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Active faulting at the Eurasian, North American and Pacific plates junction

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Abstract

The active faults known and inferred in the area where the major Pacific, North American and Eurasian plates come together group into two belts. One of them comprises the faults striking roughly parallel to the Pacific ocean margin. The extreme members of the belt are the longitudinal faults of islands arcs, in its oceanic flank, and the faults along the continental margins of marginal seas, in its continental flank. The available data show that all these faults move with some strike-slip component, which is always right-lateral. We suggest that characteristic right-lateral, either partially or dominantly, kinematics of the fault movements has its source in oblique convergence of the Pacific plate with continental Eurasian and North American plates. The second belt of active faults transverses the extreme northeast Asia as a continental extension of the active mid-Arctic spreading ridge. The two active fault belts do not cross but come close to each other at the northern margin of the Sea of Okhotsk marking thus the point where the Pacific, North American and Eurasian plates meet.

Keywords: East Asia; Active fault; Paleoseismisity; Circum-Pacific; Plate interaction

1. Introduction

Active faults in northeast Asia group by their strike into two distinct belts (Fig. 1). Firstly, these are faults that stretch roughly parallel the Pacific ocean margin. They have been recognised within the island arc systems or arc rises (Kamchatka, western Aleutian, Japanese islands and Sakhalin), and along the continental sides of the marginal Okhotsk, Japan and Bering seas. Actually, this is just a portion of much longer active fault belt of the Pacific ocean periphery. North of the region, the other side of the Bering Straight, the Pacific-parallel mostly strike-slip faults (Kobuk, Kaltag, Denali, western Tintina and others) have been mapped in Alaska (Plafker et al., 1994). Southerly, active faults stretching coastwise, are known in east China, Korea, Taiwan and southeast Asia, the Tanlu fault being the most prominent of them. Secondly, these are the faults striking NW, that is, nearly at the right angle to the Pacific margin, and forming the so-called Momsky–Chersky belt of active faults. The belt starts from the southern coast of the Laptev Sea, goes southwest clear across the continental northeast Asia and terminates at the northern coast of the Sea of Okhotsk.

In respect to the ocean–continent boundary, the two belts may be defined as marginal and intraconti-

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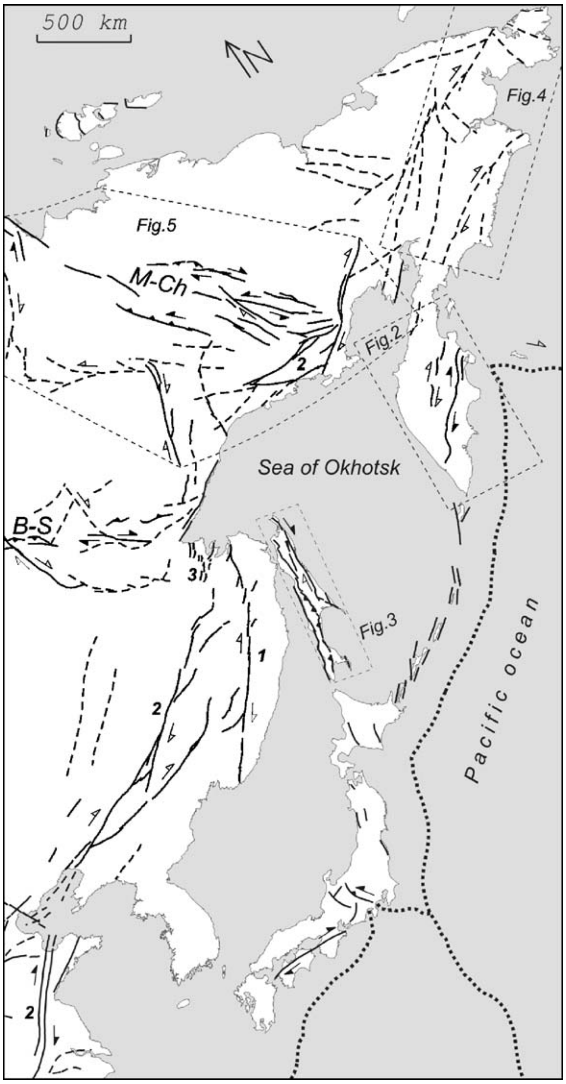


Fig. 1. Active faults of East and northeast Asia. Solid and dashed lines are known and inferred active faults. Arrows and triangles mark strike-slip and reverse or thrust faults, respectively, with teeth and arrowheads left empty if the sense of fault motions is only inferred. Thick dotted line is the axes of deep trenches. M–Ch is the Momsky–Chersky active fault belt and B-S stands for the Baikal-Stanovoy active fault belt. Numbered are the Central Sikhote-Alin fault (1), the Tanlu fault (2) and its possible northern extension in a form of young grabens (3).

nental, respectively. In terms of lithosphere plates interaction, the first of them closely following the Pacific and Eurasian plates contact has most likely been evolving due to relative movements of these two major plates. The intracontinental Momsky–Chersky belt, which lies on the continuation of the mid-Arctic spreading ridge, has been often interpreted as marking the continental portion of the NA-EU plate boundary. Although the exact position of the NA-EU Euler pole is still unknown, all the estimates of the pole location (Chapman and Solomon, 1976) fall within this active fault belt and its junction with the belt of the Pacific-parallel faults.

Thus northeast Asia represents a specific region where, firstly, peri- and intracontinental active fault belt interact in some way, and, secondly, where active faulting when studied may shed some light on movements around the plates triple junction.

The region is poorly known in terms of active fault kinematics, and even less in terms of paleoseismicity that could have been generated by those faults. More or less definite data on fault kinematics have been obtained in Kamchatka peninsula (Kozhurin, 1988, 1990). Only several major faults of the Momsky–Chersky belt have been characterised kinematically (Imaev et al., 1990, 2000). Recently, since the 1995 Neftegorsk earthquake, some works, including trenching, have been conducted in Sakhalin on major longitudinal faults (Kozhurin and Streltsov, 1995; Rogozhin, 1996; Shimamoto et al., 1996; Tsutsumi et al., 2000; Bulgakov et al., 2002).

Below, we describe briefly active faults from three typical areas. These are Kamchatka, which is an active island arc above the subduction zone, then Sakhalin, which is an island rise extension of the active Japanese arc but in the lee of the subduction zone, and the Momsky–Chersky Range System, which is the only intracontinental mobile zone in the region.

2. Active faults

2.1. Kamchatka

The present-day structure of the Kamchatka Peninsula is made of two main ridges, which are the Sredinny (Median) Range, in the west, and East Kamchatka Range, in the east (1 and 3 in Fig. 2, respectively), with the Central Kamchatka Depression between them (2 in Fig. 2). Pliocene–Quaternary volcanic belts (those of the Sredinny and East Kamchatka ranges) neighbour the depression east and west, and partially occupy its northern part (Fig. 2). All these structures are rather young and have been formed by mid–late Quaternary tectonic motions (Istoriya.., 1973). The Central Depression is in cross section asymmetrical, its eastern flank faulted and the western ascending gradually west towards the crest of the Sredinny Range.

There are two major zones of active faults in Kamchatka. The East Kamchatka fault zone starts in the south at latitude of about 53°N, by its about two thirds divides the Central depression from the Kamchatka Eastern Ranges elevation, but northerly crosses the range and gradually deviating to the east goes into the Kamchatsky Cape (the northernmost one of the three of the Pacific margin of Kamchatka).

Individual faults of the East Kamchatka zone reveal combined normal-strike-slip (right-lateral) fault movements. They offset late Pleistocene moraines and post-glacial (up to early Holocene) fluvial terraces and watercourses. The dextral/normal ratio ranges from 1–2/1 and up to 15–20/1 (Kozhurin, 1990). Amplitudes of observed late Quaternary normal displacements do not exceed some 30 m (by late Pleistocene moraines), and those of right-lateral offset reach 70–80 m at maximum. Maximum cumulative normal motion value imprinted in the topography is of an order of 1 km, counting by the height of the faceted western slope of the Eastern Ranges elevation. There are no topographic or geomorphologic markers by which lateral offsets corresponding to 1-km normal movement could be detected and measured as the surface of the depression is extremely young, not older then of late Pleistocene (Istoriya.., 1973).

Variation in the ratio values reflects mostly changes in normal component magnitude. The lower ratio values imply therefore relatively larger normal offsets and are characteristic to the individual faults that separate the Central Depression and the Eastern Ranges elevation. The highest ratio value was found for the extreme northeastern splay fault in the Kamchatsky Cape. The rate of dextral motions along the zone may have been about 10 mm/year in average over the end of the Pleistocene and beginning of the Holocene time as both radiocarbon and relative ages of offset features suggest (Kozhurin, 1988, 1990).

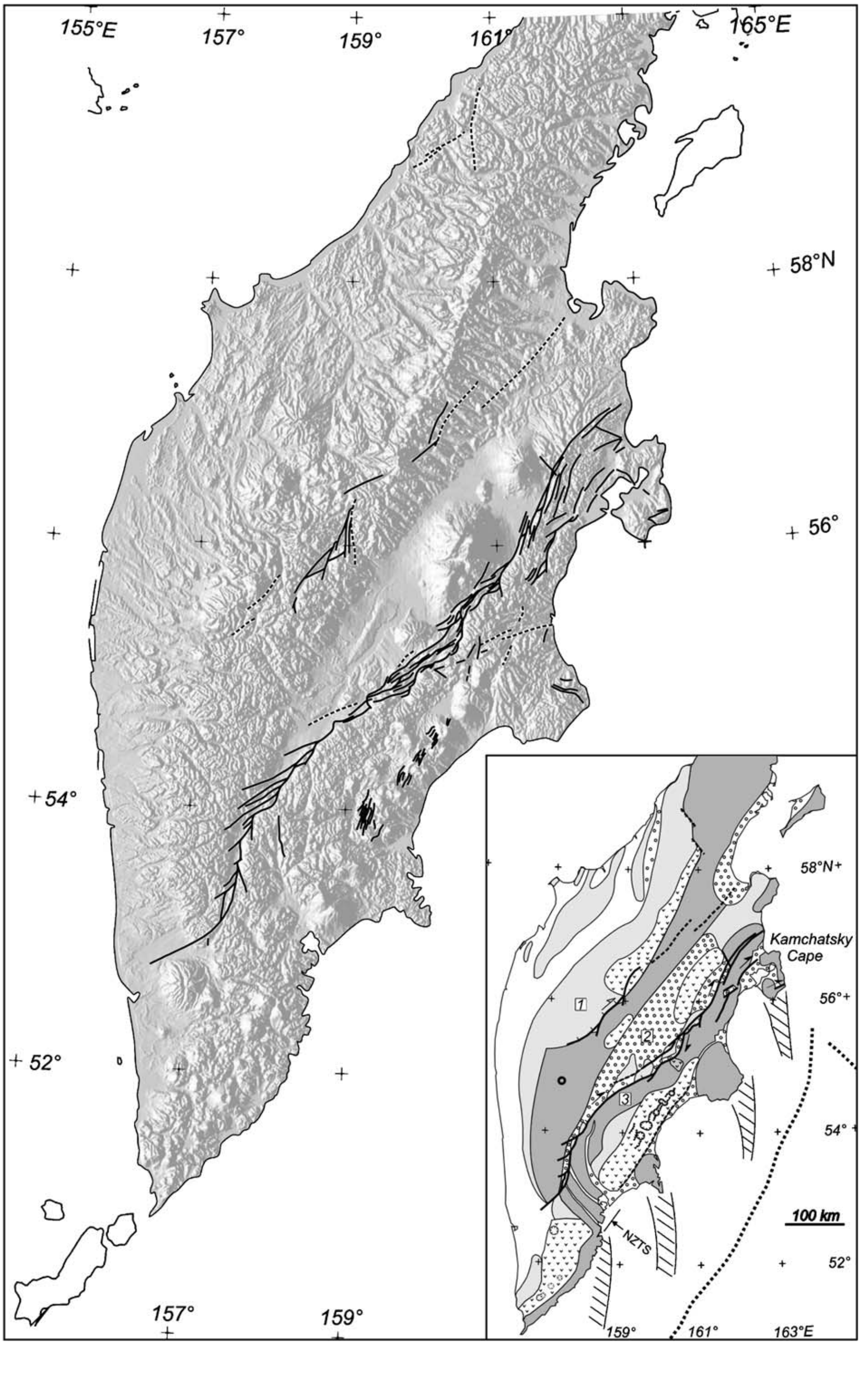
A minor fault zone was interpreted on aerial photos and by topography within the Sredinny (Median) Range, west of the Central Kamchatka Depression. Its southern segment follows the crest of the range. Due to normal movement there, west side down, a narrow asymmetric depression, its east side faulted, developed in the crest of the range. Northern half of the zone trending more northeasterly breaks the range eastern slope.

At the moment, it cannot be said whether some strike-slip component adds to the Sredinny Range fault zone movement or not. It is worth pointing out, however, that individual faults or segments of the fault zone juxtapose in the manner that is similar to that found for the East Kamchatka zone. Fault-bounded triangles at the fault junctions embrace some of active hot spring fields and could be therefore extensional segments of the zone with some right-lateral component of movement.

Specific normal faults forming graben-in-graben system has been found to closely follow the axis of the East Kamchatka volcanic belt (Florensky and Trifonov, 1985). Segments of their belt make a right-step array, the steps coinciding with major volcanic calderas. There is no sign of lateral movements along individual normal faults of the belt. It is just en echelon arrangement of the belt segments that suggests some likely very small left-lateral component of overall motion. As a whole, the belt appears to have developed as the specific intravolcanic feature (Kozhurin, 1988).

The southern extension of the East Kamchatka fault zone is obscure and several variants may still be ranked equal. On one hand, it may wane southward and its southernmost trace near the Okhotsk margin of Kamchatka may be then its real termination. On the other hand, a prominent zone of NW-striking Quaternary ridges and depressions, usually referred to as the Nachiki Zone of Transverse Dislocations (see Fig. 2, inset), looks as one that might have been accommodating a part of horizontal motions along the East Kamchatka fault zone. If so, the East Kamchatka fault zone may continue southwest from the southeastern side of the Nachiki zone along the Pacific slope of Kamchatka.

Dextral motions along the Kamchatka Peninsula commenced likely not earlier then somewhere in Pliocene time, after the late Miocene (Shapiro, 1980), or even early Pliocene (Bakhteev et al., 1997) final episode of east-directed thrusting in the east of Kamchatka.


155°E
157°
159°
161°
165°E
58°N
56°
54°
52°
157°
159°
Kamchatsky Cape
58°N
56°
54°
52°
1
2
3
100 km
NZTS
159°
161°
163°E

2.2. Sakhalin

Active faulting in Sakhalin Island concentrates in two zones that stretch along its western and eastern margins (Fig. 3). The Ehabi-Piltun fault zone, which is a part of longer East Sakhalin zone, extends north–south close to the east margin of the northern lowland of the island. The NS-trending Tym-Poronay fault zone runs between the West Sakhalin uplift in the west and the Tym-Poronay in the east. Within the south Sakhalin, it is continued by the Aprelovka active fault that makes the western limit of the Susunay depression. Both zones though parallel have been shown to display different kinematics of late Quaternary movements.

The Ekhabi-Piltun zone consists of two, the Piltun (in the north) and Garomay (in the south), faults (1 in Fig. 3), about 40 and 20 km long, respectively. The Piltun fault has been moving right-laterally during the late Quaternary time at the average rate of 3–5 mm/year. Dextral offsets that could be detected in present topography range from first meters to 50–70 m (Bulgakov et al., 2002). Trenching of the fault as well as radiocarbon dating of the faulted strata and landscape features showed that fault-related strong earthquakes took place at several hundreds to one or two thousand years interval. The Garomay fault looking very similar to the Piltun fault does not anyway show convincing signs of recent lateral slip. In its southern part, several well-expressed river terraces and minor watercourses valleys provide evidences of only vertical (up to 4 m, west side up) fault movements.

The Piltun-Garomay fault comes out as a major structure in respect to the Upper Piltun fault in its west side that moved in 1995 and has become known as the 1995 Neftegorsk earthquake fault (see Fig. 3). The latter showed up as predominantly right-lateral fault with about 3.6 m of average lateral slip (8.1 m at maximum) and only 0.15 m of average vertical (west side up) motion (Shimamoto et al., 1996). Trenching of the fault (Rogozhin, 1996) yielded much shorter, around 400 years, recurrence interval between strong fault-related earthquakes if compared with that obtained for the Piltun fault.

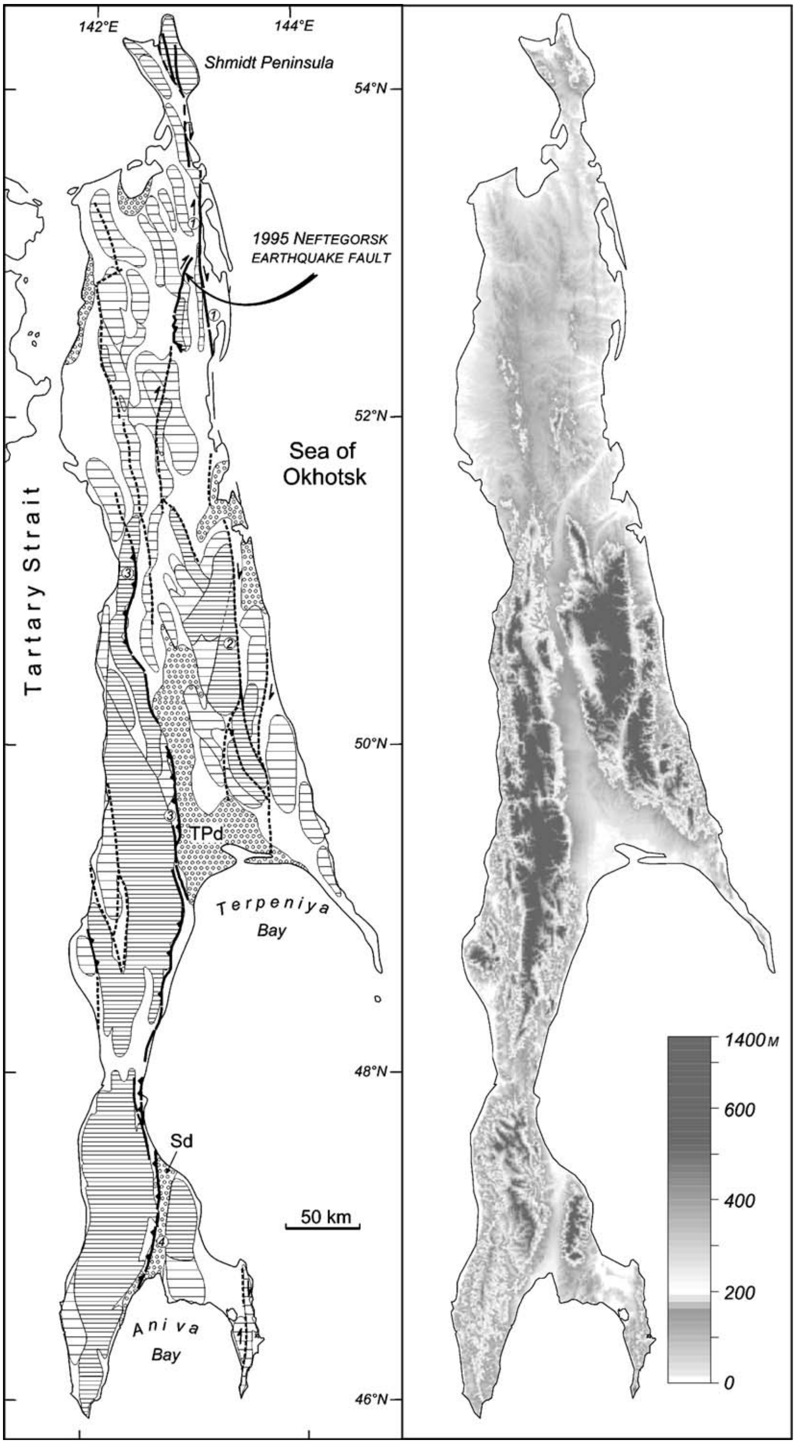
Northern extensions of the Piltun-Garomay fault zone may be the Ekhabi fault and presumably active faults in the Shmidt peninsula further north. The latter has not been studied in terms of recent activity. It is known that some of them display right-laterally contacts between Cretaceous and Neogene formations, the total amount of displacement reaching 5.5 km, or even 14 km if together with drag fold component (Rozhdestvensky, 1975).

Southerly, in the East Sakhalin mountains, the Central fault (2 in Fig. 3) of the same East Sakhalin fault zone (approximately, between 49.5°N and 51°N) displays about 25 km right-laterally Palaeozoic complexes (Rozhdestvensky, 1975), the main stage of lateral movements falling on Pliocene and early Quaternary time (Fournier et al., 1994). Detailed examination of aerial photos covering the northern half of the Central fault did not reveal any offsets of young topographic elements along its trace.

The Tym-Poronay active fault (3 in Fig. 3) with its nearly entire length inherits the older fault along which the Cretaceous units of the West Sakhalin Mountains overthrust Neogene formations, but sometimes advances east of it. The recent fault was trenched at the latitude of about N49°45′. The plane of the major frontal (easternmost) fault dips west at the angle of 55° (estimated by vertical separation and horizontal shortening of the strata and the Earth's surface). The most recent earthquake movement took place about 3700 years ago. The net slip rate was estimated to have been some 1.0–1.2 mm/year (Bulgakov et al., 2002).

It is not clear whether movements along the Tym-Poronay fault include some lateral component. As a whole, the fault movement is predominantly reverse. Uncertain in amount but obviously much smaller right-lateral component may be suggested by some en-echelon arrangement of the folds in the west fault zone side (Rozhdestvensky, 1982).

Fig. 2. Active faults in the Kamchatka Peninsula superimposed on shaded relief (generated using GTOPO30 (Global...)). Inset shows middle–late Quaternary structure of the peninsula. Darker and lighter shading show relatively higher and lower elevations (1—Sredinny Range, 2—East Kamchatka Range), circle-filling corresponds to depressions (2—Central Kamchatka Depression) and v-filling marks zones of late Quaternary and active volcanism. Lines are active faults, dashed where inferred; arrows accompany faults with strike-slip component of movement. Circles with inside-directed ticks are volcanic calderas. Oblique hatching shows location of underwater continuations of the East Kamchatka Capes and dotted line is the axis of deep trenches.


142°E
144°E
Shmidt Peninsula
54°N
1995 NEFTEGORSK
EARTHQUAKE FAULT
52°N
Sea of
Okhotsk
Tartary Strait
50°N
TPd
Terpeniya
Bay
48°N
Sd
50 km
Aniva
Bay
46°N
1400 M
600
400
200
0

2.3. Other Pacific-parallel presumably active faults

The Lankovaya-Omolon fault zone (1 in Fig. 1, see also Fig. 5) is one of the westernmost faults among the Pacific-parallel faults in the region. Well expressed both in topography and on satellite images of the region the Lankovaya-Omolon fault zone is believed to be dextral though no evidences proving this have been reported so far. These are just landslides and rock falls of presumably seismogravitational origin found along the fault trace the inference of the fault Holocene activity basis on (Smirnov, 1988, 1989; Smirnov and Vazhenin, 1985).

West of the Lankovaya-Omolon fault zone, a set of faults (the Inya-Yama fault zone, 2 in Fig. 1, see also Fig. 5) of unknown kinematics and the age of last activity have been recognised on satellite images (Smirnov, 1989).

Northeast of Kamchatka, close to the Bering Sea, a set of linear features, presumably late Quaternary faults, has been mapped using satellite images (Figs. 1 and 4). Several Harvard CMT focal plane solutions showing combined reverse-dextral slip along the NE-oriented planes, their ratio differing, may serve as evidences for the activity of those inferred faults (Fig. 4). Northeast-striking nodal planes are inclined either northwest or southeast and are relatively steep.

Some models (Lander et al., 1994; Mackey et al., 1997) incorporate some of the inferred faults as the Bering plate western boundary.

South of the region, the most prominent and largest fault is the Tanlu (Tancheng-Lujiang) fault (3 in Fig. 1). Its zone may extend to the north as far as to the Okhotsk Sea southwestern margin, though not in a form of one or several single lines but as a right-lateral array of en-echelon left-stepping young grabens (4 in Fig. 1), first outlined by Streltsov and Rozhdestvensky (1995). The fault must have been moving as a dextral fault over at least the late Cenozoic time. Data supporting this view include both observations of Holocene right-lateral offsets (Wu et al., 1981) and earthquake mechanisms for the paralleling faults to the west (Chen and Nábelek, 1988). Having incorporated recent seismicity and the geometrical patterns of the North China basin, Chen and Nábelek came to the conclusion that right-lateral movements along the NE-striking faults within the North China basin may have commenced as early as in the Eocene time.

The Tanlu fault seems to connect trough a series of splay faults (the "pinnate"-type of fault junction) with the Central Sikhote-Alin fault (5 in Fig. 1) that may be therefore the dextral fault too though no evidences of young motions of this sense have been reported yet.

As it shown in Fig. 1, the Tanlu fault zone nearly reaches the Baikal-Stanovoy belt of seismicity and young faulting (B-S in Fig. 1), presumably of overall left-lateral kinematics. It is still unclear whether the latter continues as active one farther east beneath the waters of the Sea of Okhotsk, and whether it crosses there the Sikhote-Alin and Sakhalin trends. Noteworthy is that there are several faults branching north off the belt and skirting the Sea of Okhotsk along its western margin towards the Sette-Daban Range where the Burkhala presumably dextral fault extends about N-S (see Fig. 5).

2.4. Momsky–Chersky belt of active faults

The Momsky–Chersky belt of active faults is commonly thought by many as manifesting the continental segment of the NA-EU plate boundary.

The largest fracture of the territory is the Ulakhan fault (Fig. 5), apparently left-lateral, with much smaller reverse component of motion. It laterally displays 20–25 to 75 m, and when judging by the topography alone, up to the first hundreds of meters, watercourses, small river valleys and water divides. The fault plane steeply dips northeast at the angle of

Fig. 3. Active faults in the Sakhalin Island. With hatching Quaternary zones of elevation and subsidence, which may be either fault-bounded blocks or broad gentle folds or combinations of both types, are shown (denser hatching corresponds to relatively higher topography). Heavier solid lines are the faults either proved or presumably active (Bulgakov et al., 2002). Dashed thinner lines are the faults that might be active but that remain unstudied in terms of recent activity (mainly from Rozhdestvensky (1975, 1976, 1982) slightly generalized or modified). Arrows and teeth are for strike-slip and thrust-reverse faults, respectively, teeth in upthrown side; lines without markers are faults with unknown sense of motion. Encircled numerals designate the Piltun-Garomai fault (1), the Central fault (2), the Tym-Poronay fault (3) and the Aprelovka fault (4). Note that both the East Sakhalin and West Sakhalin ranges find their continuations within the north Sakhalin lowland in the arrays of topographically expressed gentle folds. DEM-generated relief (Global...) shows major topographically expressed structural elements of the island.

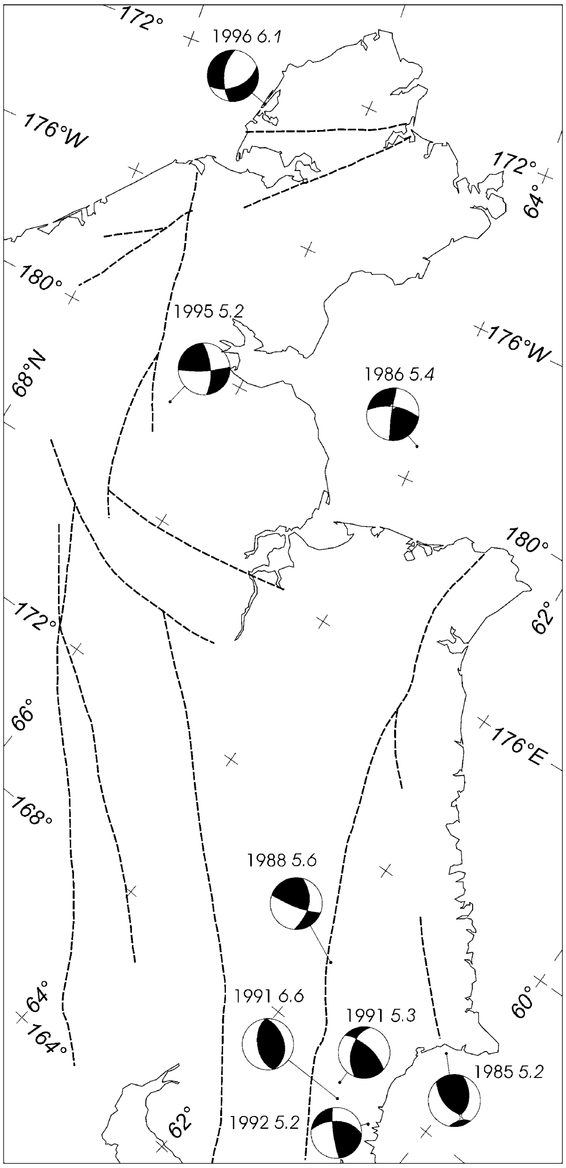


Fig. 4. Inferred late Quaternary faults and earthquake mechanism CMT solutions (from the Harvard database) in the Bering Sea northeast surrounding.

75–80° towards the axial depression between the Momsky and Chersky Ranges. Another major fault zone including the Arga-Tass and Ilin'-Tass faults extends with the strike of the Ulakhan fault but along the opposite flank of the axial chain of depressions. The fault zone offsets but right-laterally from 10–12 up to 100–120 m side water divides and valleys with much lesser reverse component. Its plane dips southwest at the same angle as the Ulakhan fault does. Thus, two major faults of nearly the same strike, paralleling the general trend of the Chersky mountain system, reveal opposite sense of horizontal motions, at least over mid-late Quaternary time. Among the horizontal offsets mentioned above, those with values up to 100–120 m are most likely of postglacial age. If so, the rate of both right-and left-lateral motions along these NW-striking faults may have been not less then 8–10 mm/year. There are several paleoseismic dislocations, mainly of gravitational nature, found along the faults (Smirnov and Vazhenin, 1985; Smirnov, 1988, 1989; Imaev et al., 2000).

The sense of fault motion substantially changes, if we turn to the faults of the northeast and southwest flanks of the Chersky system. Along the northeastern foot of the Momsky Range, a series of young thrust faults their planes dipping gently under the Momsky Range (the Myatiss thrust) have been mapped (Imaev et al., 1990). The fault affects deposits as young as of Miocene age, but there no data proving its late Quaternary activity. Another fault of the same thrust kinematics but with the opposite direction of the plane dip, probably with a much smaller left-lateral component, the Adycha-Taryn fault, bounds the Chersky Range in the southwest. In its northwestern segment, Triassic sandstones overthrust onto the Holocene deposits of the Adycha River terrace (after Imaev et al., 2000).

The third type of faults we find along the flanks of the axial depression between the Chersky and Momsky Ranges. Faceted slopes of N-W striking segments of the depression can not be interpreted otherwise than as resulted from normal motions. Actually, normal faulting and fault-bounded young depressions were the first features recognised and then interpreted as evidences of Cenozoic rifting process (Grachev et al., 1970).

In the extreme northwestern part of the region, a number of presumably active fault zones and paleoseismodislocations, mainly gravitational, were mapped south of the Buor-Khaya Bay of the Laptev Sea (see Fig. 5) (Imaev et al., 2000). Among them, the about N–S striking Kharaulakh fault was found to display 25–30 m right-laterally young topographic elements. Other faults should be still defined as just late Cenozoic as there are no data any definite on their recent activity.

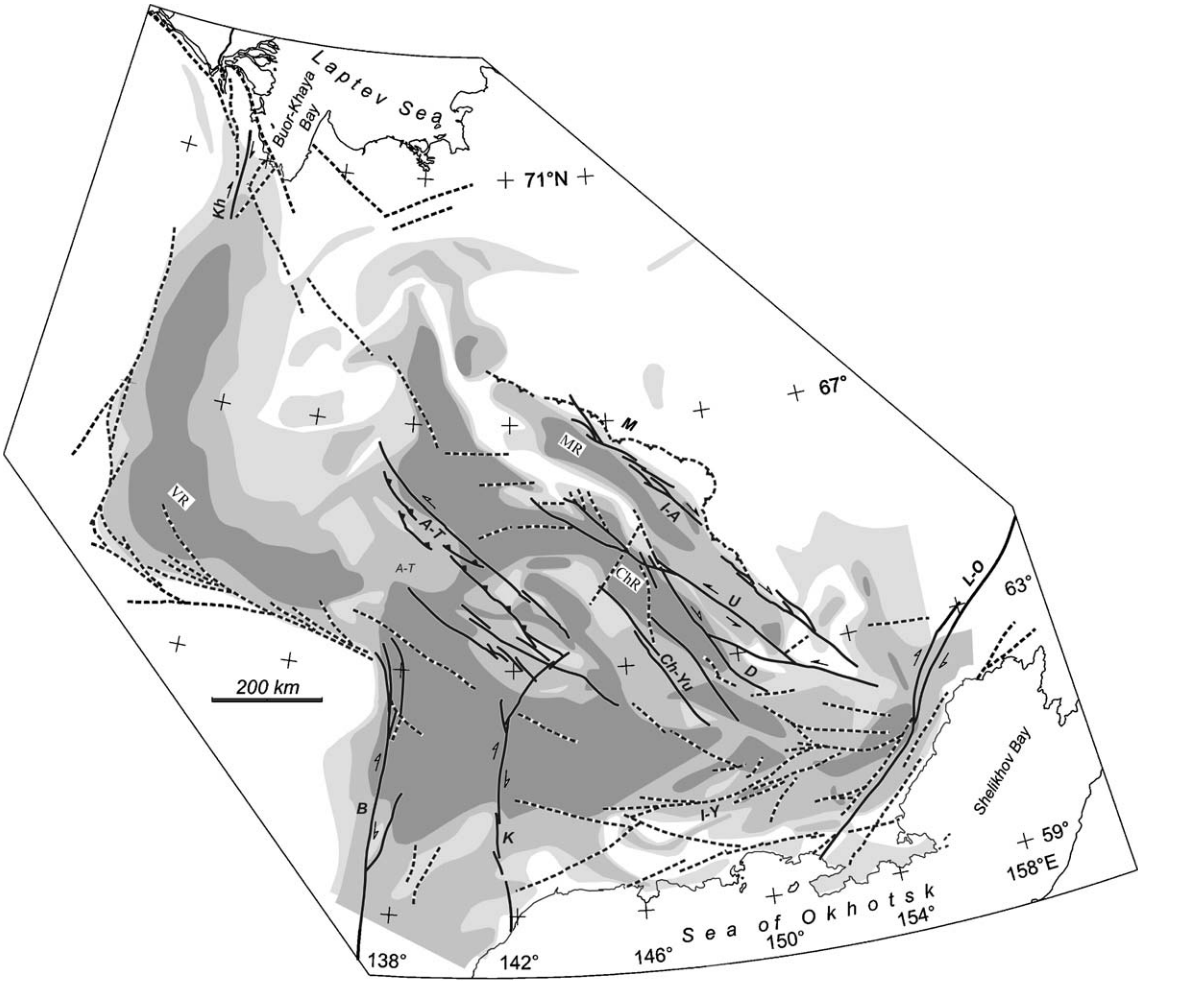


Fig. 5. Active faults known (solid lines) and inferred (dashed lines) in the Momsky–Chersky ranges area. Fault kinematics is indicated by the same symbols as in Figs. 1 and 2. Letters designate major active faults of the region, which are the Myatiss thrust (M), the Adycha-Taryn fault (A-T), the Ulakhan fault (U), the Chai-Yureya fault (Ch-Y), the Darpir fault (D), the Ketanda fault (K), the Ilin'-Tas-Arga-Tas fault zone (I-A), the Burkhala fault (B) and the Lankovaya-Omolon fault (L-O). Thin dashed lines are minor faults interpreted by topography and on satellite images (I-Y is for the Inya-Yama fault zone). MR, ChR and VR are the Momsky, Chersky and Verkhoyansky ranges, respectively. Gradations of grey shading correspond to (from lighter to darker) topography higher than 600, 1000 and 1500 m above sea level.

So, the principal features of active faulting in the region are longitudinal strike-slip faults, both dextral and sinistral, then flanking thrust faults and, finally, axial normal faults, all of them displaying (as far as the resolution of dating allows to conclude) coeval motions. Important is that this set of faults, and the Momsky–Chersky Mountain system as a whole, are limited in their southeast extension by the Lankovaya-Omolon dextral fault zone. All of the structural features of the Momsky–Chersky system, extremely contrast and sharp in appearance in the central part of the system, seem to melt away among the lowlands of the northern Okhotsk Sea margin. Neither the coastal ridges nor the Lankovaya-Omolon fault zone of the western Shelikhov Bay margin appear to be disturbed by any transverse structural trends.

Two about N-S striking faults splay south off of the Momsly–Chersky range. Basing on focal mechanism solutions, both faults have been interpreted as moving predominantly right-laterally (Imaev et al., 1990, 2000). The Burkhala fault (the western one) dies out in the south at about 58°N. It is unclear whether the Ketanda fault (the eastern one) extends farther south under the waters of the Sea of Okhotsk.

3. Discussion

There are still too little data that could allow to make any conclusions about such characteristics of active faulting in the region as variation in fault slip rates or earthquake recurrence intervals. Thus, we constrain ourselves to several notions about distribution and suggestions on probable geodynamic nature of the fault zones.

All the data though uncertain and unevenly distributed show that all the Pacific-parallel faults in the region have been moving with significant, sometimes dominant, component of strike-slip motion, which is always right-lateral. It is worth emphasising that this partial or dominant lateral kinematics does not show any correlation with how far from the active Pacific margin (subduction zones) a fault is, either inland or marginwise.

Since the Fitch's paper on the great faults of the Philippine Sea western surrounding (Fitch, 1970) the island arcs longitudinal strike-slip faults have been interpreted as accommodating a portion of a tangent component of plate interaction whenever it is oblique (Jarrard, 1986a,b; Kimura, 1986; McCaffrey, 1992; DeMets, 1992). The models of this kind do not (and cannot) account for strike-slip movements along the faults further inland: once the partition has occurred within the narrow contact zone plane of the interacting plates, there is no relative motion left to resolve on them. Commonly, interpretation of those faults involves relative movements between minor lithosphere plates, such as the Okhotsk, Bering and Amurian plates.

In our consideration, the uniformity in the sense of fault movements (pervasive right-lateral component) is not just random, and we suggest that all the Pacific-parallel faults represents constituents of a single belt and that movements throughout the belt reflect therefore some portion of relative movement between the Pacific and surrounding continental plates.

Simple quantitative estimation shows that the Pacific plate relative motion, its total amount gradually increasing from West America and Alaska to East Asia and its vector getting more and more normal to the strike of the belt, remains nevertheless essentially tangential in respect to the general trend of the north and west Pacific margins. The tangential component is always right-lateral and keeps being approximately constant all along the belt (Fig. 6). Its value in west and northeast Asia is about 4–5 cm/years approximately equalling the rate at which the Pacific plate passes the western North America along the San Andreas fault. It seems large enough to explain the phenomena of dextral motions along most of the faults of the East and northeast Asia margin, with the rate of fault movement most likely diminishing gradually with the distance from the Pacific, on one side, and North American and Eurasian plates, on the other side, contact. Following this line we then suggest that the PA-EU convergence do not resolve entirely at the plates contact but affects rather a wide marginal parts of the surrounding continental plates. A well-studied example of the oblique convergence related deformation is provided by the Cascadia margin of North America. Both paleomagnetic (England and Wells, 1991) and structural (Goldfinger et al., 1997) data suggest northward translation of the Cascadia submarine forearc, likely in a form of small block translation and rotation, and that the forearc deformation and translation accommodate nearly all of the tangential component of the Juan de Fuca plate subduction. Noteworthy is that post-middle Miocene deformation of the American continental edge spreads over about 300 km from the convergence line (England and Wells, 1991) and that this 300-km wide (about one-third of the terrane-built edge of the North American plate) zone of deformation relates to the oblique subduction at rather a moderate, around 4 cm/year, rate. It does not look thus improbable that at least twice faster Pacific–Eurasia convergence may be capable of deforming even a wider edge of the overriding plates. Characteristically, degree of deformation of the Cascadian margin, described through rotation angles, decreases inland but smoothly (England and Wells, 1991). Similarly, diminishing of fault motion rates away from the Pacific–Asian convergence line should be expected.

All the models of plates interaction in northeast Asia, either incorporating the Okhotsk plate or not, are similar in assuming that the major plate boundary goes first along the Momsky–Chersky seismic and

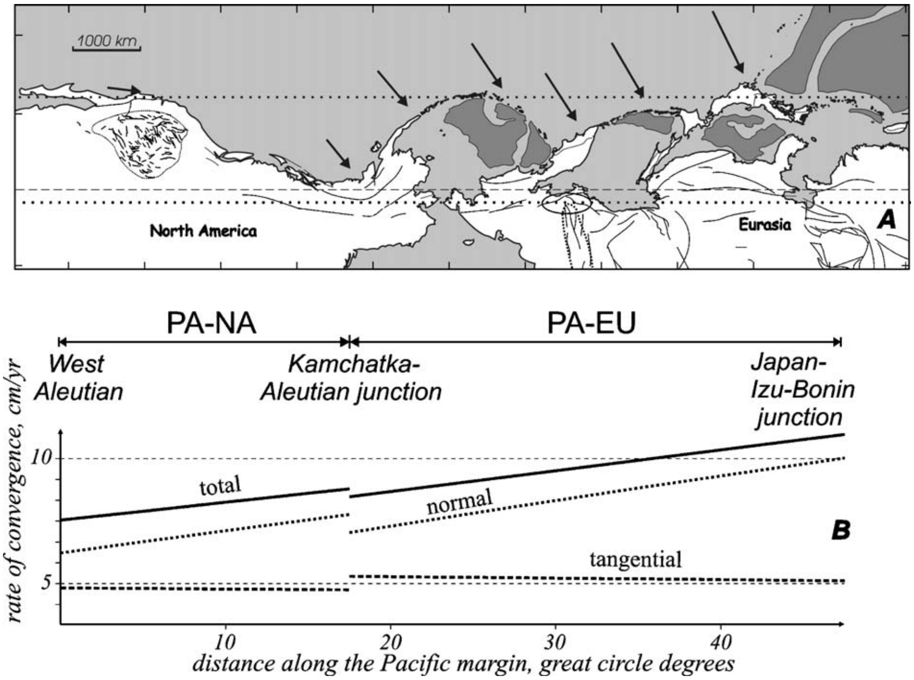


Fig. 6. (A) Vectors of convergence (black arrows) of the Pacific plate with the Eurasian and North American plates. The Eurasian and North American plates are fixed, vectors lengths are rate-dependant (relative rates and poles of plates rotation are from DeMets et al., 1990). Thick dotted lines approximate oceanic and continental limits of the Asia and tentatively North America edges affected by plate convergence. Thin solid lines are major faults generalized. Note that the Basin and Range Province (thinner lines in the left part of the figure are B and R normal faults) by its size, configuration and position looks much as a member of the marginal seas and back-arc basins sequence. Oval shows where two active fault belts marking the major plates boundaries join (finer dotted line outlines the Momsky–Chersky belt). Mercator projection with 7°N and 7°S as standard parallels, latitudes and longitudes scaled with 10° steps. Dashed line (0° latitude) is the Earth's surface projection of the great plane that passes through the point with true 56°N and 143.8°E and makes an angle of about 64.4° with the Earth's equatorial plane, and that was used, as providing the most rectilinear appearance of the Pacific ocean margin, for generating the projection for the figure. (B) Total and componential values of the Pacific and Eurasia plates convergence rate calculated at 2° steps along the 12°N Latitude (in the projection of A) from North Kamchatka to Central Japan.

active fault belt and then continues to the southeast toward the western Aleutians. Nowadays, at least two interpretations of late Quaternary fault movements in the region are available. The first implies dominant about NE–SW extension in the Momsky–Chersky Ranges region, which represents the continental rift zone on the continuation of the mid-Arctic spreading ridge (Grachev et al., 1970). Another model suggests significant alongwise left-lateral movements under slightly oblique compression (Imaev et al., 1990, 2000), which has been dominating in the region since the middle Quaternary time.

As it was shown above, one of peculiar features of the region is coeval evolution of both left-lateral and right-lateral longitudinal strike-slip faults. It seems therefore that other interpretations of active faulting, perhaps more complicated, may be possible.

In terms of plate interaction, the most popular model incorporates slightly oblique convergence of the North American and Eurasian plates in Northeast Asia, shortening of the Momsky and Chersky Ranges between them, and the S- or SW-directed extrusion of the Okhotsk plate from between the two major lithosphere plates (Cook et al., 1986; Riegel et al., 1993; Imaev et al., 2000). The clockwise rotation of the plate around the pole that was estimated to lie close to northern tip of Sakhalin was proposed by Seno and Sakurai (1996).

The Momsky–Chersky belt is indeed the only possible location of the continental segment of be it the NA-EU boundary or the NA-Okhotsk plates boundary. What should not be missed, however, is that the belt stretches southeastward no farther than to the Shelikhov Bay in the north of the Sea of Okhotsk and, in fact, does not reach the western margin of the bay. The Lankovaya-Omolon fault zone together with the Inya-Yama inferred fault zone, which are the westernmost of the Pacific-parallel faults in the region, extend all along the Shelikhov Bay coast and Sea of Okhotsk northern coast undisturbed, and to the southeast of them no active tectonic structures that could mark the supposed plate boundary segment have been so far discovered (e.g. Tectonic.., 2000). In this case, the northern boundary of the supposed Okhotsk plate appears unclosed. The same seems true in respect to the so called Bering block (Lander et al., 1994) or plate (Mackey et al., 1997) whose eastern boundary has been delineated as running right across the active faults of western Alaska (Fig. 3 in Mackey et al., 1997), the configuration that seems entirely impossible.

Under all the uncertainties with those minor plates and basing on the distribution of active faults in the region, it seems that the only place where we can find the North American, Eurasian and Pacific plates coming together lies immediately west of the Shelikhov Bay where a remarkably sharp change in dominating fault trends from NW–SE (the trend of the Momsky–Chersky belt) to NE–SW (Pacific-parallel) direction occurs (see Figs. 1, 5 and 6)). The Pacific plate takes part in this specific triple junction by only the continental limit of its boundary zone, towards which, as we expect, the fault movement rates may tend to lower. Apparent changes occur also along the strike of the Momsky–Chersky belt, which mark the NA-EU plates boundary. The triple junction is where it finally looses the clarity of topographic and structural manifestations or, in other words, where the motions of the Asian continent break-up driven by spreading in the mid-Arctic ridge cease.

4. Conclusions

1. Two belts of active faults in east and northeast Asia known and inferred mark the boundaries of the major North American, Pacific and Eurasian lithosphere plates. The distribution of active faults does not provide convincing evidences for the existence of minor plates in-between the major ones.
2. Most of the Pacific-parallel faults of the continental periphery seem to move with some, sometimes dominant, strike-slip component, which is always right-lateral. We suggest that the source of dextral shear within the wide zone of the northern Pacific Ocean margin, amount of which is likely diminishing away from the ocean, lies primarily in the oblique convergence of the Pacific plate with the surrounding continental plates.
3. The faults of the NW–SE-striking Momsky–Chersky belt reveal different sense of movement. Their set as a whole appears to have been evolving due to spreading in the mid-Arctic ridge. The southwestern termination of the belt marks where the Arctic ocean spreading induced deformation penetrates into the Asian continent to.
4. The two belts do not cross but meet each other at the northern margin of the Sea of Okhotsk. This is where the triple junction of the three lithosphere plates can be placed.

References

Bakhteev, M.K., Morozov, O.A., Tikhomirova, S.R., 1997. Structure of the eastern Kamchatka Ophiolite-free collisional suture—Grechishkin thrust. Geotectonics 31 (3), 74–85.

Bulgakov, R.F., Ivashchenko, A.I., Kim Chun Un, A.I., Sergeev, K.F., Streltsov, M.I., Kozhurin, A.I., Besstrashnov, V.M., Strom, A.L., Suzuki, Y., Tstsumi, H., Watanabe, M., Ueki, T., Shimamoto, T., Okumura, K., Goto, H., Kariya, Y., 2002. Active faults in northeastern Sakhalin. Geotectonics 36 (3), 227–240.

Chapman, M.B., Solomon, S.C., 1976. North American–Eurasian plates boundary in northeast Asia. J. Geophys. Res. 81 (5), 921–930.

Chen, W.-P., Nábelek, J., 1988. Seismogenic strike-slip faulting and the development of the North China Basin. Tectonics 7 (5), 975–989.

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, 33–51.

DeMets, C., 1992. Oblique convergence and deformation along the Kuril and Japan trenches. J. Geophys. Res. 97, 17615–17625.

DeMets, C.R., Gordon, R.G., Argus, D.F., Stein, S., 1990. Current plate motions. Geophys. J. Int. 101, 425–478.

England, P., Wells, R.E., 1991. Neogene rotations and quasicontinuous deformation of the Pacific Northwest continental margin. Geology 19, 978–981.

Fitch, T.J., 1970. Earthquake mechanisms and island arc tectonics in the Indonesian–Philippine region. Bull. Seismol. Soc. Am. 60, 565–591.

Florensky, I.V., Trifonov, V.G., 1985, (19 A.V.85): Neotektonika i

vulkanism Vostochno-Kamchatskoy vulkanicheskoi zony. Geotectonika 4, 78–87 (in Russian).
Fournier, V., Jolivet, L., Huchon, P., Sergeyev, K.F., Oscorbin, L.S., 1994. Neogene strike-slip faulting in Sakhalin and Japan Sea. J. Geophys. Res. 99, 2701–2725.
Global digital elevation model (DEM) GTOPO30, http://edcdaac.usgs.gov/gtopo30/.
Goldfinger, C., La Verne, D., Yeats, R.S., McNeill, L., Hummon, C., 1997. Oblique strike-slip faulting of the central Cascadia submarine forearc. J. Geophys. Res. 102, 8217–8243.
Grachev, A.F., Demenitskaya, R.M., Karasik, A.M., 1970. The mid-Arctic ridge and its continental continuation. Geomorphology 1, 30–32.
Imaev, V.S., Imaeva, L.P., Kozmin, B.M., 1990. Aktivnye razlomy i seismichnost' severo-vostoka Yakutii. Ya F SO AN SSSR, Yakutsk. 138 pp. (in Russian).
Imaev, V.S., Imaeva, L.P., Kozmin, B.M., 2000. Seismotektonika Yakutii. GEOS, Moskva. 277 pp. (in Russian).
Istoriya razvitiya rel'efa Sibiri i Dal'nego Vostoka: Kamchatka, Kuril'skie i Komandorskie ostrova (1973). Nauka, Moskva. 438 pp. (in Russian).
Jarrard, R.D., 1986a. Relations among subduction parameters. Rev. Geophys. 24, 217–284.
Jarrard, R.D., 1986b. Terrane motion by strike-slip faulting of forearc slivers. Geology 14 (9), 780–783.
Kimura, G., 1986. Oblique subduction and collision: forearc tectonics of the Kuril arc. Geology 14, 404–407.
Kozhurin, A.I., 1988, The Kuril-Kamchatka island arc: neotectonic zoning, late Quaternary structure of Central Kamchatka, tectonic layering of the lithosphere in Central Kamchatka, some general features of the neotectonic structures of the circum-Pacific mobile belt. Neotektonika i sovremennaya geofinamika podvizhnykh poyasov. Nauka, Moskva, pp. 67–115 and 135–151 (in Russian).
Kozhurin, A.I., 1990. Recent strike-slip faults in the Kumroch range and Kamchatskiy peninsula area, eastern Kamchatka. Tikhookeanskaya Geologiya, vol. 6, pp. 45–55 (in Russian).
Kozhurin, A.I., Streltsov, M.I., 1995, Seismotectonic consequences of the May 28, 1995, Northern Sakhalin earthquake. FSSN Neftegorsk Special Issue, pp. 93–98.
Lander, A.V., Bukchin, B.G., Droznin, D.V., Kiryushin, A.V., 1994. The tectonic environment and source parameters of the Khailino (Koryakiya) earthquake of March 8, 1991: does a Beringia plate exist? Geodinamika i prognoz zemletriaseniy (Vychislitel'naya Seismologiya 26). Nauka, Moskow, pp. 103–117 (in Russian).
Mackey, K.G., Fujita, K., Gunbina, L.V., Kovalev, V.N., Imaev, V.S., Koz'min, B.M., Imaeva, L.P., 1997. Seismicity of the Bering Strait region: evidence for a Bering Block. Geology 25 (11), 979–982.
McCaffrey, R., 1992. Oblique plate convergence, slip vectors, and forearc deformation. J. Geophys. Res. 97, 8905–8915.
Plafker, G., Gilpin, L.M., Lahr, J.C., 1994. Neotectonic Map of Alaska. In: Plafker, G., Berg, H.C. (Eds.), The Geology of Alaska. Geological Society of America, Boulder, Colorado, Decade of North American Geology Volume G-1, 1 sheet, scale: 1:2,500,000.
Riegel, S.A., Fujita, K., Koz'min, B.M., Imaev, V.S., Cook, D.B., 1993. Extrusion tectonics of the Okhotsk plate, northeast Asia. Geophys. Res. Lett. 20 (7), 607–610.
Rogozhin, E.A., 1996. Focal mechanism of the Neftegorsk, Sakhalin, earthquake of May 27 (28), 1995. Geotectonics 30 (2), 124–130.
Rozhdestvensky, V.S., 1975. Strike-slip faults in northeastern Sakhalin. Geotectonics 9 (2), 116–121.
Rozhdestvensky, V.S., 1976. On strike-slip movements along the Tym'-Poronay fault in the Sakhalin Island. Doklady AN USSR 230 (3), 678–680 (in Russian).
Rozhdestvensky, V.S., 1982. The role of wrench-faults in the structure of Sakhalin. Geotectonics 16 (4), 323–332.
Shapiro, M.N., 1980. The Grechishkin overthrust on the shores of Kamchatka Gulf. Geotectonics 14 (3), 234–240.
Seno, T., Sakurai, T., 1996. Can the Okhotsk plate be discriminated from the North American plate? J. Geophys. Res. 101 (B5), 11305–11315.
Shimamoto, T., Watanabe, M., Suzuki, Y., Kozhurin, A.I., Streltsov, M.I., Rogozhin, E.A., 1996. Surface faults and damage associated with the 1995 Neftegorsk earthquake. J. Geol. Soc. Japan 102 (10), 894–907.
Smirnov, V.N., 1988. Neotectonics and seismology of strong earthquake epicentral areas in Okhotsk-Kolyma region. Abstracts for the Seminar "Physics of Earthquake Prediction and Rock Failures". Inst. of the Earth's Crust USSR Acad. of Sci, Irkutsk, pp. 20–21 (in Russian).
Smirnov, V.N., 1989. Active faults of the Kolyma Highland. Abstracts of the All-Union Seminar "Active Faulting- Methods of Study, Hydrology, Kinematics and Application for Geodynamics". Moscow-Irkutsk (in Russian).
Smirnov, V.N., Vazhenin, B.P., 1985. Earthquake-generated relief in the Tumansky Range (northern Okhotsk Sea margin). Abstracts for the 5th Scientific Session of the Far East Branch of the MSSSS. IMGG, Yuzhno-Sakhalinsk, pp. 56–67 (in Russian).
Streltsov, M.I., Rozhdestvensky, V.S., 1995. Active faults of the Kuril-Okhotsk region, Sakhalin, Far East and near-Amur region. In: Seismichnost′ i seismicheskoe raionirovanie Severnoi Evrasii 2–3. OIFZ RAN, Moscow, pp. 387–407 (in Russian).
Tectonic map of the Sea of Okhotsk region, Scale 1:2 500 000, 2000. Bogdanov, N.A., Khain, V.E. (Eds.), Kartografiya. Moskva.
Tsutsumi, H., Kozhurin, A.I., Strel'tsov, M.I., Ueki, T., Suzuki, Y., Watanabe, M., 2000. Active faults and paleoseismology in northeastern Sakhalin. J. Geogr. 109 (2), 294–301 (in Japanese, with Engkish abstract).
Wu, F.T., Zhang, Y., Fang, Z., Zhang, S., 1981. On the activity of the Tancheng-Lujiang fault zone in China. Seismol. Geol. 3 (4), 15–26.