normal, strike-slip, and thrust faults and their modifications).

Seismic dislocations of various geneses were detected in aerial and satellite images (Fig. 7). Geostructural methods were used to determine their locations and possible earthquake magnitudes of suffi-

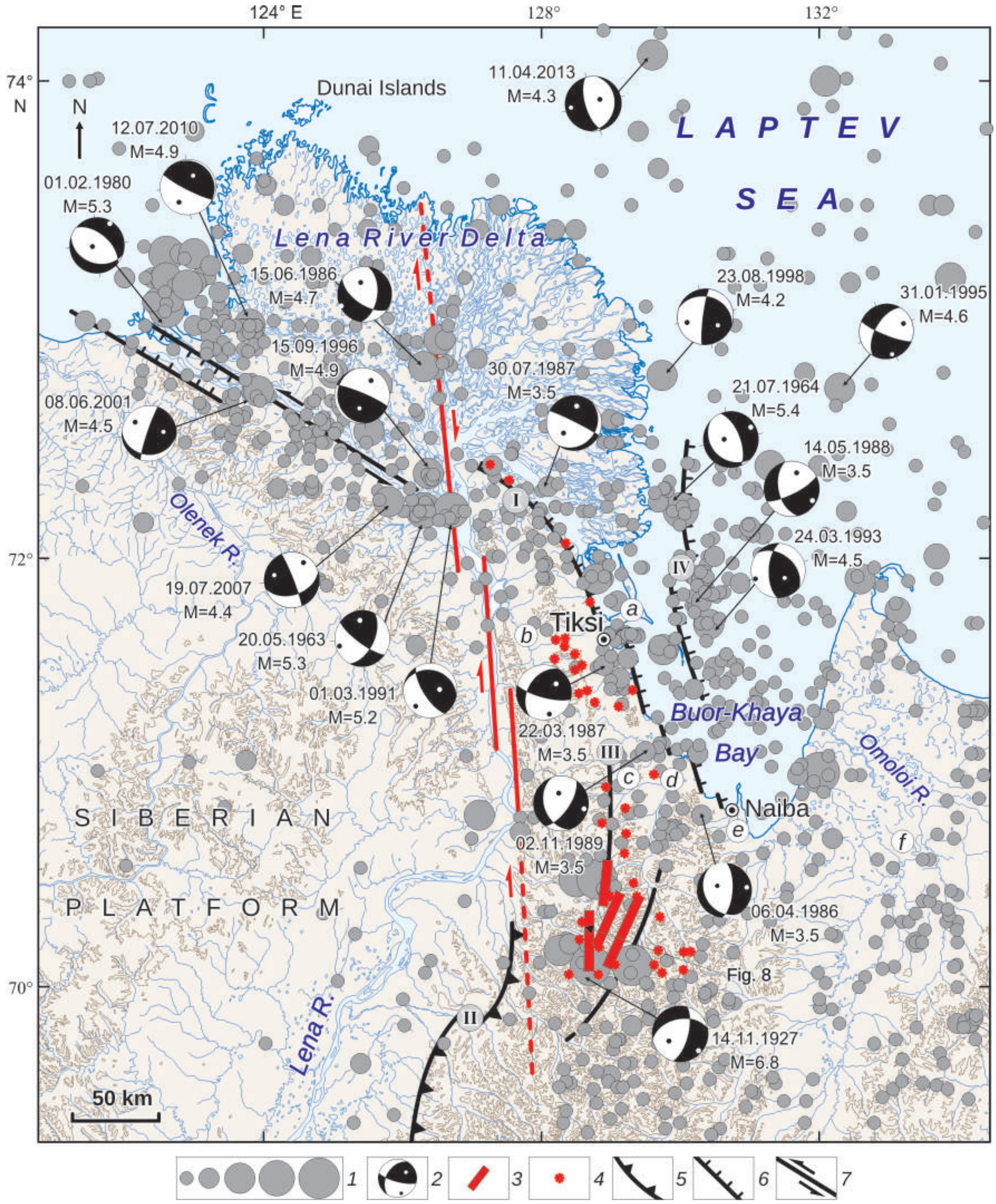

Fig. 7. Earthquake epicenters in the northeastern sector of the Verkhoyansk fold system.
Active fault systems: I – Primorsky, II – Verkhoyansk, III – Kharaulakh, IV – Buor-Khaya.
Cenozoic basins: Khorogor (*a*), Kengdei (*b*), Kunga (*c*), Kharaulakh (*d*), Naiba (*e*), Omoloi (*f*).
1 – earthquake epicenters (M_w): < 3.0, 3.1–4.0, 4.1–5.0, 5.1–6.0, 6.1–7.0 (data from [6]); *2* – earthquake focal mechanisms: date and magnitude (lower hemisphere), emergence of the main compression and extension stress axes (black and white dots, respectively); *3* – seismodislocations; *4* – seismic traces; *5* – thrusts, *6* – normal faults; *7* – strike-slip faults (red – Ust-Lena fault).

cient intensity for the occurrence of such dislocations. For each seismic dislocation, its probable occurrence time was determined by the dislocation size, morphological features, and types of primary (seismotectonic) and secondary (seismogravitational) deformations. In general, the identified seismogenic structures differ in size and morphology and belong to different genetic types, that is, their formation is re-

Table 1

Earthquake focal mechanisms (M_w = 3.5) in the northeastern sector of the Verkhoyansk fold system

Day.month.year; Hour:min: sec	Hypocenter coordinates			M_w	Focal mechanisms			Data sources	Fault types
	Φ (°N)	Λ (°E)	h (km)		strike	dip	slip		
14.11.1927 00:12:08	70.10	128.70	15	6.8	268	46	–35	F, 2009	Normal fault
20.05.1963 17:01:35	72.2	126.3	15	5.3	356	70	–164	F, 2009	Strike-slip fault
21.07.1964 9:56:17	72.2	130.0	35	5.4	130	45	–112	F, 2009	Normal fault
01.02.1980 17:30:27	73.04	122.61	27	5.3	315	55	–78	HRVD	Normal fault
06.04.1986 01:27:21	70.8	130.3		3.5	5	66	–74	F, 2009	Normal fault
15.06.1986 06:55:36	72.8	126.3	10	4.7	130	60	–134	F, 2009	Strike-slip fault with normal component
22.03.1987 01:14:10	71.5	128.9	7	3.5	212	42	22	F, 2009	Reverse fault with right-lateral strike-slip component
30.07.1987 18:51:28	72.3	128.1	18	3.5	295	86	–70	F, 2009	Normal fault
14.05.1988 13:25:50	71.8	130.3		3.5	167	51	–160	F, 2009	Normal fault
02.11.1989 04:40:42	71.1	129.5	31	3.5	161	38	–136	F, 2009	Normal fault
01.03.1991 01:57:06	72.2	126.7	39.4	5.2	290	7	49	F, 2009	Thrust and reverse faults
24.03.1993 22:43:29	71.69	130.40	9–10	4.5	329	41	46	S, 2017	Reverse fault
31.01.1995 12:43:43	72.71	132.28	37	4.6	135	79	–34	S, 2017	Strike-slip fault with normal component
15.09.1996 00:21:23	72.36	126.38	4–5	4.9	170	12	140	S, 2017	Reverse and thrust faults
23.08.1998 09:59:03	72.77	129.73	33–35	4.2	302	29	14	S, 2017	Thrust fault
08.06.2001 04:59:02	72.70	123.92	10–12	4.5	205	84	67	S, 2017	Reverse and thrust faults
19.07.2007 06:18:44	72.24	125.80	37–38	4.4	79	45	7	S, 2017	Reverse fault with strike-slip component
12.07.2010 10:06:43	72.98	123.79	6–7	4.9	325	9	112	S, 2017	Thrust and reverse faults
11.04.2013 20:01:09	74.11	129.62	36	4.3	20	25	–70	S, 2017	Normal fault

Note. M_w – moment magnitude; parameters of nodal planes: strike, dip, and slip in degrees. Data sources: S, 2017 [18], F, 2009 [19], HRVD [20].

lated to seismic events (M_w = 6.0–7.5) that occurred at different times and locations.

A major seismic dislocation in the zone of dynamic influence of the Kharaulakh fault is the Baris fault which is a 12-km long linear sublongitudinal normal fault with a strike-slip component (Fig. 8). Displacements of some landforms are predominantly right-lateral. In field observations, the fault was detected as a system of ditches 10–15 m wide. On the slopes and peaks of the watersheds, the fault is

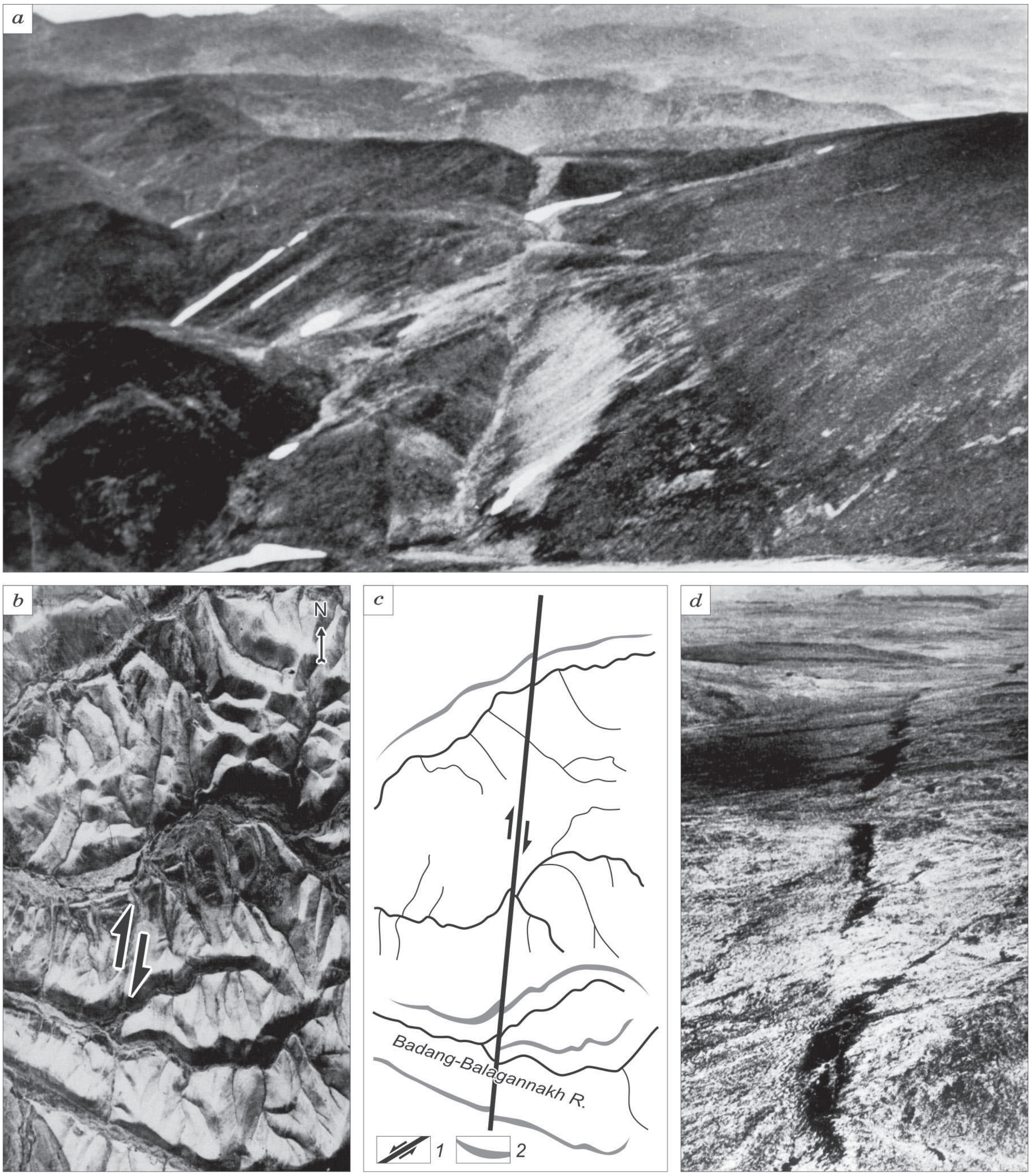

Fig. 8. Beris seismodislocation.
a – photograph of the system of ground surface ruptures resulting from the Bulun earthquakes of 1927–1928 ($M_w \geq 7.0$); *b* – aerial photograph of the Beris seismodislocation (arrows show the fault plane); *c* – fragment of the deciphered image: strike-slip faults (*1*), watershed axes (*2*); *d* – photograph of seismogenic extension fractures in the Kharaulakh fault zone (origin place of the Beris seismodislocation).

marked by troughs 4–6 m wide and filled with argillite and sandstone fragments crushed to debris. At the edges of the ditches and troughs, there are steep (80–90°) walls rising 2.0–2.5 m above the bottoms and composed mainly of fragments of silicified dense sandstones. The fault wings' displacement direction is reliably determined from the displacement of the sublatitudinal tributaries of the rivers, as well as the axial lines of the watershed ridges. The western wing is horizontally displaced by 25–30 m. The displacement involved the youngest deposits of the fluvioglacial complex up to the floodplain and above-floodplain terraces. Based on these data and the rock fracturing analysis, this is a right-lateral normal fault with a strike-slip component. In our calculation, the age of the Baris seismodislocation is a thousand years, considering an estimated earthquake magnitude of 7.0–7.5. Structural-dynamic studies of the Kharaulakh segment of the Verkhoyansk fold system reveal areas that differ in the state of crustal stress and fault kinematics, including normal, strike-slip, and thrust faults and their combinations.

Seismotectonics of the Lena River Delta

Geologic and tectonic structure. The tectonic structure of the Lena River Delta is defined by the junction of large crustal geoblocks—the ancient Siberian Platform and the Mesozoic Laptev Sea Plate—separated by the Kharaulakh segment of the Verkhoyansk fold system (Fig. 1–3). Their fragments compose a specific structural pattern. The ideas concerning the geological structure of the pre-Cenozoic base of the delta were formulated according to geophysical data interpretations [3, 4, 21] and geological data on the contact structures of the Lena-Anabar and Kharaulakh segments of the Verkhoyansk fold system [22, 23]. It is assumed that the delta base is a complex fold-block structure that is similar in structure and history to the Hercynides of the northern Taimyr Peninsula. In the delta, the pre-Quaternary formations outcrop mainly on the banks of the Bykovsky, Olenek, and Bulkur distributaries and also occur as erosive remnants on islands in the estuary of the Lena River valley (Fig. 3).

The structure of the pre-Cenozoic delta base is represented by a series of northwest-trending blocks covered by Cenozoic sediments of different thicknesses. Based on the gravity field interpretations, the Archean formations are presumably confined to the uplifted block of the delta [24]. According to other data, the Archean formations may occur at a depth of about 100 m, and the pre-Cenozoic base at the northeastern part of the delta is assumed to occur at a depth of about 3,000 m [25]. Abundant Ordovician–Lower Carboniferous deposits in the delta were identified from seismic profiles [21, 25]. The age and composition of the Ordovician rocks are conditionally determined by analogy with the deposits in the neighboring areas (Fig. 3).

Paleogene deposits comprise the major depression grabens of the delta. A general idea of their structure is based on studies of similar sediments in the grabens adjacent to the delta in the northern sector of the Kharaulakh segment [22, 23]. Eocene sandstones and 0.3 to 2.4 m thick aleurolite and brown-coal seams can be seen in outcrops observed along the Bykov distributary. Neogene sediments are exposed fragmentarily in outcrops observed on islands in the delta. Paleogene and Neogene sediments formed in a setting of differentiated displacements of large blocks, therefore total thickness ranges from several tens of meters to 2–3 km at the most subsided sites [24].

The surface cover of the delta is composed of Quaternary sediments. However, their age is conditional and determined only by the stratigraphic and geomorphological positions of the strata without sufficient paleontological and palynological data. The delta surface is mostly composed of modern sediments, such as alluvial, lacustrine-boggy, lacustrine-boggy-aeolian, aeolian, gravitational, and marine sediments. The islands in the delta are composed of heterochronous and heterogeneous sediments. Their geological structure suggests a sharp change in sedimentation conditions in both lateral and vertical directions within a short time [24].

The Quaternary history of the Laptev Sea shelf, including the Lena River Delta, is sharply different from that of the continental part of the Kharaulakh segment. It is related to opening of the Eurasian sub-basin, the onset of which is assumed to occur at the end of the Paleocene (~56 Ma) [4, 21]. This region was dominated by strike-slip and normal-strike-slip tectonic movements that predetermined the block structure of the delta, as is clearly evidenced by different hypsometric positions of Late Quaternary and Holocene sediments (Fig. 3). According to Galabala [16], in the central part of the delta, the bottom of the Holocene alluvial sediments can be traced at the current level of the Trofimov distributary (a borehole drilled to a depth of 25 m in the northeastern end did not reach these sediments). In the western part of the delta, the fault displaced Zyryansk-Sartansk (Upper Pleistocene) horizons by 30 m.

Normal-fault structures observed in this area suggest an extensional phase with the axes presumably oriented sublatitudinally and to the northeast [6]. Under these geodynamic conditions, faults of two orientations were active in the Cenozoic. Heterochronous normal and normal strike-slip displacements are typical of submeridional faults, whereas the kinematics of sublatitudinal faults are more complex, and differently-oriented oblique-slip components are predominant [6].

Geomorphological structure. The activity of the newest structures of the Lena River Delta is evidenced by morphodynamical indicators and geomorphological characteristics of the present-day relief (Fig. 9). The current structure of the delta includes separate segments of regional fill deltas. According to the age analysis of fan deposits, the most ancient (8570 years BP) parts of the delta are the islands in its western segment, which are bordered by the Aryn and Tumat distributaries, and the youngest (1500–2000 years BP) parts are the islands of the Bykov distributary in the southeastern segment of the delta [24, 26].

The Lena River Delta shoreline is segmented in accordance with the positions of the regional fill deltas. In the western part of the delta (Kuba Bay), there are Holocene marine terraces (up to 8 m high; age of 3000 years BP) that are mapped in Grigoriev et al. [25]. The northern part of the delta is represented by the abrasion-accumulation shores of the Tumat alluvial fan. The abrasion bench (up to 1 m high) is periodically flooded during tides and surges leading to active accumulation. To the east, the delta shoreline is exclusively abrasional. In the eastern part of the delta, the mouth areas of the Sardakh, Trofimov, and Bykov distributaries are actively developing estuaries. The overall water flow in the delta area concentrates in the eastern and southeastern distributaries, which indicates topographi-

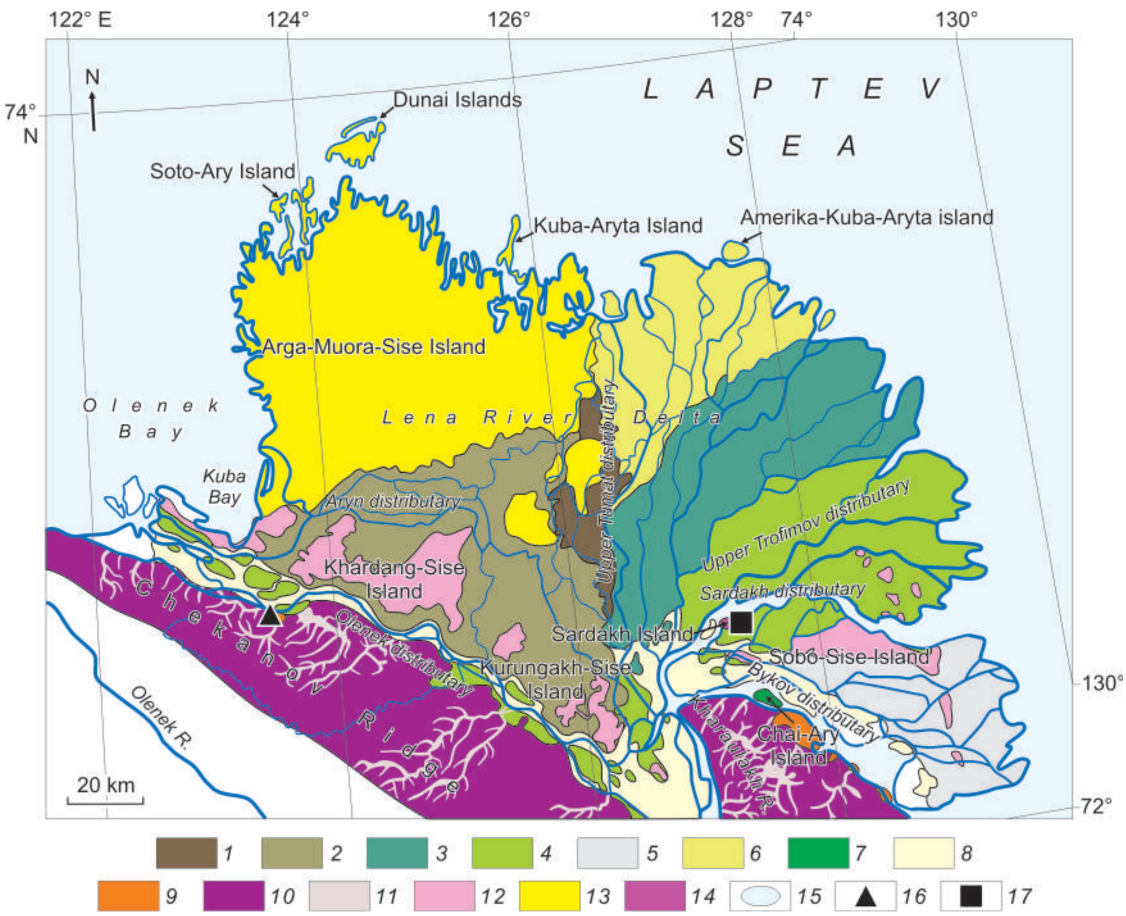

Fig. 9. Geomorphological map showing cumulative and denudation relief structures of the Lena River Delta (data from [24]). *1–6* – alluvial-marine terraces, ages: *1* – 8000; *2* – 6000–4000; *3* – 3000; *4* – 2500–3000; *5* – 1500–800; *6* – 1200–500 yrs BP; *7* – Chai-Ary Island terrace consisting of coarse clastic sediments (height up to 12 m); *8* – floodplain terrace consisting of sands (height up to 7 m; age from 200 yrs to the current time); *9* – alluvial fan of glacial water deposits (age 500–200 yrs BP); *10* – structural denudation relief of low hills consisting of Pre-Quaternary rocks; *11* – terraceless stream valleys; *12* – thermally-denuded surface of glacial complex rocks (height up to 50 m); *13* – remnant of the alluvial marine terrace of Arga-Muora-Sise Island (height of 20–22 m); *14* – erosion-abrasion rock of Sardakh Island (height up to 50 m; Neogene); *15* – lacustrine thermokarst basins filled with high-terrace water. Legend, not to scale: *16* – basin terrace (height up to 30 m; age 138 kyr BP); *17* – basin terrace (height of 10–15 m; age 48 Kyr BP).

cal subsidence of the delta surface to the east and southeast, away from the sublongitudinal system of the Tumat distributaries.

The topographical subsidence of the northwestern part of the Lena River delta towards the southeast was observed in the field study of the Quaternary sediments of the Kurungnakh-Sise Island [24]. In this area, a lithological boundary is clearly detected at a height of 8 m between the glacial rock complex and the underlying sands. It is traced at the same height for almost 4 km along the Bulkur distributary and then roughly descends towards the Olenek distributary.

Different elevations of the glacial rock complex's surface are noted in the western and eastern parts of the delta [24–26]. Thus, the general uplift of the crust in the western segment of the Lena River Delta and differentiated block movements along the faults offer a reasonable explanation of the anomalous redistribution of water flow among the distributaries. Water and debris flow primarily to the east and southeast into the Bykov and Trofimov distributaries, rather than taking a straight route to the northwest in the Olenek distributary. Tectonic subsidence is most intensive near the Bykov distributary (southeast), which predetermines the largest water flow exclusively in this direction.

Seismicity and seismotectonic deformations. Seismically-active zones of the newest structures of the Lena River Delta were revealed by analyzing the field of earthquake epicenters. The diagram in Figure 10 shows the earthquake epicenters record-

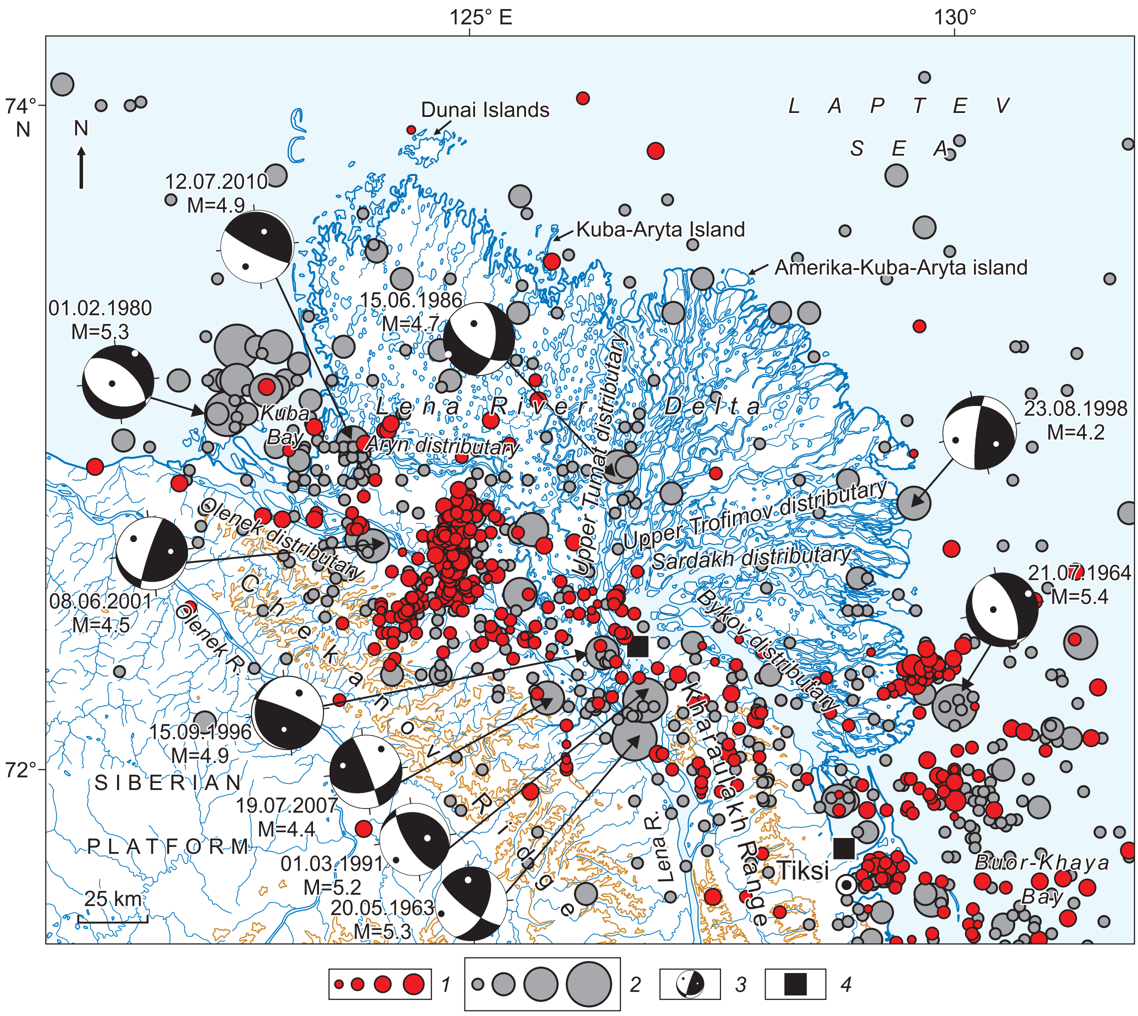

Fig. 10. Earthquake epicenters and focal mechanisms for the Lena River Delta (data from [6, 18]).
1 – earthquake epicenters (M_w): –1.5 to –0.1, –0.1 to 1.2, 1.2–2.6, 2.6–4.0 (data from [27]); *2* – earthquake epicenters (M_w): < 3.0, 3.1–4.0, 4.1–5.0, 5.1–6.0; *3* – earthquake focal mechanisms: date and magnitude (lower hemisphere), emergence of the main compression and extension stress axes (black and white dots, respectively); *4* – stationary seismic stations of Yakutsk Branch UGS RAS.

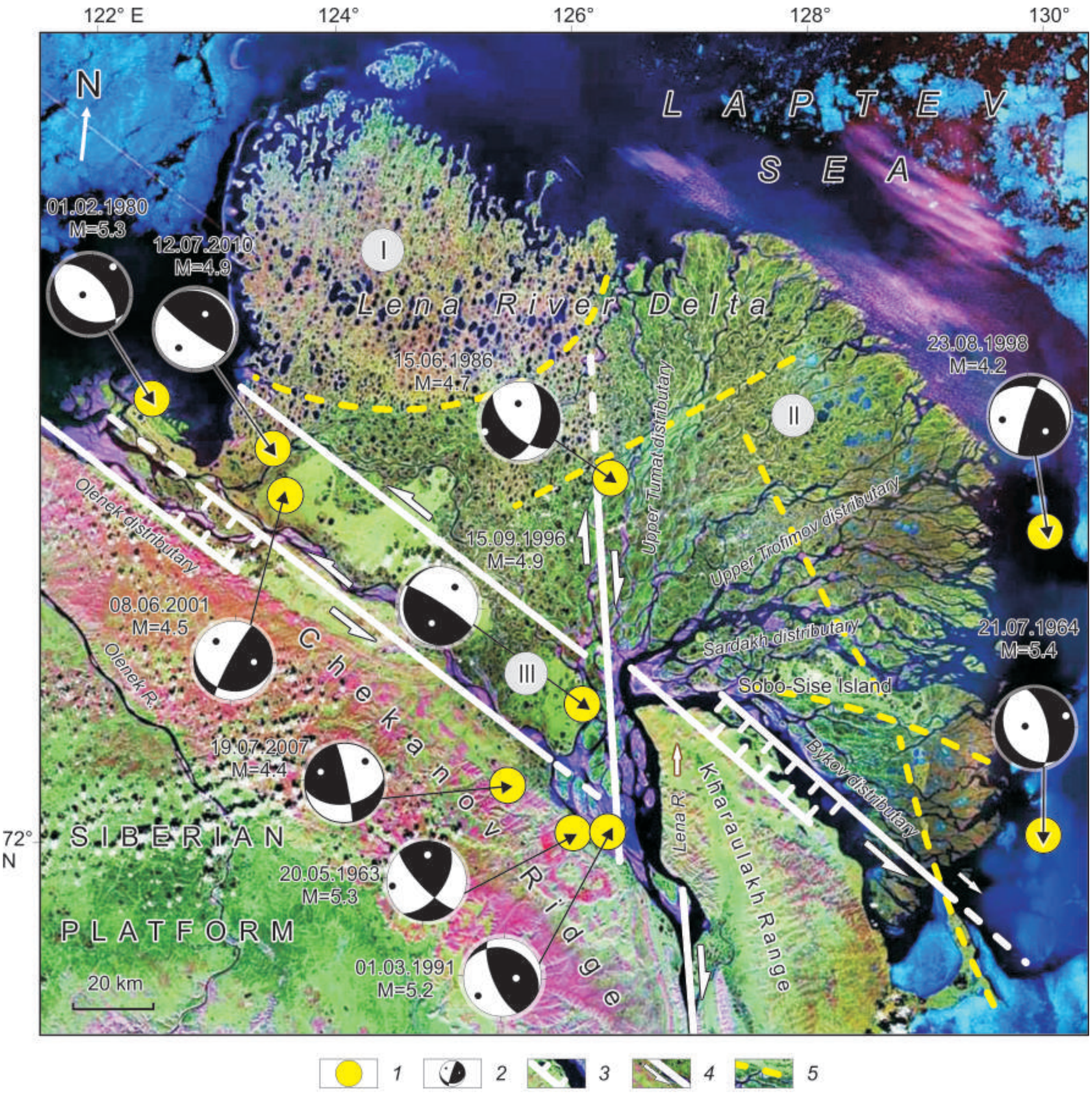

Fig. 11. Landsat-7 satellite image of the Lena River Delta in 2000, showing active tectonic elements (data from [32]). Types of tectonic regimes: I – transpression; II – transtension; III – compression.
1 – earthquake epicenters (data from [6]); *2* – earthquake focal mechanisms: date and magnitude (lower hemisphere), emergence of the main compression and extension stress axes (black and white dots, respectively); *3* – normal faults, *4* – strike-slip faults; *5* – activated fault structures of Holocene (?) age.

ed by stationary and temporary field seismometers within the delta area and the coastal shelf zone [27]. The database of focal parameters of seismic events of medium magnitude was supplemented with seismic moment tensors, moment magnitudes, mechanisms, and depths of earthquake foci with M_w = 4.3–5.5 [18].

Seismotectonic data and remote images were used to map the active faults and diagnose their kinematics. Such faults are confined to zones influenced by earthquakes, and their focal mechanism solutions are indicative of the dynamics and directions of neotectonic movement. The structural-kinematic plan of the newest structures in the Lena River Delta was detected from Landsat-7 satellite images (Fig. 11) and confirmed by the geological, geophysical, and morphodynamic features in the present-day relief. The data revealed that the patterns of the main distributaries of the delta are tectonically predetermined and correlate with the strike of the conjugated Lena-Anabar and Kharaulakh segments of the Verkhoyansk fold system (Fig. 1, 2).

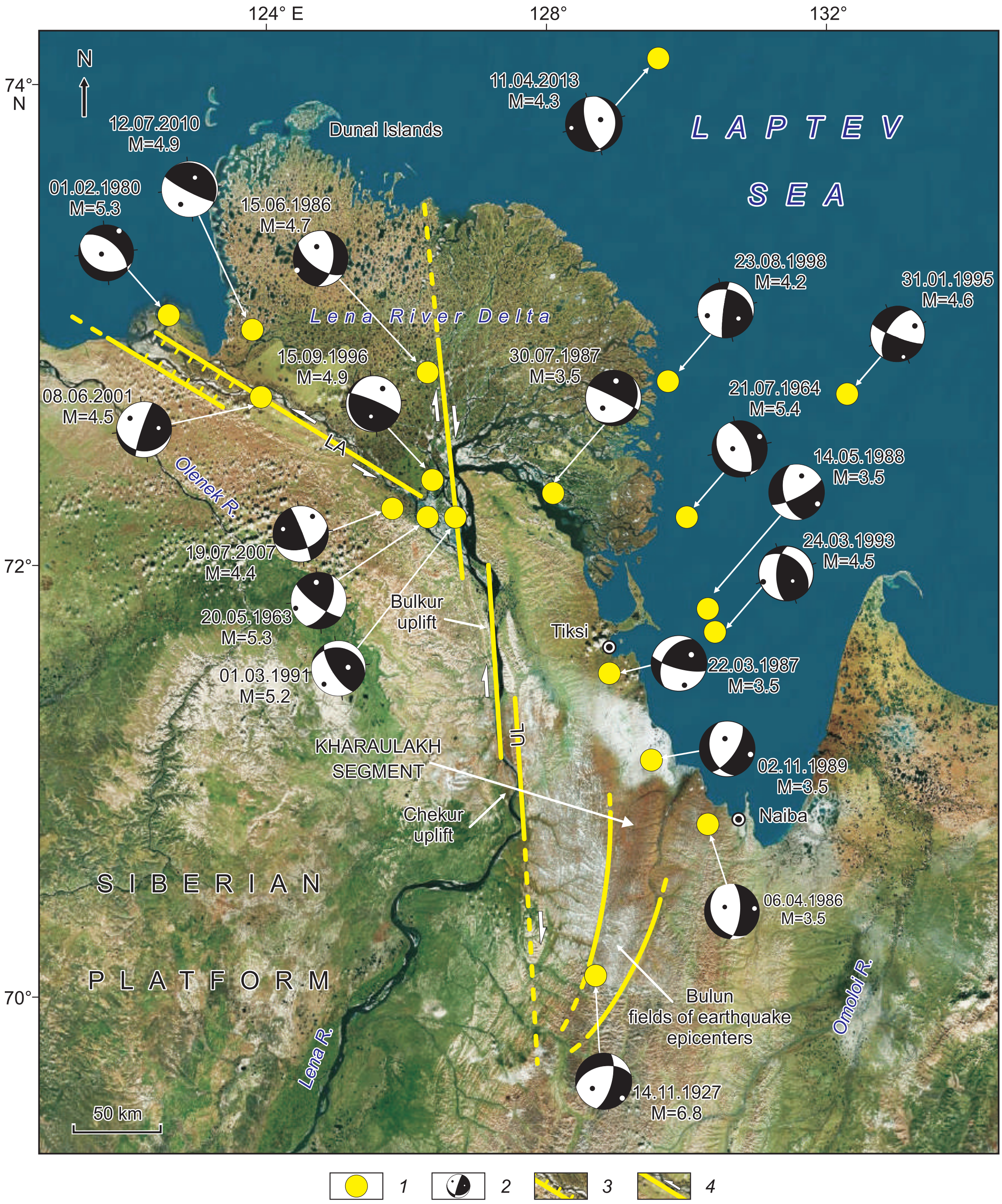

Fig. 12. Geodynamics and active tectonic elements of the northeastern sector of the Verkhoyansk folded system (Google Earth image).
Faults: LA – Lena-Anabar, UL – Ust-Lena.
1 – earthquake epicenters (data from [6]); *2* – earthquake focal mechanisms: date and magnitude (lower hemisphere), emergence of the main compression and extension stress axes (black and white dots, respectively); *3* – normal faults, *4* – strike-slip faults.

In the satellite image, color differences show that the Ust-Lena right-lateral strike-slip fault divides the Lena River Delta into two main segments. In the western segment, the number of river channels is considerably reduced, and numerous ‘spots’ in the satellite image depict large thermokarst lakes (Fig. 11). It is likely that the delta zones to the west of the fault experience are currently subjected to tectonic uplifting, while subsidence takes place in zones to the east of the fault. This assumption is confirmed by geodetic data [28]. In the western segment, positive velocities of recent vertical tectonic movements amount to 2–4 mm/year and; further to the east, velocities decrease to weakly negative values.

A system of lineaments of left-lateral strike-slip kinematics at the base of the delta is interpreted as belonging to active faults comprising the sublatitudinal branch of the zone of dynamic influence of the Verkhoyansk marginal suture. Near the Bykov distributary, a vast pull-apart zone formed along the system of left-lateral strike-slip faults. This system of lineaments is associated with the main epicentral field, wherein the source depths range from 4–12 to 37–40 km and the earthquake focal mechanism solutions show reverse-fault, transpressional, and thrust displacements.

The above-described observations ascertain the seismotectonic activation of the sublatitudinal segments of the active faults in the zone of dynamic influence of the Verkhoyansk marginal suture. Other lineaments (see satellite image in Fig. 11) are second-order structures resulting from activation of the conjugated main fault systems. The two dynamic segments of the Lena River Delta, which are separated by the Ust-Lena right-lateral strike-slip fault, experience seismotectonic crustal destruction due to transpression (in the west) and transtension (in the east). In the area between the Olenek and Aryn distributaries, the compression strain regime is uniform and associated with active faults comprising the sublatitudinal branch of the zone of dynamic influence of the Verkhoyansk marginal suture.

Discussion

The Ust-Lena system of strike-slip faults has been identified for the first time in this study. It is the main structure-forming element in the kinematic plan of the newest structures in the northern sector of the Verkhoyansk fold system, which controls the parameters of the seismotectonic activation zones. In the small-scale geological and tectonic maps (Fig. 2, 3) and the satellite images (Fig. 11, 12), the Ust-Lena right-lateral strike-slip fault is structurally traced from the Lena River Delta to the Orulgan sector of the Verkhoyansk fold system. The Bulun epicentral field (M_w = 6.8–7.0) with a maximum seismic potential is located at the southeastern termination of the fault, where a wide zone of seismic dislocations differing in genesis has been identified (see Fig. 7).

At the northwestern flank of the fault, along the system of the Tumat distributaries in the Lena River Delta, there is a wide and structurally-shaped near-fault extension zone consisting of several depressions that are regularly developed in the northeast direction (Fig. 11). In the Lena River Delta, there are no extension structures typical of rifting that affected the Laptev Sea shelf. The system of Tumat depressions was formed in a transtension–strike-slip regime.

A continuation of the lineament from the Lena River Delta to the south is evidenced by the straight-line channel of the Lena River at the delta base before the river channel is divided into the distributaries. The Bulkur and Chekurov anticlines, where reverse thrusts (both cross-cutting and subparallel to the foliation) are observed in outcrops, can be interpreted as compression blocks at the strike-slip faults (Fig. 3, 12). Taking into account a clearly-revealed structural pattern of compression blocks and extension structures relative to the strike of this lineament, their morphological features, and earthquake focal parameters, the kinematics of the Ust-Lena fault was established as a right-lateral strike-slip fault with a normal component. Table 1 and Figures 7 and 12 show a summary of the focal mechanism solutions from publications on the northern sector of the Verkhoyansk fold system.

Conclusion

1. The present-day morphotectonic plan of the northern sector of the Verkhoyansk fold system has largely inherited the regularities of the tectonic regime of the Late Mesozoic stage. The newest structures are due to the conjugation of the Ust-Lena and Lena-Anabar strike-slip fault systems that differ in strike and reflect the junction zone of the main regional geostructures—the Siberian platform, the Laptev Sea plate, and the Kharaulakh segment of the Verkhoyansk fold system. The structures of the extension zone and the seismic activation of neotectonic structures in the northern sector of the Verkhoyansk fold system and in the Lena River delta are not related to the influence of riftogenic processes on the Laptev Sea shelf.

2. Based on the initial seismogeodynamic analysis, structural-dynamic segments differing in the stress-strain state of the crust (transpression, transtension, and compression) are distinguished in the northern sector of the Verkhoyansk fold system. The data revealed that the seismotectonic destruction regimes change in the areas to the west and east of the Lena River Delta, and the field of tectonic stresses in the Laptev Sea shelf is mixed. Thus, a unique

transition area is identified in the northern sector of the Verkhoyansk fold system, wherein the mid-oceanic and continental crust structures are conjugated and the tectonic stress field of extension is replaced with compression.

3. The potential seismic hazard of the newest structures in the northern sector of the Verkhoyansk fold system was assessed by analogy with the potential seismic hazard assessment carried out in our study of the sectors of the Arctic-Asian seismic belt [5–7, 29 et al.]. These structures are capable of producing seismic events with $M_w = 6.5–7.0$ and intensities up to 8–9 on the MSK-64 scale.

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