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Plate boundaries in the Far East region of Russia (from GPS measurement, seismic-prospecting, and seismological data)

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Abstract

The recent geodynamics of the Far East region of Russia is considered, where three large tectonic plates converge—Eurasian, North American, and Pacific, as well as several microplates—Okhotsk, Bering, and Amurian—have been hypothesized to exist. The available data on the position of the plate boundaries, the relative plate rotation poles, and the regional seismicity were analyzed, and parameters of plate motion models for northeastern Russia were determined in this study. The regional deep structure was investigated, using data obtained by different geophysical methods. The results of observations of the Magadan–Vrangel Island profile by deep seismic sounding (DSS), common-depth point (CDP) method, and correlation refraction method (CRM) are presented.

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Keywords: tectonic plates; plate boundaries; space geodesy method; seismological and seismic methods for investigating the deep structure of the Earth's crust

Introduction

The modern geodynamics and seismicity of the Far East region are determined mostly by the interaction of the Eurasian, Pacific, and North American Plates and smaller Amurian, Okhotsk, and, probably, Bering plates. The shape and position of the boundaries of the latter three plates are an object of active study. Considering the position of the plate boundaries, let us dwell on the known signs of such boundaries: geologic (shape, paleontological information, fault structures), age distribution of rocks, bands of magnetic anomalies and heat flow, “young” (Cenozoic) basaltic volcanism, deep-level structure and relief, and seismicity. This approach can be illustrated by the famous scheme proposed by [Zonenshain and Savostin \(1981\)](#) for the Asian plates (Fig. 1), when only parameters of relative plate rotation are determined, e.g., the rotation of the Amurian or North American Plate relative to

the Eurasian Plate (position of the Euler pole: 56.95° N, 117.45° E and 61.94° N, 143.1° E at the rotation rate of 1×10^{-7} °/yr and 2.5×10^{-7} °/yr, respectively). New facts were obtained using space geodesy methods actively developed in recent years. They permit determination of the parameters of the present-day plate rotation and recognition of individual “solid” plates on the sphere. Space geodesy methods have been applied to study the territory for the recent 15 years, with invoking permanent seismic stations and network methods. Regional seismological investigations have been performed since the middle 20th century, when networks of special stations began to develop. The kind of seismicity of northeastern Russia reflects the specific stress at the plate boundaries. Recent deep seismic sounding and GPS measurements have helped to clarify the relationship between the plate displacements and the deep-level structure of the Far East region. Geophysical and profile seismic CDP, DSS, and other measurements have been performed in the region since the second half of the 20th century. In this paper we present results of study along the Magadan–Vrangel Island profile in the recent decade. The goal of this work was to determine the

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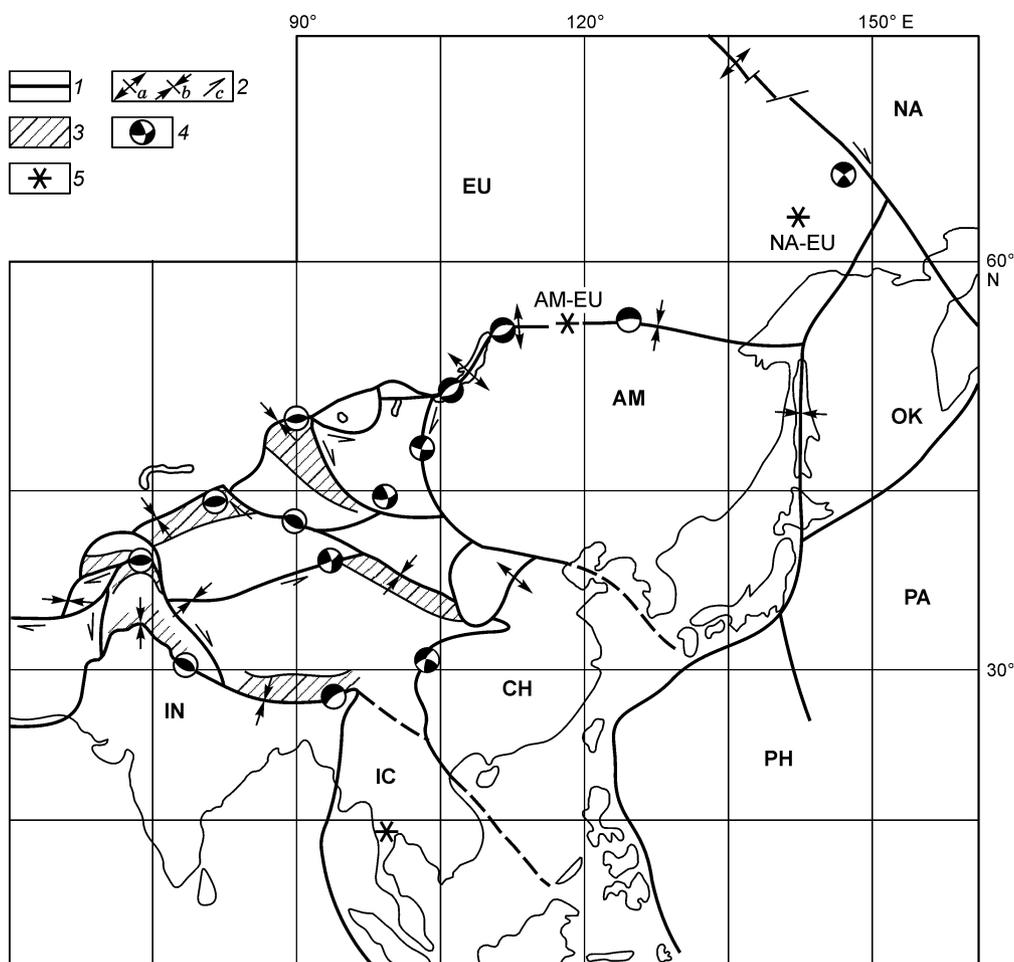


Fig. 1. Lithospheric plates and microplates (blocks) of Inner Asia (Zonenshain and Savostin, 1981). 1, plate and microplate (block) boundaries; 2, direction of relative displacement along boundaries: *a*, dilatation, *b*, compression, *c*, shift; 3, compression and plastic-deformation zones; 4, type of the focal mechanism of earthquakes; 5, position of the pole of relative rotation. Plates: NA, North American; EU, Eurasian; AM, Amur; OK, Okhotsk; IN, Indian; IC, Indo-Chinese; CH, Chinese; PH, Philippinean; PA, Pacific.

characteristics of plate boundaries, using modern seismic, seismological, and geodesic data.

The seismicity of the boundary zones of lithospheric plates in northeastern Asia

Most of northeastern Asia is subject to strong earthquakes, which are confined to neotectonic structures forming the large Arctic–Asian seismic belt (Imaev et al., 2000) (Fig. 2).

The seismotectonic position of the belt and the nature of strong earthquakes are determined by the interaction of large lithosphere plates (Eurasian, North American, and Pacific) and their blocks and microplates (Okhotsk, Amurian, and Bering) in northeastern Asia and neighboring regions (Bogdanov, 1998; Bogdanov and Khain, 1996; Dobretsov et al., 2001; Gatinskii et al., 2005; Khain, 1994; Zonenshain and Kuz'min, 1993; Zonenshain and Savostin, 1979, 1981; Zonenshain et al., 1990, 1991). The Arctic–Asian seismic belt crosses the Arctic Ocean and northeastern Asia and makes a boundary between the North American Plate and the Eurasian (Fig. 3) and Okhotsk Plates for more than 8000 km. Three zones are

recognized in Yakutia according to seismotectonic features: Laptev Sea (shelf of the Laptev Sea), Kharaulakh (shore zone of the North Upper Yana area between the Lena River valley and Buor-Khaya Bay), and Chersky Ridge zone (Upper Yana–Kolyma folded system) (Fig. 4) (Koz'min, 1984). Below we give their description.

The Arctic and Laptev Sea seismotectonic zones. The seismicity in the water area of the Arctic Ocean is determined by a chain of earthquake epicenters running parallel to the island line Spitsbergen–Franz Josef Land–Severnaya Zemlya from the De Giere transform fault traceable between Spitsbergen and Greenland to the mouth of the Lena River. This chain is spatially confined to the structures of the 80–160 km wide mid-ocean Gakkel Ridge stretching from the Greenland shelf to the Laptev Sea shelf (Figs. 2 and 4). Since the early 20th century, more than 200 local $M = 4.5–7.0$ earthquakes have occurred there. Their foci are localized mainly within the Earth's crust (Avetisov, 1996; Fujita et al., 1990).

The Arctic Gakkel Ridge is one of the Earth's underwater mid-ocean ridges. It is a northern fragment of the Earth, continuing the North Atlantic Mid-Ocean Ridge in the basin of the Arctic Ocean. Its seismicity is due to rifting and

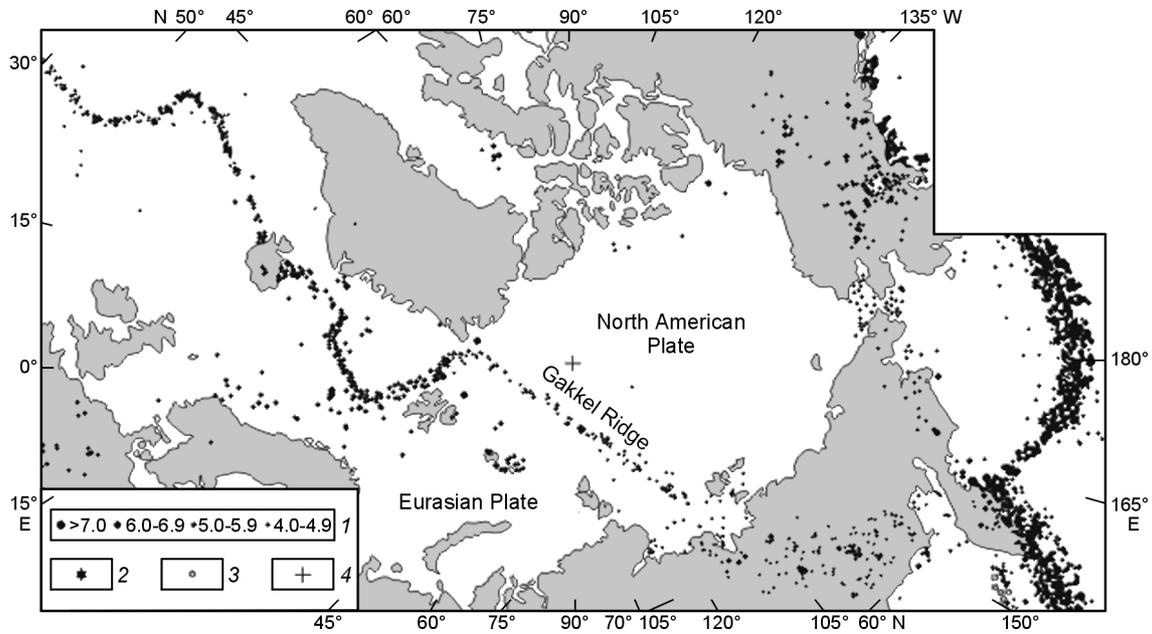


Fig. 2. Epicenters of earthquakes in the Arctic and adjacent regions. 1, magnitude of earthquakes with a focus depth of 0–60 km; 2, 3, earthquakes with a focus depth of: 2, 60–300 km, 3, >300 km; 4, North Pole.

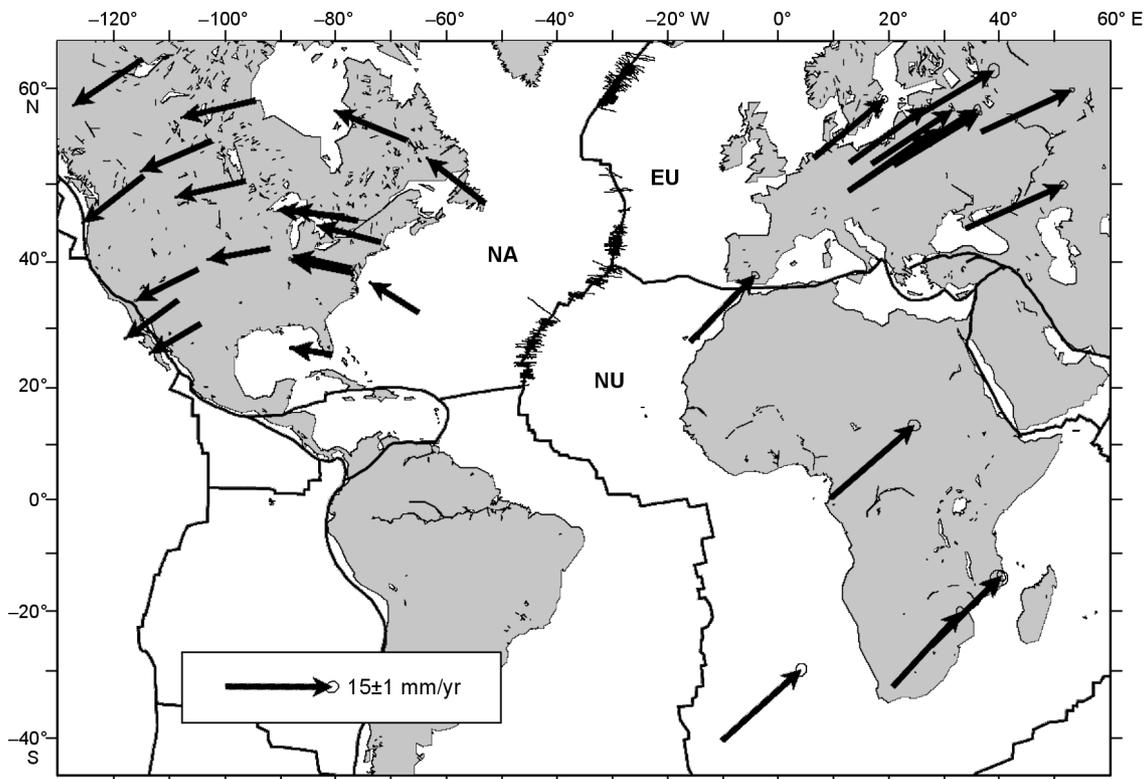


Fig. 3. Boundaries of tectonic plates in the Atlantic region. NU, Nubian plate. Other designations follow Fig. 1. Arrows show the plate displacement (mm/year) and error ellipses.

lithosphere dilatation, which cause the ocean bottom spreading (Grachev, 1987).

The Laptev Sea shelf and coastal areas are a transition zone located between the dilatation structures of the Gakkel Ridge and the compressional structures of the Chersky Ridge in the northeast of the Asian continent (Fig. 5). This zone is

characterized by expansion of the seismicity field to 600 km, which occupies the entire Laptev Sea shelf between the Novosibirsk Islands and the coast area located between the Taimyr Peninsula and the Lena River delta (Fig. 6). Surely, the zone with earthquake epicenters localized on the extension of the Gakkel Ridge passing via the Laptev Sea shelf to the

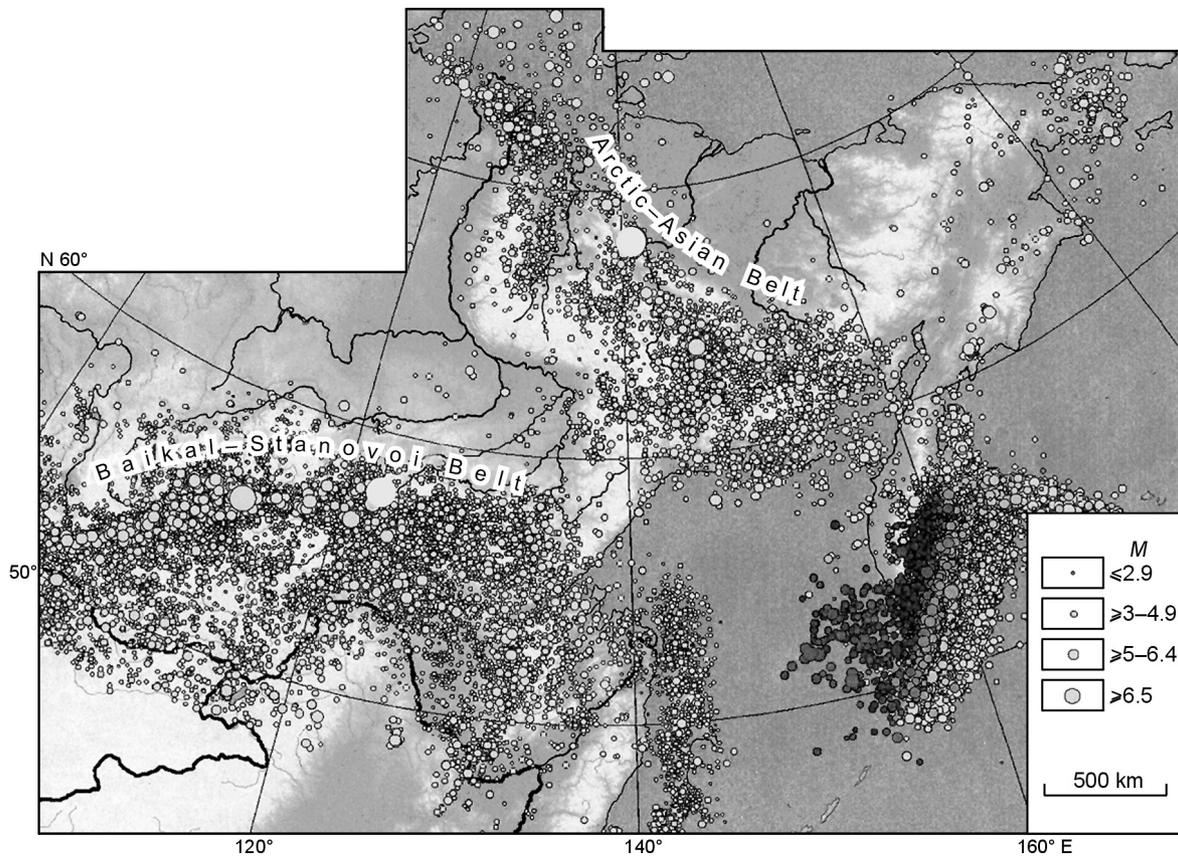


Fig. 4. Seismicity of the Russian Far East recorded for the study period.

mouths of the Omoloi and Yana Rivers shows the highest seismicity. It is in this area that the main grabens of the Laptev Sea rift were revealed, where foci of $M = 6.0-7.0$ earthquakes ($K = 15-17$) marking the boundary between the North American and Eurasian Plates are localized.

The Kharaulakh seismotectonic zone. The strongest earthquakes (Bulun) occurred in northeastern Asia in the area of the Kharaulakh Ridge (northern Upper Yana region) in 1927–1928 (Bune and Gorshkov, 1985; Mushketov and Orlov, 1893). The epicenters of the $M = 5.8-6.8$ Bulun earthquakes are localized 140–160 km south of Tiksi Village (Table 1).

This is a region where the Tit-Aryn $M = 5.0$ and Bykovo $M = 5.3$ earthquakes took place in 1963 and 1964, respectively. In 1980, two $M = 5.7$ earthquakes occurred in Olenek Bay of the Laptev Sea, as well as a $M = 4.0$ earthquake near Tiksi Village. The next serious earthquake ($M = 4.5$) occurred in the Lena River delta in 1986; last strong local event ($M = 5.1$) was registered 105 km northwest of Tiksi Village on 1 March 1991.

The Kharaulakh seismotectonic zone (KhSZ) lies within the Arctic–Asian seismic belt. On the northwestern flank of the belt, it is located in the zone transitional between the Gakkel Ridge oceanic structures and the continental deposits of the seismotectonic zone of the Chersky Ridge. More than 2500 Earth shocks were registered in the KhSZ for the last 40 years.

In general, the foci of local earthquakes stretch as a band from north to south-southeast, connecting seismic events in the Laptev Sea with those in the Chersky Ridge. Calculations

of the average recurrence of strong earthquakes in the KhSZ area showed that $M = 5.5$ earthquakes ($K = 14$) should be expected every 25 years, $M = 6.0$ earthquakes ($K = 15$) every 75 years, $M = 6.5$ earthquakes ($K = 16$) every 225 years, and $M = 7.0$ earthquakes ($K = 17$) every 715 years.

The epicenters of earthquakes in the KhSZ are confined mainly to large systems of faults (Kharaulakh, Primor’e,

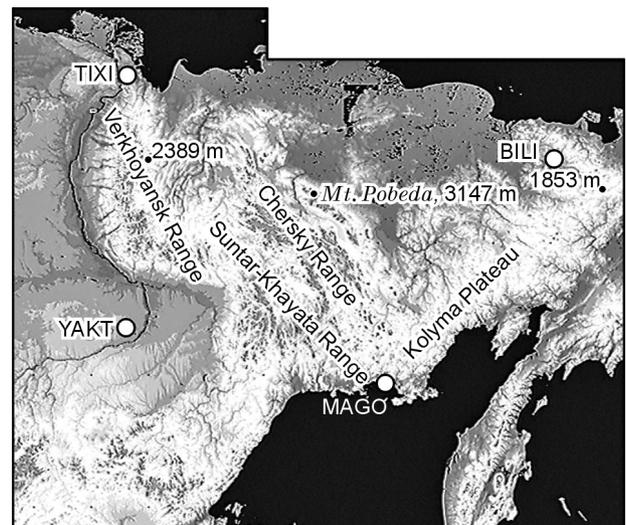


Fig. 5. The relief of northeastern Russia. Permanently working space geodesy stations: TIXI, Tiksi, YAKTO, Yakutsk, MAGO, Magadan, BILI, Bilibino.

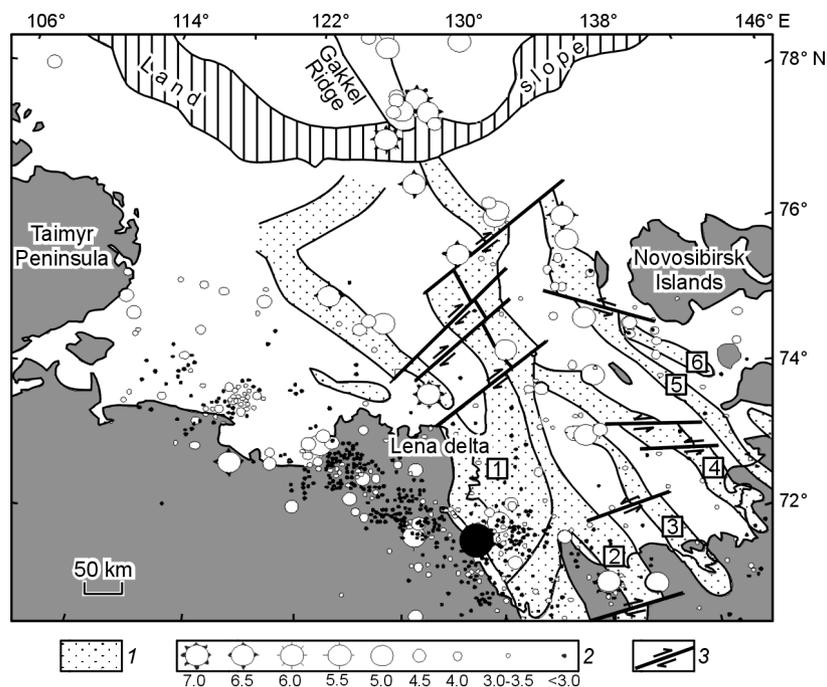


Fig. 6. Seismicity of the Laptev Sea shelf and Lena River delta. Filled circle marks the position of the GPS station. 1, grabens at the bottom of the Laptev Sea; 2, Ust'-Lena, 2, Ust'-Yana, 3, Chondon, 4, Shiroston, 5, Bel'kovskii-Svyatoi Nos, 6, Lyakhovskii; 2, epicenters of earthquakes and their magnitude; 3, active strike-slip faults.

Buorkhaya, and West Upper Yana), thus confirming their recent activity. Note that most of the earthquakes in this zone were registered in the Earth's crust at depths of ≤ 35 km. Local earthquakes most often occur at a depth of 15 km. The depth of the foci of the Earth shocks in the KhSZ is given in Table 2.

Analysis of the stressed state of the lithosphere in the Kharaulakh zone evidences the existence of a unique zone in northern Yakutia, where the dilatation field is changed by a compression field. There are only a few such areas on the

Earth, e.g., the Afar Rift (East Africa), whose structures are associated with the MOR structures in the Indian Ocean, and the North California region, where the northern margin of the East Pacific Rise is connected via the San Andreas Fault with a system of the Gorda, Juan de Fuca, and Explorer Ridges in the Pacific.

The Chersky Ridge seismotectonic zone (ChRSZ). The Chersky Ridge is a system of parallel 60–250 km long ridges localized en-echelon or continuing each other (Fig. 7). It looks

Table 1. List of strong earthquakes in the Kharaulakh and Chersky Ridge zones

Earthquake	Date (day, month, year)	Latitude, °N	Longitude, °E	<i>M</i>	<i>S</i> , thousand km ²	<i>I</i> ₀ , intensity
Yama	27.11.1851	59.5	153.3	6.5	150	8
Bulun-1	14.11.1927	69.9	129.9	6.8	50	8–9
Bulun-2	14.11.1927	70.1	129.2	6.8	50	8–9
Tau	03.11.1936	59.0	151.2	5.7	150	7–8
Adychan	12.02.1951	65.8	137.0	6.4	300	8
Irgichan	19.04.1962	69.5	138.5	6.2	60–80	7–8
Artyk	18.05.1971	64.0	146.1	7.1	900	9
Kulino	13.01.1972	61.9	147.1	5.7	200	7
Seimchan	19.06.1974	63.2	150.9	4.9	60	7
Gizhiga	19.08.1979	61.6	158.8	5.2	50	7
Olenek	01.02.1980	73.3	122.6	5.5	170	7
Kupka	08.11.1981	61.8	153.6	5.4	180	7
Uyanda	22.11.1984	68.6	140.5	5.4	130	7
Andrei-Tas	22.06.2008	67.73	141.25	6.1	400	8

Note. *M*, Earthquake magnitude; *S*, area of strong shocks; *I*₀, intensity of shocks at the earthquake epicenter by the MSK-64 scale.

Table 2. Depth interval of earthquake foci in the Kharaulakh and Chersky Ridge zones

Region	Interval, km
Buor-Khaya Bay of Laptev Sea	(5–23) ± 5
Naiba Range	(15–18) ± 5
Tuostakh basin	21 ± 8
Chersky Ridge system (18.05.71 Artyk earthquake)	22 ± 5
Aftershocks of the Artyk (Oimyakon) earthquake	(4–29) ± 3
Aftershocks of the 13.01.72 Kulino earthquake	(10–25) ± 5
Northern Okhotsk region	10–27
Northern Kamchatka region	0–50

like an arc concave to the southwest and is located in the Yana–Kolyma interfluve (Fig. 7). In the middle part, it is crossed by the Indigirka River. There is a chain of the

Moma–Selennyakh basins between the Chersky and Moma Ridges, where basaltic volcanism is manifested. The general view of Late Cenozoic Balagan-Tas Volcano near the north-eastern edge of the Moma–Selennyakh basins is shown in Fig. 8.

The ChRSZ is bounded by two faults—the Adycha–Taryn thrust in the southwest, crossing the Yana River, and Matis thrust in the northeast, crossing the Indigirka River. In the axial part of the ChRSZ, at the center of the Chersky Ridge system, the most active sinistral faults of NW strike were revealed (Ulakhan, Chai-Yureya, In'yali-Debin, etc.), to which strong $M > 5.0$ earthquakes and most of seismic dislocations are confined. The NW faults crossing the axial part of the Moma Ridge are also sinistral. Normal faults are atypical in this area. Rare local normal faults are related to the formation of small near-shear pull-apart basins (Dogda, Chibagalakh, Upper Nera, etc.) and do not run beyond them. Analysis of

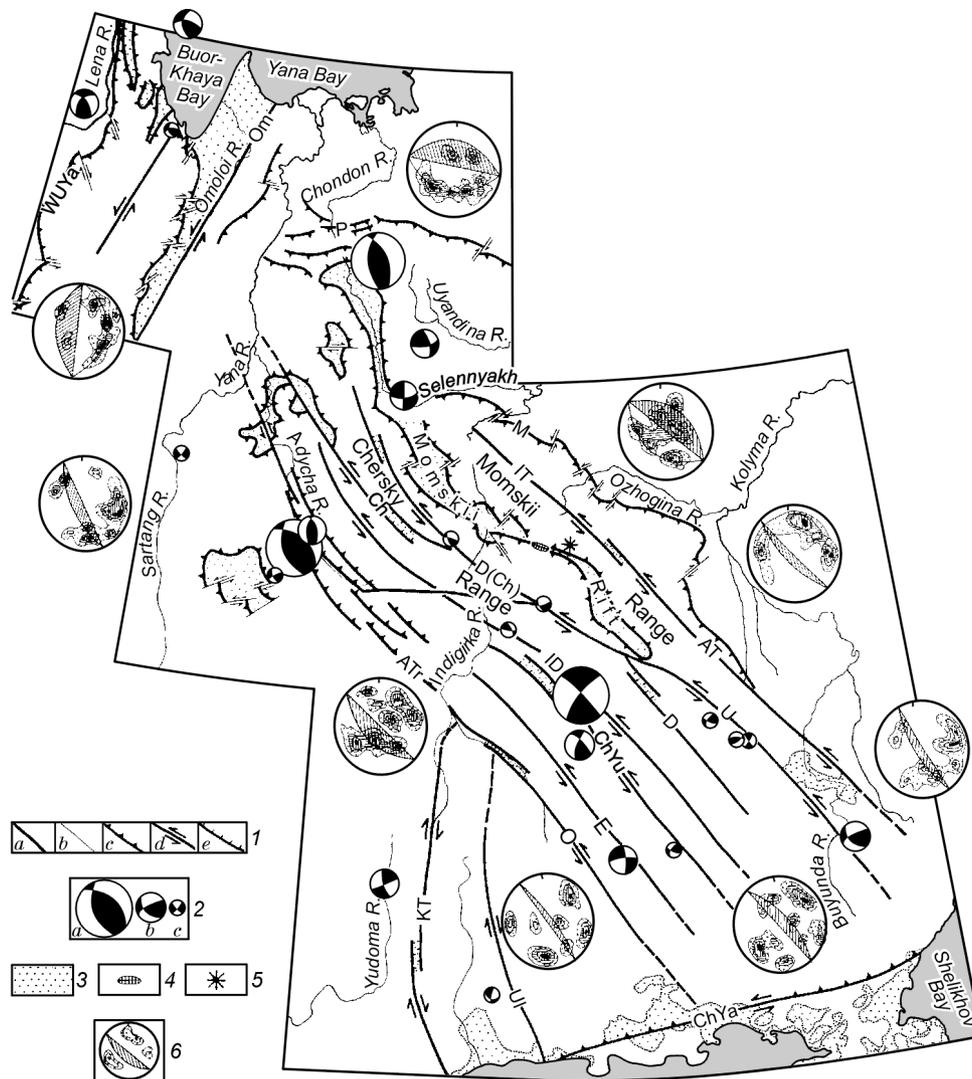


Fig. 7. Schematic map of active faults in the Chersky Ridge seismotectonic zone. 1, faults: a, general, b, local, c, thrusts (WUYa, West Upper Yana, M, Myatis, P, Polousnen, ATr, Alycha–Taryn, ChYa, Chelomdza–Yama), d, strike-slip faults (Om, Omolon, Ch, Chemaga, D(Ch), Dogdan (Chibagalakh), IT, Ilin'-Tas, AT, Arga-Tas, ID, In'yali-Debin, ChYu, Chai-Yureya, D, Darpir, U, Ulakhan, E, El'ganda, O, Oimyakon, Ul, Ul'bei, KT, Ketanda), e, normal faults; 2, focal mechanisms of earthquakes with magnitudes: a, >6.1, b, 5.1–6.0, c, <5.0; 3, Cenozoic basins; 4, Ulakhan–Taryn ice body in the Moma River; 5, Late Cenozoic Balagan-Tas Volcano; 6, diagrams of rock fracturing, with isolines of crack density and hatched active (main) fault plane.



Fig. 8. General view of Balagan-Tas Volcano near the northeastern edge of the Moma–Selennyakh basins.

the morphologic characteristics of the fault using geolo-structural (fracturing, gliding planes) and seismological (focal mechanisms of earthquakes) data shows that the plane of its shear is subvertical (75° – 90°) and the fault is of NW strike (280° – 320°). The determined parameters of the focal mechanisms of earthquakes in the ChRSZ evidence that most of movements in the foci are mainly strike-slip and reverse faults (62%) and thrusts (24%); combined strike-slip and normal faults make up only 14% (Imaev et al., 1990). Study of the modern relief in the region where the upper reaches of the Rassokha and Omulevka Rivers (basin of the Yasachnaya River, a tributary of the Kolyma River) are crossed by the Ulakhan Fault showed a systematic sinistral shift of their riverbeds with an amplitude of up to 24 km throughout the

Middle Pleistocene–Holocene. This permitted estimation of the average rate of horizontal tectonic movements along this fault, 0.5–0.7 cm/year (Mal'kov, 1971; Shakhtyrov, 1985).

The spatial distribution of earthquakes shows that most of seismic events of the 20th century took place in the mountainous system of the Chersky Ridge, where 70% of all Earth shocks of the ChRSZ were registered. The seismotectonic zone of the Chersky Ridge, being part of the Arctic–Asian seismic belt, marks the modern boundary between the Eurasian and North American Plates (Fig. 9, a) drifting together in the W–E direction. This drifting is confirmed by the parameters of the focal mechanisms of strong earthquakes with a predominance of horizontal compression in the SW direction. In general, the seismic events in the seismotectonic ChRSZ form a single arc-like band (where >20,000 earthquakes occurred in the 20th century) stretching in the SE direction toward the Sea of Okhotsk. It is ~2000 km long and 600 km wide. Analysis of the parameters of the focal mechanisms of strong earthquakes shows the existence of an area where a dilatation field is changed by a compression field. This area passes along the plate boundary; the mid-ocean lithosphere structures there are changed by continental ones. South of it, along the northern coast of the Sea of Okhotsk, shear structures are predominant tectonic stresses (Fig. 9, a).

Plate displacements according to space geodesy data (GPS method)

The interaction between tectonic plates is actively investigated, based on the data of space geodesy (Altamimi et al., 2007; Apel et al., 2006; Argus and Gordon, 1996; Boucher et al., 2001; Calais et al., 2003, 2006; DeMets et al., 2010; Fujita et al., 1997, 2009; Kreemer et al., 2003, 2006; Prawirodirdjo and Bock, 2004; Shestakov et al., 2011; Steblov, 2004). Let

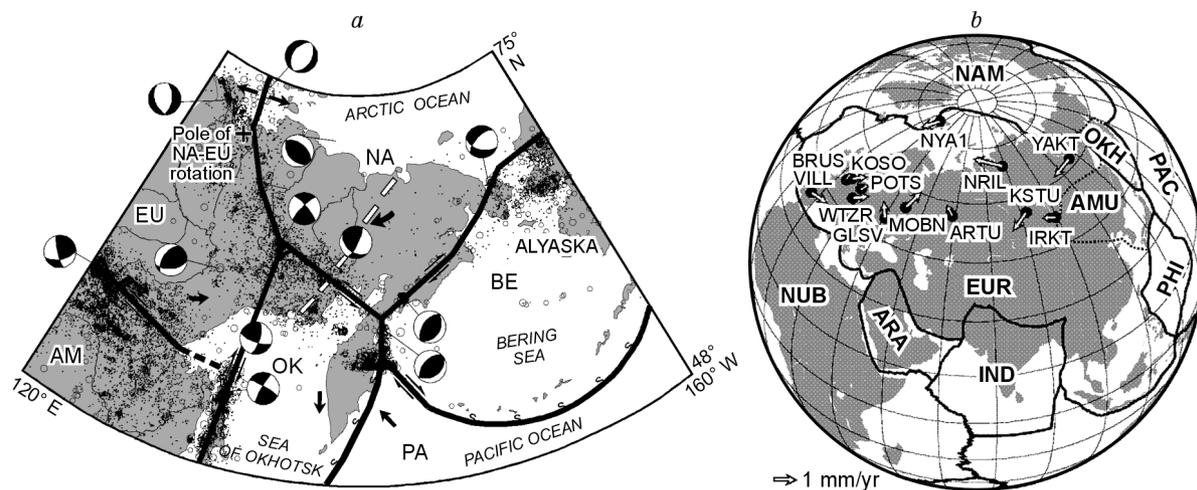


Fig. 9. The position and boundaries of plates in northeastern Asia, after Fujita et al. (1997), with supplements after Imaev et al. (2000) (a), and position of the Eurasian and surrounding plates on a sphere, after Boucher et al. (2001) (b). a, White dashed line shows the Magadan–Vrangell Island seismic profile (2001–2008) and focal mechanisms of earthquakes at the boundaries, arrows schematically show the direction of plate displacement. BE, Bering Sea plate. Other designations follow Fig. 1. b, Position of the IGS stations, arrows show the direction of residual vectors relative to the Eurasian Plate. Plates: NAM, North American; OKH, Okhotsk; PAC, Pacific; AMU, Amurian; EUR, Eurasian; PHI, Philippinean; NUB, Nubian; ARA, Arabian; IND, Indian.

Table 3. Parameters of solid-body rotation of the Eurasian Plate

Model	Latitude, °N	Longitude, °E	Rotation rate, °/Myr
NNR-Nuvel-1A	50.631	247.725	0.2337
APKIM-2000	57.9	262.9	0.2587
SOPAC-2008	55.851	262.622	0.263
Shestakov-2008	54.2	259.3	0.251
ANI-2010	53.1	259.5	0.244

us dwell on the available kinematic models describing plate rotations and analyze them by the example of the Eurasian Plate. The most recent of them is the NNR-Nuvel-1A geological and geophysical model and APKIM-2000 model based on the experimental data obtained at the Eurasian Plate seismic stations by 2000. The latter model was developed using data from all Asian and European stations, including those in seismically active zones, where the modern tectonic processes cause catastrophic earthquakes. On constructing plate motion models, data on actively deformable southern and central Asian areas are usually excluded from analysis (Fig. 9, *b*). Study of the parameters of plate rotation is performed for progressively longer temporal periods. Differences between the observed and model velocities of GPS sites determining the stable plate interiors are less than 1 mm/year. It is in agreement with the repeatability of experimental results in different time series.

In the model for plate rotation on a sphere, the rates of the horizontal displacements of a point with coordinates φ and λ are determined from the equations

$$\partial\varphi/\partial t = R\omega \cos(\Phi) \cdot \sin(\lambda - \Lambda);$$

$$\partial\lambda/\partial t = R\omega [\sin(\Phi) - \cos(\lambda - \Lambda) \cdot \tan(\varphi) \cdot \cos(\Phi)],$$

where Φ , Λ , and ω are the coordinates of the plate rotation pole and the angular rate of rotation, respectively, and R is the Earth's radius.

Some models for the Eurasian Plate (position of the Euler pole and angular rate, °/Myr) are given in Table 3.

Table 4. Northeastern Asia, rates obtained by the Eurasian Plate model (2010) and experimental data from permanent GPS stations on the International IGS network

Station (measurement period)	Latitude, °N	Longitude, °E	Model ANI-2010		Experimental data		
			v_n	v_e	v_n	v_e	v_h
NRIL (2001–2010)	69.362	88.360	−2.52	22.84	−1.915 ± 0.005	21.803 ± 0.007	1.699 ± 0.015
IRKT (1995–2010)	52.219	104.316	−6.85	25.10	−6.613 ± 0.003	24.853 ± 0.006	0.370 ± 0.011
IRKJ (2002–2010)					−6.274 ± 0.007	24.766 ± 0.012	−0.357 ± 0.021
YAKT (2001–2010)	62.031	126.680	−12.00	20.06	−12.072 ± 0.007	18.508 ± 0.011	0.763 ± 0.021
TIXI (1999–2010)	71.634	128.866	−12.43	17.01	−11.390 ± 0.004	16.821 ± 0.005	1.508 ± 0.012
BILI (2000–2007) (1999–2008)	68.076	166.437	−16.35	8.96	−20.41 −20.546 ± 0.006	+8.14 +8.493 ± 0.008	+1.75 +0.588 ± 0.018
MAGO (1998–2006) (second variant in 1998–2006)	59.575	150.770	−15.49	15.58	−20.17 ± 0.003 −19.513 ± 0.010	+7.51 ± 0.004 +9.964 ± 0.015	+0.26 ± 0.010 −0.552 ± 0.028

Note. Hereafter, v_n and v_e are the rates of horizontal N–S and E–W displacements, respectively (mm/year).

The ANI-2010 model considered below was elaborated using the results obtained at three seismic stations: ARTU (Middle Urals), NVSK (Novosibirsk), and IRKT (Irkutsk). The stations are located in the band 52°–56° N in a tectonically stable part of the Eurasian Plate. Tables 4 and 5 present the experimental and model data for comparison. Differences between the observed and model velocities of GPS sites determining the stable plate interiors are less than 1 mm/year. It is in agreement with the repeatability of experimental results in different time series. The rates of vertical displacements (v_h) are minimum, which corresponds to the model of plate motion on a sphere.

The position of the plates in the Far East is shown in Figs. 9 and 10. The boundaries of the Okhotsk microplate are determined by zones with the maximum number of seismic events. They are confined to the Sakhalin–Hokkaido dextral strike-slip and reverse fault in the west, which passes into a system of N–S-striking dextral strike-slip faults (Ketanda, Nyut-UI'bei, etc.) in the northern Okhotsk region, to the sinistral strike-slip faults in the Chersky Ridge zone in the northeast, and to the thrusts and reverse faults in the Kuril–Kamchatka zone in the east and south (focal mechanisms of earthquakes, morphokinematic characteristics of faults, etc.). The northern boundary of the Amurian plate passes along the Baikal–Stanovoi seismic belt (Fig. 4), and the eastern boundary, along the Sakhalin–Hokkaido Fault, though, according to some concepts, it passes west of it, along the Tan-Lu Fault. Figure 10 shows the displacements in the east of the Amurian plate relative to the Eurasian Plate (data of network GPS measurements). Despite the low residual values of displacements (2 mm/year), the parameters of the Amurian plate rotation have been actively studied by space geodesy methods in recent years (Ashurkov et al., 2011; Timofeev et al., 2008, 2011). It was established that the most likely coordinates of the rotation pole of the Amurian plate are 57–60° N, 117–123° E. The most reliable rotation rate of the plate ranges from 0.07 to 0.10 °/Myr.

The rates of displacements relative to the Eurasian Plate according to the data of network and GPS stations in

Table 5. Eastern Asia, displacements relative to the Eurasian Plate

Station (measurement period)	Latitude, °N	Longitude, °E	Difference between experimental and model data	
			v_n	v_e
NRIL (2001–2010)	69.362	88.360	+0.60	–1.03
IRKT (1995–2010)	52.219	104.316	+0.23	–0.24
IRKJ (2002–2010)			+0.57	–0.33
YAKT (2001–2010)	62.031	126.680	–0.07	–1.55
TIXI (1999–2007)	71.634	128.866	+1.09	–0.51
(1999–2010)			+1.04	–0.19
BILI (2000–2007)	68.076	166.437	–4.68	–0.82
(1999–2008)			–4.196	–0.467
MAGO (1998–2006)	59.575	150.770	–3.68	–8.07
(second variant in 1998–2006)			–4.023	–5.616

northeastern Asia are given in Fig. 10, *b*. For the stations located east of the plate boundary, the south- and southwestward displacements are shown. As seen from the residual values (experimental and model displacement rates) obtained at these stations, the anomalous displacements were most exactly determined at the Bilibino (BILI) and Magadan (MAGO) stations (Table 5). All these results evidence that the eastern stations are located on a different plate (North American).

Tables 6–8 list the model parameters of rotation of the Far East tectonic plates obtained by different researchers (Jin et al., 2007; Munekane and Fukuzaki, 2006). The number of stations whose data were used in the calculations was different

in these studies (up to 22). Statistical methods help to reveal the existence of two-, three-, four-, or five-plates combination (Stein and Gordon, 1984). Analysis of the five-plate combination in the Far East models was made by Apel et al. (2006), who showed the existence of the Amurian and Okhotsk plates. For subsequent calculations for the North American Plate, we used the parameters from the MORVEL-2010 model, obtained by data from more than 450 stations (DeMets et al., 2010), the Euler pole coordinates 6.8° N, 84.8° E, and the rotation rate of 0.189 °/Myr (Table 9).

A quantitative analysis of data obtained at permanently working IGS stations was carried out. Table 9 shows the position of the BILI, MAGO, and TIXI stations. It is seen that

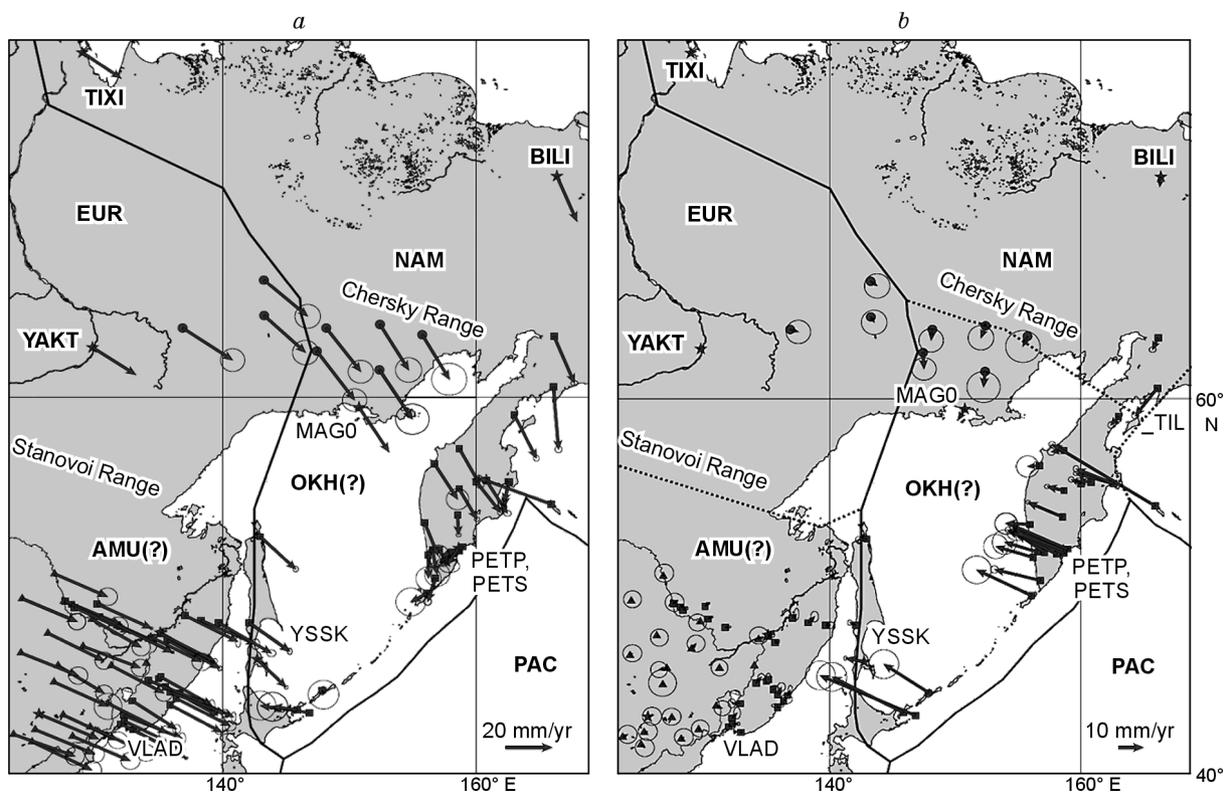


Fig. 10. Geocentric rates of horizontal displacements in eastern Russia (*a*) and rates of horizontal displacements relative to the Eurasian Plate (*b*). Designations follow Fig. 9, *b*.

Table 6. Model parameters of plates merging in the Russian Far East, four-plate combination, after Munekane and Fukuzaki (2006)

Plate	Longitude, °W	Latitude, °N	Rate, °/Myr	Error ellipse		Azimuth, deg	N
				max	min		
AMU	125.5	64.2	0.303 ± 0.016	4.9	3.1	13.0	5
EUR	101.0	56.6	0.252 ± 0.005	1.3	0.8	99.0	10
NAM	86.3	7.1 S	0.194 ± 0.004	1.3	0.5	99.0	10
PAC	112.5 E	63.5 S	0.684 ± 0.003	0.4	0.2	94.6	14

Note. N, Number of measurement stations.

Table 7. Model parameters of plates merging in the Russian Far East, after SOPAC [<http://sopac.ucsd.edu>]

Plate	Longitude, °W	Latitude, °N	Rate, °/Myr	Error ellipse		Azimuth, deg	N
				max	min		
AMU	101.663	56.763	0.282 ± 0.005	5.44	0.45	124.0	3
EUR	97.378	55.851	0.263 ± 0.001	0.53	0.16	54.0	17
NAM	88.473	6.207 S	0.187 ± 0.002	0.90	0.23	97.0	22
OKH	158.673	7.537	0.091 ± 0.007	9.07	1.96	132.0	3
PAC	112.235 E	62.225 S	0.680 ± 0.003	0.51	0.25	174.0	6

Table 8. Parameters of the North American Plate determined from data from 13 observation stations localized on the plate

Station coordinates		v_n , mm/year				v_e , mm/year			
°N	°E	Calc.	Obs.	Difference	Error	Calc.	Obs.	Difference	Error
46.0	281.9	1.9	1.4	-0.5	± 0.6	-16.8	-16.5	0.3	± 0.6
32.4	295.3	6.9	7.2	0.3	± 0.6	-12.6	-12.4	0.2	± 0.6
58.8	265.9	-4.1	-3.8	0.3	± 0.6	-19.1	-17.9	1.2	± 0.7
50.3	264.1	-4.7	-4.6	0.1	± 0.7	-17.4	-17.4	0.0	± 0.7
54.7	258.0	-6.9	-8.0	-1.1	± 0.6	-17.8	-17.5	0.3	± 0.6
67.0	309.1	11.5	11.2	-0.3	± 0.6	-17.5	-17.8	-0.3	± 0.6
30.7	256.0	-7.6	-6.8	0.8	± 0.6	-12.0	-12.5	-0.5	± 0.6
41.8	268.4	-3.1	-2.4	0.7	± 0.6	-15.7	-15.5	0.2	± 0.6
34.3	251.9	-9.1	-8.7	0.4	± 0.6	-12.6	-13.1	-0.5	± 0.6
54.8	293.2	6.1	6.8	0.7	± 0.7	-18.0	-18.2	-0.2	± 0.7
47.6	307.3	11.0	11.6	0.6	± 0.6	-15.0	-15.2	-0.2	± 0.6
76.5	291.2	5.4	4.5	-0.9	± 0.6	-20.7	-21.8	-1.1	± 0.6
62.5	245.5	-11.2	-11.3	-0.1	± 0.6	-17.2	-16.6	0.6	± 0.6

Note. Model of the North American Plate: pole coordinates $5.2 \pm 1.2^\circ$ N, $83.2 \pm 0.5^\circ$ E, angular velocity 0.194 ± 0.003 °/Myr.

Table 9. Residual values of horizontal rates (mm/year) for stations localized in northeastern Asia

Station (measurement period)	Latitude, °N	Longitude, °E	Difference between experimental and model data	
			v_n	v_e
BILI (2000–2007)	68.076	166.437	+0.75	+0.55
MAGO (1998–2006)	59.575	150.770	-2.12	-3.89
TIXI (1999–2010)	71.634	128.866	-0.02	-1.609

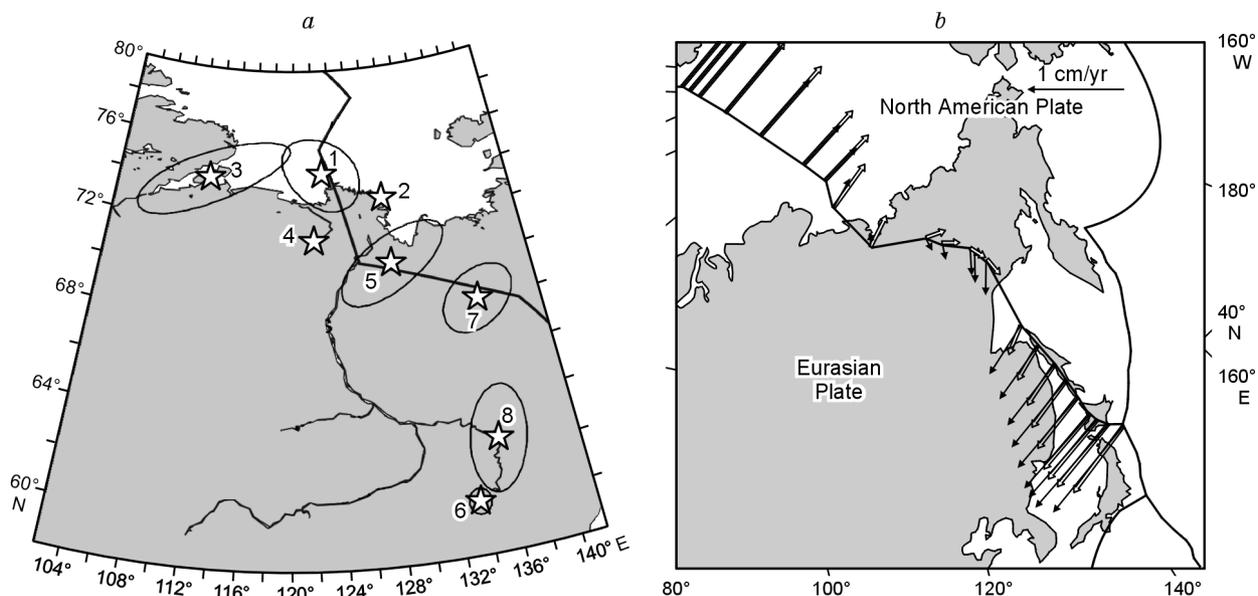


Fig. 11. The position of the pole of the mutual rotation of the Eurasian and North American Plates, after the results obtained by different authors (a), and displacement along the plate boundary according to different models (Steblov, 2004) (b). a, 1, Kogan et al. (2000); 2, Altamimi et al. (2007); 3, Argus and Gordon (1996); 4, Cook et al. (1986); 5, 6, Calais et al. (2006): 5, from GPS data, 6, from geological data; 7, Sella et al. (2002); 8, Boucher et al. (2001).

the position of the BILI station corresponds to the model plate motion (deviation of the parameters is within 1 mm). The TIXI station is obviously located at the plate boundary and approximately corresponds to the modeled motion of the Eurasian and

North American Plates (Tables 5 and 9). Analysis of the motion rates of the Asian stations located on the North American Plate (Table 9) showed an anomalous displacement of the MAGO station relative to the BILI station. This

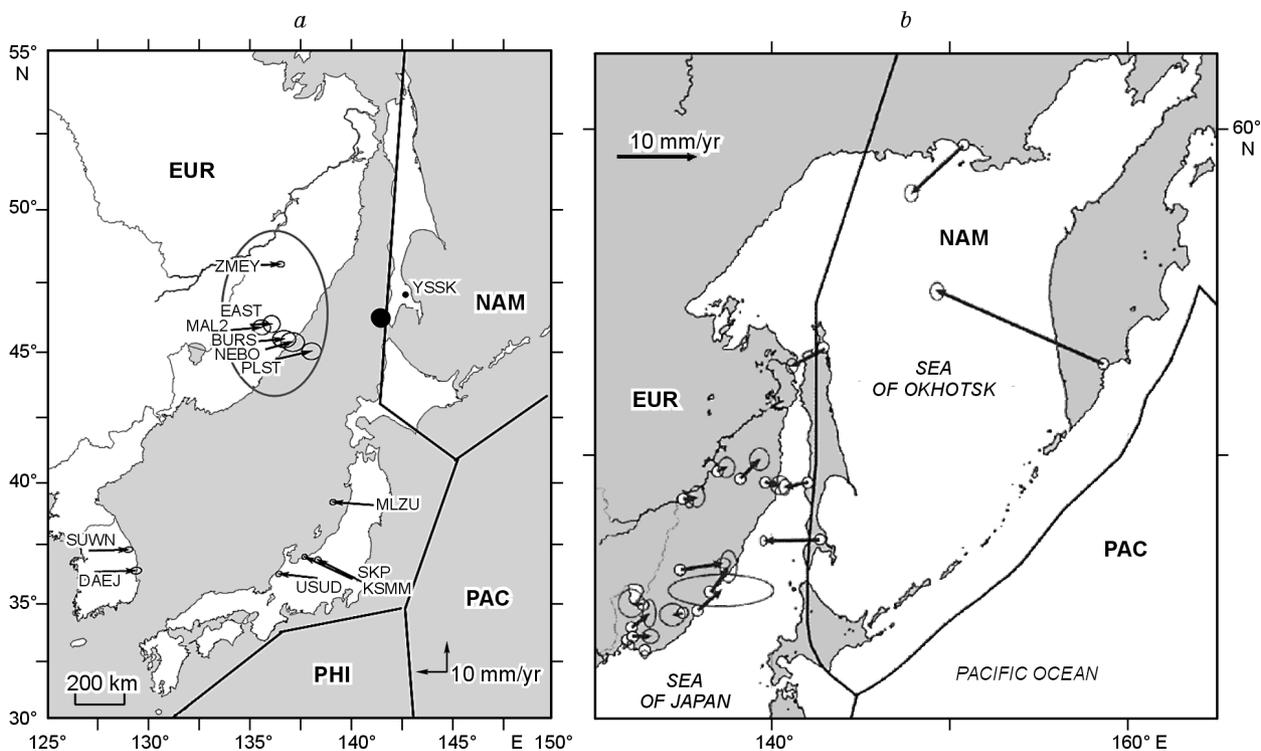


Fig. 12. Displacement of observation points in the Sikhote-Alin' network (outlined by an oval) relative to Yuzhno-Sakhalinsk (YSSK, 2003–2006) before the *M* 6.5–7.0 Nevel'sk earthquake (2 August 2007) (a) and displacement of observation points on Sakhalin Island relative to the Eurasian Plate (b).

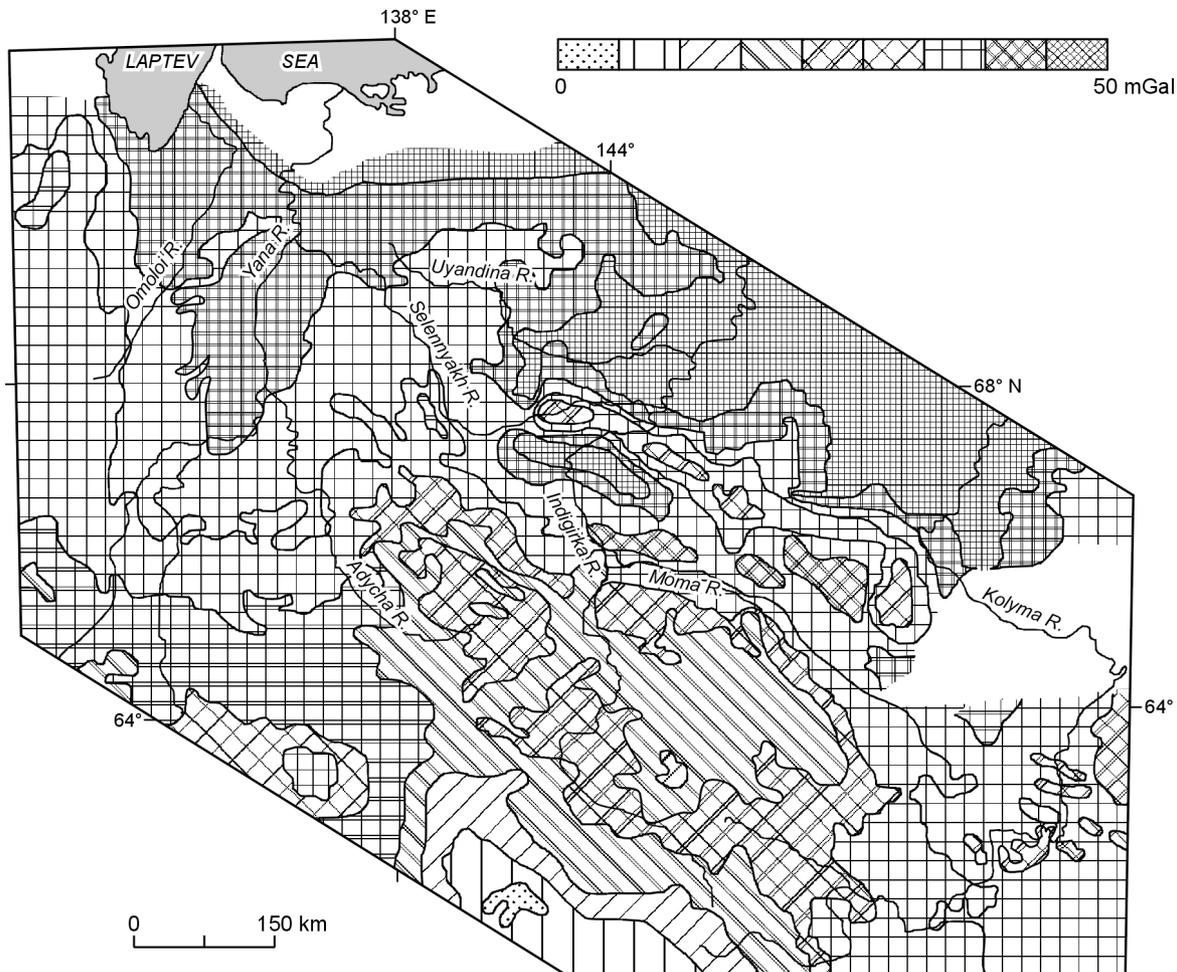


Fig. 13. Anomaly of the gravity field in the plate boundary zone.

evidences the existence of a modern-deformation zone near the plate boundary between the two stations. The MAGO station is shifted in the SW-W direction relative to the BILI station. The boundary between the Okhotsk and North American Plates passes, most likely, in the south of the Chersky Ridge, in the Ulakhan Fault zone.

There are different data on the position of the pole of the mutual rotation of the Eurasian and North American Plates: from 74° N, 110° E to 60° N, 135° E, i.e., in the zone along the plate boundary (Fig. 11, *a*) (Altamimi et al., 2007; Argus and Gordon, 1996; Calais et al., 2003; Cook et al., 1986; Kogan et al., 2000; Sella et al., 2002; Steblov et al., 2003). According to the latest estimates (Kogan and Steblov, 2008), the pole is localized at 67.41° N, 137.87° E, and the rotation rate is 0.226 ± 0.005 °/Myr.

The relative displacement at the boundary can be illustrated by the example of two boundary points in the models for the Eurasian and North American Plates (data are as 2010). For the point on the ocean coast (72° N, 129° E), the displacement relative to the Eurasian Plate is 2.05 mm/year (–0.16 mm/year to the south and –2.05 mm/year to the west) to the west, and for the point on the continent (65° N, 141° E), 5.22 mm/year (–1.37 mm/year to the south and –5.04 mm/year to the west) to the southwest-west. In general, the displacements at the

boundary correspond in direction and value to the scheme given in Fig. 11, *b*.

The scheme of the plate interaction shows that the compression of the Asian part of the North American Plate relative to the Eurasian Plate increases from north to south along their boundary, from Tiksi Village along the Chersky Ridge. In the southern sublatitudinal part of the ridge, one more horizontal displacement, a strike-slip fault, appears at the boundary between the North American and Okhotsk Plates (Table 9). As mentioned above, the displacement can reach 4 mm/year. According to the earlier calculations (Apel et al., 2006), the displacement is ~3 mm/year. South of it, on Sakhalin Island, the mutual relative displacement of the plates (Eurasian and North American or Amurian and Okhotsk) reaches 10 mm/year. Figure 12 shows the model and experimental data obtained at the Sikhote-Alin' permanently working and network stations in the Far East.

The Earth's crust structure at the plate boundaries according to geophysical data

Let us dwell on the Earth's crust structure in the plate boundary region, moving from north to south, starting from

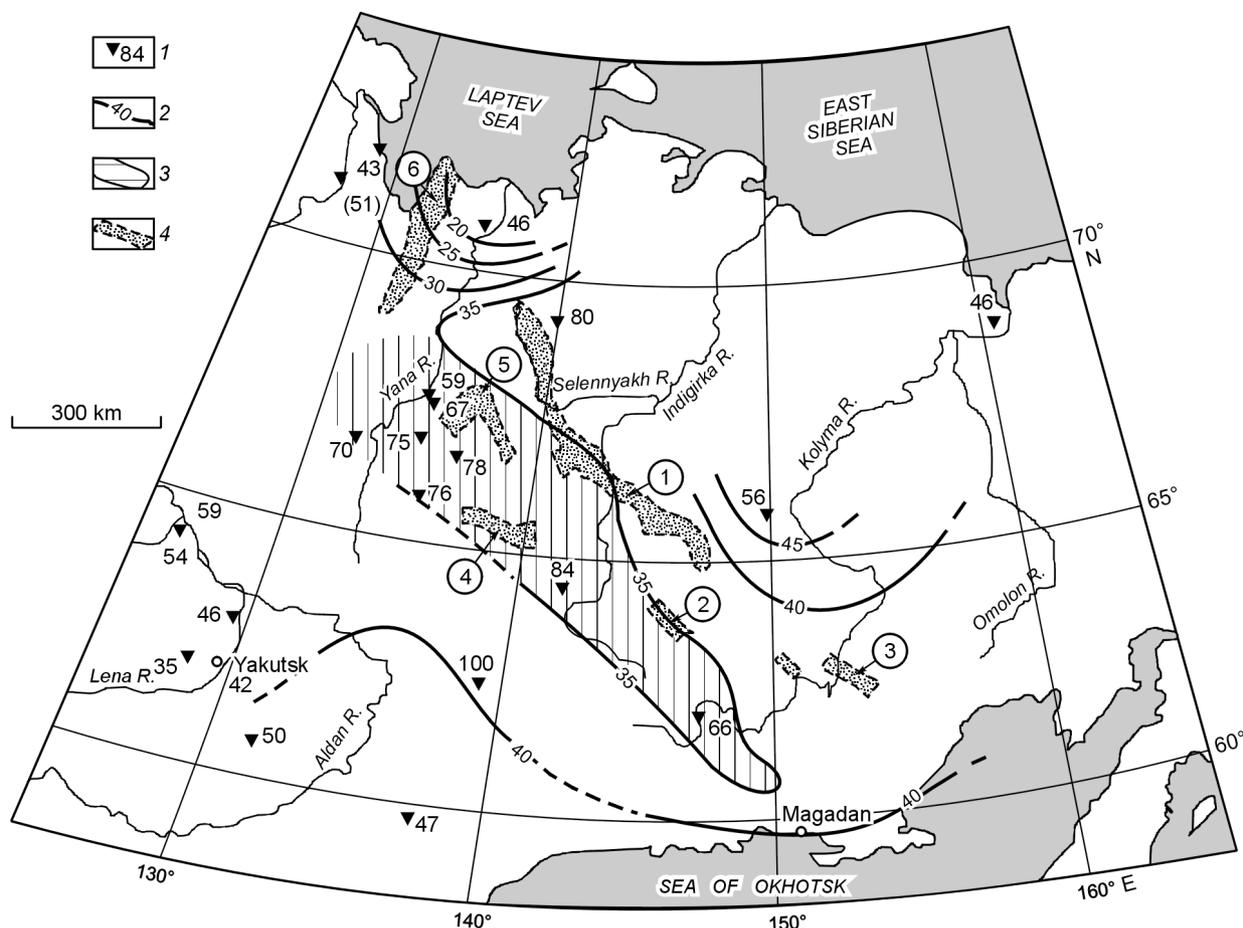


Fig. 14. The Earth's crust thickness and heat flow on the southeastern flank of the Arctic–Asian seismic belt (Mackey et al., 1998). 1, point determinations of heat flow (mW/m^2); 2, isolines of the Earth's crust thickness (km); 3, area of the Earth's crust thinning; 4, Cenozoic basins (encircled numerals): 1, Moma–Selennyakh, 2, Upper Nera, 3, Seimchan–Buyunda, 4, Upper Adychan, 5, Tuostakh, 6, Omoloi.

the Arctic zone. The available sea-geophysical data supplemented with the materials of the Sea Arctic Geological Prospecting Expedition (SAGPE) and Sevmorgeologiya Enterprise show the specific structural features of the Laptev Sea shelf (Avetisov, 1996; Avetisov and Guseva, 1991; Gramberg et al., 1990). The main structural units of the shelf are long grabens and horsts separating them, which occupy its southern part and form a rift system of the Laptev Sea. According to the SAGPE data, this system is also observed north of the shelf, where it merges with the Gakkel Ridge zone on the continental slope. The southern part of the rift system is 350–400 km wide and 400–450 km long. A system of narrow grabens and troughs of NW strike (Ust'-Lena, Omoloi, Ust'-Yana, Chondon, Bel'kovskii–Svyatoi Nos, etc.), up to 200–250 km long and 40–60 km wide, was revealed at the bottom of the Laptev Sea from seismic data obtained by the reflection wave method by the Sevmorgeologiya Enterprise (Fig. 6). The existence of grabens is confirmed by the specific distribution of the gravity field in the eastern part of the Laptev Sea in the form of alternating narrow linear high-gradient zones of NW and N–S strikes extending from the continental slope on the coast. The magnetic field in the transition zone is nearly uniform in contrast to the band pattern of magnetic

anomalies in the Gakkel Ridge linear structure. These troughs are separated from each other and bounded by a series of underwater rises: Central-Laptev rise, Shilon structural terrace, Stolbov horst, etc.

In the continental area, the boundary zone of the Eurasian and North American Plates is well detected in the gravity and heat flow fields. In the gravity field (Fig. 13), the zone is confined to a large gravitational scarp separating the heavy rocks of the Kolyma block from the lighter rocks of the Upper Yana–Kolyma folded area. The scarp axis nearly coincides with the traces of the Ulakhan and Darpir Faults.

The existence of the plate boundary is also evidenced by a high heat flow (Fig. 14) detected by direct measurements in wells (88 mW/m^2 in the Chersky Ridge and 100 mW/m^2 in the Suntar-Khayata Ridge) (Gornov, 2011; Gornov et al., 2009; Mackey et al., 1998). Other evidence is manifestation of Late Cenozoic basaltic volcanism (Balagan-Tas and Uraga-Khaya Volcanoes) and mineralized underground springs (up to 20°C) within the system of the Momo–Selennyakh basins.

A complex analysis of seismological data and materials of deep seismic studies revealed a zone of the junction of the North American and Okhotsk Plates (Fig. 15) in the Earth's crust at different depths, down to the Moho.

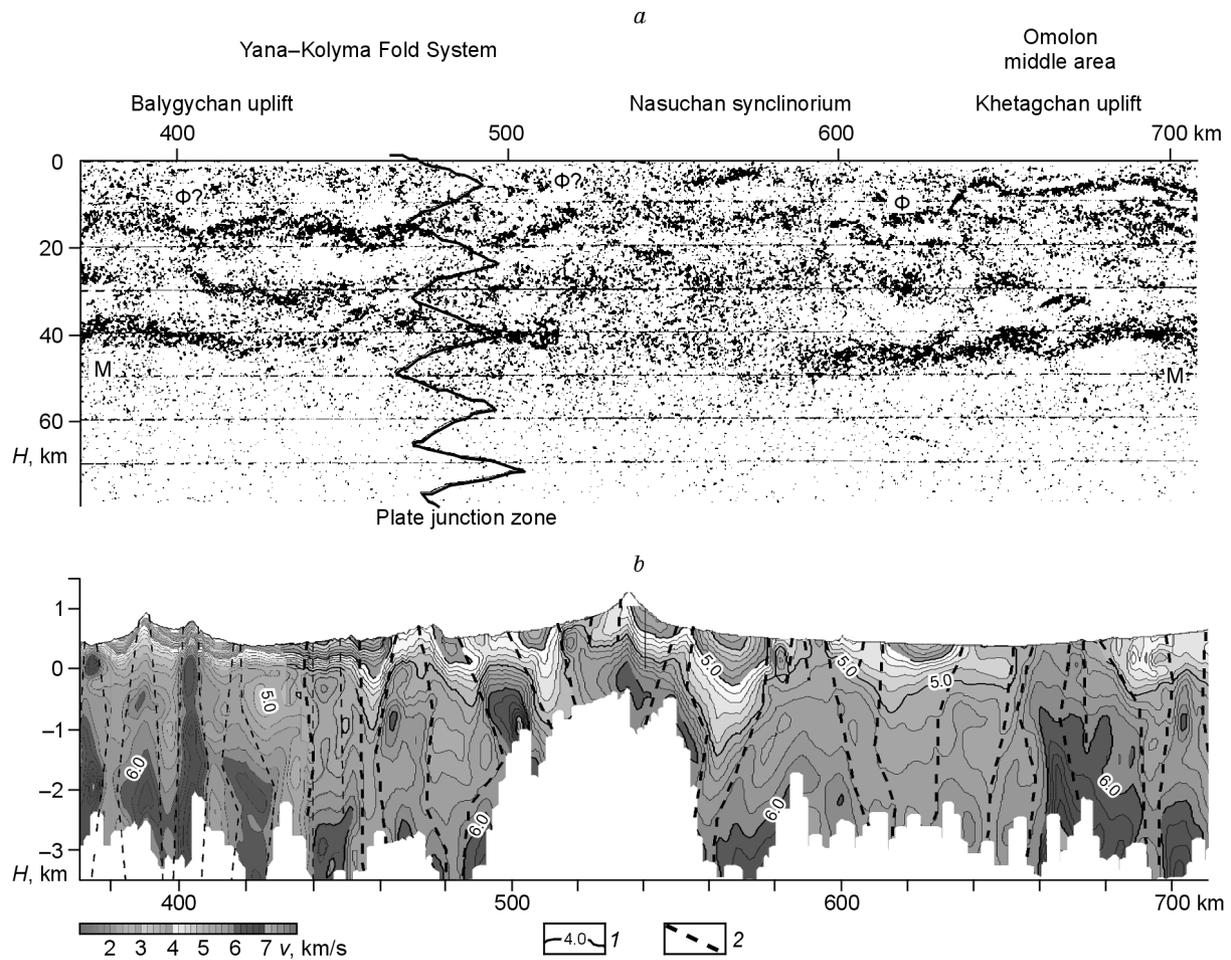


Fig. 15. Fragments of CDP (a) and CRM (b) sections along the Magadan–Wrangel Island profile. 1, velocity isolines, km/s; 2, deep faults.

The reference geologo-geophysical 2DV profile (Surkov et al., 2007) in the south of the zone crosses the neighboring sites of the Okhotsk and North American Plates. According to the modern geodynamic concepts, the plate boundary passes along the Ulakhan Fault in the southern part of the Chersky Ridge (Figs. 15 and 16).

The Ulakhan Fault is the largest shear system in northeastern Russia. Most of its area is seismically active, and several seismic dislocations were revealed in the zone of its influence (Mal'kov, 1971; Shakhtyrov, 1985). According to DSS data, the regional 2DV geotranssect (Magadan–Wrangel Island) in the junction zone shows a significant decrease in the boundary velocities of seismic waves along the Moho (to 7.5–7.7 km/s) and a local rise of the Moho boundary by 2–4 km (Fig. 16).

Earlier, a decrease in the boundary velocities along the Moho was also established during DSS at the sites of junction of large terranes and at other sites of the 2DV profile and in the 2DV-A profile. It might be due to the transformation of the Earth's crust substratum, which led to crust thinning in the junction area and a velocity decrease along the Moho (Surkov et al., 2007).

The middle crust along the deep-level seismotomographic profile in this zone is extremely nonuniform. Weakening of

the reflection contrasts in the lower crust and on the Moho is also observed in a wider zone in a CDP section. In this zone, the average (efficient) velocities decrease throughout the Earth's crust section, which suggests a tectonic break of the crustal structures. These data, together with the high seismicity at depths of to 30 km, evidence the junction of the Okhotsk and North American Plates not only in the upper crust but also in the middle and lower crust and on the Moho.

Conclusions

Analysis of the models for the rotation of the Eurasian Plate in 2008 and 2010 was carried out, and the model parameters have been obtained.

The position of the boundary of the Eurasian and North American Plates in northeastern Russia has been refined. It extends from north (Tiksi Village) to south along the Chersky Ridge. According to seismological data and results of GPS measurements, the boundary is a zone of present-day compression and displacements of up to 5 mm/year.

North of the Sea of Okhotsk, the boundary of the North American and Okhotsk Plates passes as a wide belt in the south of the Chersky Ridge, in the Ulakhan Fault region.

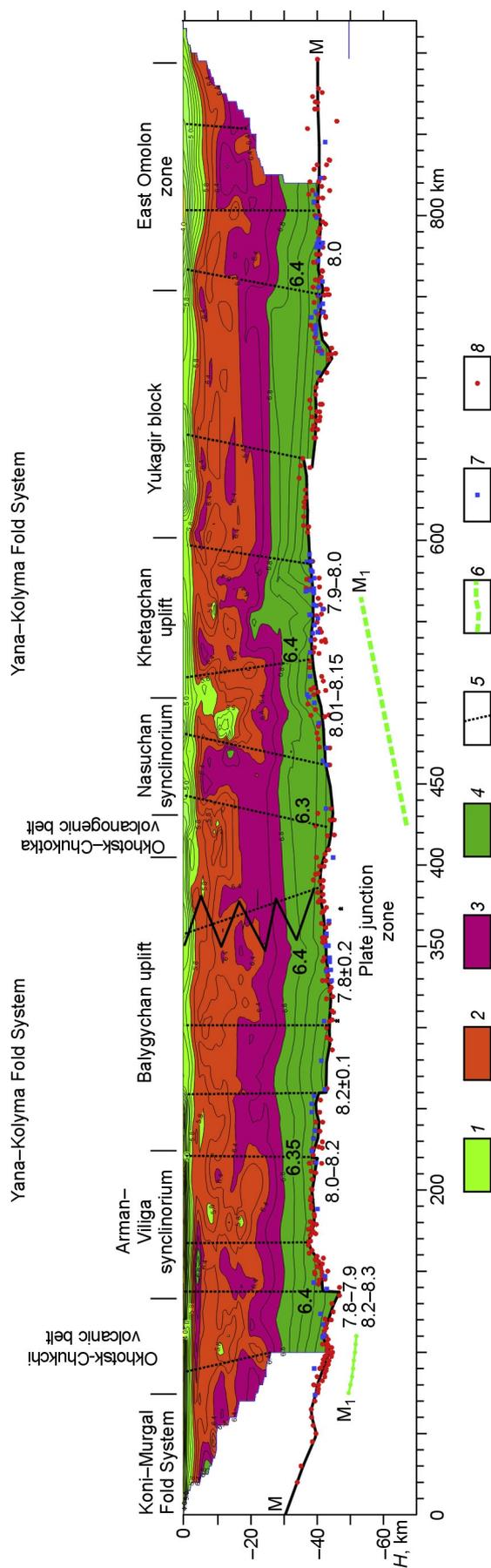


Fig. 16. Fragment of DSS section along the Magadan–Wrangel Island profile. 1, volcanosedimentary complex ($v_P < 5.8$ km/s); 2, granite-gneiss layer ($v_P = 5.8$ – 6.4 km/s); 3, granulite layer ($v_P = 6.4$ – 6.8 km/s); 4, basic layer ($v_P > 6.8$ km/s); 5, faults; 6, upper-mantle (M_1) surface; 7, 8, M surface, from data on: 7, refracted and 8, reflected waves. Numerals show the velocities of seismic waves, km/s.

According to seismological and GPS data, the displacements (up to 3–4 mm/year) here are mainly strike-slip faults.

The earthquakes registered at both boundaries occurred within the Earth's crust (up to 40 km thick). The maximum magnitude (by Richter's scale) was $M = 7$.

Note that the boundaries passing in the continent look like a fan of boundaries occupying an area of hundreds of kilometers.

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References

- Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B., Boucher, C., 2007. ITRF 2005: a new release of the International Terrestrial Reference Frame based on time series of station positions and Earth orientation parameters. *J. Geophys. Res.* 112, B09401.
- Apel, E.V., Burgmann, R., Steblov, G., Vasilenko, N., King, R., Prytkov, A., 2006. Independent active microplate tectonics of northeast Asia from GPS velocities and block modeling. *Geophys. Res. Lett.* 33, L11303.
- Argus, D.F., Gordon, R.G., 1996. Test of the rigid-plate hypothesis and bounds on intraplate deformation using geodetic data from the very long baseline interferometry. *J. Geophys. Res.* 101, 13,555–13,572.
- Ashurkov, S.V., San'kov, V.A., Miroshnichenko, A.I., Likhnev, A.V., Sorokin, A.P., Serov, M.A., Byzov, L.M., 2011. GPS geodetic constraints on the kinematics of the Amurian Plate. *Russian Geology and Geophysics (Geologiya i Geofizika)* 52 (2), 239–249 (299–311).
- Avetisov, G.P., 1996. Seismoactive Zones of the Arctic [in Russian]. VNIIOkeanologiya, St. Petersburg.
- Avetisov, G.P., Guseva, Yu.V., 1991. The deep-level structure of the Lena delta region, from seismological data. *Sov. Geologiya*, No. 4, 73–81.
- Bogdanov, N.A. (Ed.), 1998. Tectonic Map of the Kara and Laptev Seas and Northern Siberia. Scale 1 : 2,500,000 [in Russian]. IL RAN, Moscow.
- Bogdanov, N.A., Khain, V.E. (Eds.), 1996. An Explanatory Note to the Tectonic Map of the Barents Sea and Northern European Russia. Scale 1 : 2,500,000 [in Russian]. IL RAN, Moscow.
- Boucher, C., Altamimi, Z., Sillard, P., Feissel-Vernier, M., 2001. The ITRF 2000. IERS Technical Note, No. 31.
- Bune, V.I., Gorshkov, G.P. (Eds.), 1985. Seismic Regionalization of the USSR Territory [in Russian]. Nauka, Moscow.
- Calais, E., DeMets, C., Nocquet, J.-M., 2003. Evidence for a post-3.16-Ma change in Nubia–Eurasia–North America plate motions? *Earth Planet. Sci. Lett.* 216, 81–92.
- Calais, E., Dong, L., Wang, M., Shen, Z., Vergnolle, M., 2006. Continental deformation in Asia from a combined GPS solution. *Geophys. Res. Lett.* 33, L24319.
- Cook, D.B., Fujita, K., McMullen, C.A., 1986. Present day plate interactions in northeast Asia: North American, Eurasian and Okhotsk plates. *J. Geodyn.* 6 (1–4), 33–51.
- DeMets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. *Geophys. J. Int.* 181, 1–80.
- Dobretsov, N.L., Kirdyashkin, A.G., Kirdyashkin, A.A., 2001. Deep-Seated Geodynamics [in Russian]. Izd. SO RAN, Filial "Geo", Novosibirsk.
- Fujita, K., Cook, D., Hasegawa, H., Forsyth, D., Wetmiller, R., 1990. Seismicity and focal mechanisms of the Arctic region and North American plate boundary in Asia, in: Grantz, A., Johnson, G.L., Sweeney, J.F. (Eds.), *Geology of North America. Vol. L. The Arctic Ocean Region*. Geol. Soc. Am., Boulder, pp. 77–100.

- Fujita, K., Stone, D.B., Layer, P.W., Parfenov, L.M., Koz'min, B.M., 1997. Cooperative program helps decipher tectonics of north-east Russia. *EOS T. Am. Geophys. Un.* 78 (24), 252–253.
- Fujita, K., Koz'min, B.M., Mackey, K.G., Riegel, S.A., McLean, M.S., Imaev, V.S., 2009. Seismic belt, eastern Sakha Republic (Yakutia) and Magadan District, Russia. *Stephan Mueller Spec. Publ. Ser.* 4, 117–145.
- Gatinskii, Yu.G., Rundkvist, D.V., Tyupkin, Yu.S., 2005. The block structure and kinematics of East and Central Asia, from GPS data. *Geotektonika*, No. 5, 3–19.
- Gornov, P.Yu., 2011. *Geothermics of Eastern Eurasia: Characteristics and Detailed Analysis*. Lap Lambert Academic Publishing, Saarbrücken, Deutschland.
- Gornov, P.Yu., Goroshko, M.V., Malyshev, Yu.F., Podgornyi, V.Ya., 2009. Thermal structure of lithosphere in Central Asian and Pacific belts and their adjacent cratons, from data of geoscience transects. *Russian Geology and Geophysics (Geologiya i Geofizika)* 50 (5), 485–499 (630–647).
- Gramberg, I.S., Demenitskaya, R.M., Sekretov, S.B., 1990. A system of rift grabens on the Laptev Sea shelf as a lacking link of the rift belt of the Gakkel–Moma Ridge. *Dokl. Akad. Nauk* 311 (3), 689–694.
- Grachev, A.F., 1987. Rift Zones of the Earth [in Russian]. Nedra, Leningrad.
- Imaev, V.S., Imaeva, L.P., Koz'min, B.M., 1990. Active Plumes and Seismotectonics of Northeastern Yakutia [in Russian]. *YaNTs SO AN SSSR, Yakutsk*.
- Imaev, V.S., Imaeva, L.P., Koz'min, B.M., 2000. Seismotectonics of Yakutia [in Russian]. *GEOS, Moscow*.
- Jin, Sh., Park, P.-H., Zhu, W., 2007. Micro-plate tectonics and kinematics in Northeast Asia inferred from a dense set of GPS observations. *Earth Planet. Sci. Lett.* 257, 486–496.
- Khain, V.E., 1994. Plate tectonics. Analysis of the present-day state. *Vestnik MGU. Ser. 4. Geologiya*, No. 1, 3–10.
- Kogan, M.G., Steblov, G.M., 2008. Current global plate kinematics from GPS (1995–2007) with the plate-consistent reference frame. *J. Geophys. Res.* 113, B04416.
- Kogan, M.G., Steblov, G.M., King, R.W., Herring, T.A., Frolov, D.I., Egorov, S.G., Levin, V.Y., Lerner-Lam, A., Jones, A., 2000. Geodetic constraints on the rigidity and relative motion of Eurasia and North America. *Geophys. Res. Lett.* 27, 2041–2044.
- Koz'min, B.M., 1984. Seismic Belts of Yakutia and Focal Mechanism of Their Earthquakes [in Russian]. Nauka, Moscow.
- Kreemer, C., Holt, W.E., Haines, A.J., 2003. An integrated global model of present-day plate motions and plate boundary deformation. *Geophys. J. Int.* 154 (1), 8–34.
- Kreemer, C., Lavalle'e, D.A., Blewitt, G., Holt, W.E., 2006. On the stability of a geodetic no-net-rotation frame and its implication for the International Terrestrial Reference Frame. *Geophys. Res. Lett.* 33, L17306.
- Mackey, G.K., Fujita, K., Ruff, L.J., 1998. Crustal thickness of Northeast Russia. *Tectonophysics* 284, 283–297.
- Mal'kov, B.I., 1971. Schematic development of the southeastern Yana-Kolyma geosynclinal system, in: *Mesozoic Tectogenesis*. Proc. Seventh Session of Research Board on the Siberian and Far Eastern Tectonics [in Russian]. ITiG DVO RAN, Khabarovsk, pp. 35–41.
- Munekane, H., Fukuzaki, Y., 2006. A plate motion model around Japan. *Bull. Geographical Survey Institute* 53, 35–41.
- Mushketov, I.V., Orlov, A.P., 1893. *Catalogue of Earthquakes in the Russian Imperia* [in Russian]. Tipografiya Imperatorskoi Akademii Nauk, St. Petersburg, Vol. 26.
- Prawirodirdjo, L., Bock, Y., 2004. Instantaneous global plate motion model 12 years of continuous GPS observations. *J. Geophys. Res.* 109, B084405.
- Sella, G.F., Dixon, T.H., Mao, A., 2002. REVEL: A model for recent plate velocities from space geodesy. *J. Geophys. Res.* 107 (B4), 2081.
- Shakhtyrov, V.G., 1985. Fault and shear morphostructures of the northeastern USSR, in: *Morphostructural Studies. Theory and Practice* [in Russian]. Nauka, Moscow, pp. 190–194.
- Shestakov, N.V., Gerasimenko, M.D., Takahashi, H., Kasahara, M., Bormotov, V.A., Bykov, V.G., Kolomiets, A.G., Gerasimov, G.N., Vasilenko, N.F., Prytkov, A.S., Timofeev, V.Yu., Ardyukov, D.G., Kato, T., 2011. Present tectonics of the southeast of Russia as seen from GPS observations. *Geophys. J. Int.* 184 (2), 529–540.
- Steblov, G.M., 2004. Interaction between lithospheric plates in northeastern Asia. *Dokl. Earth Sci.* 395 (2), 226–229.
- Steblov, G.M., Kogan, M.G., King, R.W., Scholz, C.H., Burgmann, R., Frolov, D.I., 2003. Imprint of the North American plate in Siberia revealed by GPS. *Geophys. Res. Lett.* 30 (18), 1924.
- Stein, S., Gordon, R., 1984. Statistical tests of additional plate boundaries from plate motion inversions. *Earth Planet. Sci. Lett.* 69, 401–412.
- Surkov, V.S., Sal'nikov, A.S., Kuznetsov, V.L., Lipilin, A.V., Seleznev, V.S., Emanov, A.F., Solov'ev, V.M., 2007. The structure of the Earth's crust in the Magadan sector of northeastern Russia, from DSS data, in: *The Structure of the Earth's Crust in the Magadan Sector of Russia, from Geologo-Geophysical Data. Collection of Scientific Works* [in Russian]. Nauka, Novosibirsk, pp. 13–21.
- Timofeev, V.Yu., Ardyukov, D.G., Gornov, P.Yu., Malyshev, Yu.F., Boiko, E.V., 2008. Results of analysis of GPS measurement data (2003–2006) for the Sikhote-Alin' network in the Far East. *Tikhookeanskaya Geologiya* 27 (4), 39–49.
- Timofeev, V.Yu., Kazansky, A.Yu., Ardyukov, D.G., Metelkin, D.V., Gornov, P.Yu., Shestakov, N.V., Boiko, E.V., Timofeev, A.V., Gil'manova, G.Z., 2011. The parameters of rotation of the Siberian domain and its eastern framing in different geologic epochs. *Tikhookeanskaya Geologiya* 30 (4), 21–31.
- Zonenshain, L.P., Kuz'min, M.I., 1993. Deep geodynamics of the Earth. *Geologiya i Geofizika (Russian Geology and Geophysics)* 34 (4), 3–12 (1–9).
- Zonenshain, L.P., Savostin, L.L., 1979. *Introduction into Geodynamics* [in Russian]. Nedra, Moscow.
- Zonenshain, L.P., Savostin, L.L., 1981. Geodynamics of the Baikal rift zone and plate tectonics of Asia. *Tectonophysics* 76, 1–45.
- Zonenshain, L.P., Kuz'min, M.I., Natapov, L.N., 1990. *Plate Tectonics of the USSR Territory* [in Russian]. Nedra, Moscow, Vols. 1 and 2.
- Zonenshain, L.P., Kuzmin, M.I., Bocharova, N.Yu., 1991. Hotfield tectonics. *Tectonophysics* 199, 165–192.

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