Tectonic position of the Khailino and Olyutorka earthquakes

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[1] The continent-ocean transition zone has various exogenous and endogenous processes that reflect the geodynamic ecological function of lithosphere. The East Kamchatka suffers the earthquakes with MSK-64 over 9 points. Petropavlovsk-Kamchatsky is in zone of 9.5 points. The area of strong earthquakes included the Hailinskoye (1991) the Olyotorskoye (2006) events with both magnitudes 7.1 that caused the area broadening. We suggest their tectonic position valuation in the block-mass-key (a piano-like) structure in the earth crust in concept of the continent active margin. This structure was formed by the system of the northwestern (320–330°) lateral deep faults. They are located logically and cross Kamchatka, Okhotskoye sea, Okhotsko-Chukotskiy volcanogenic belt and appear on the continent as linear (45°) faults. In Koryak-Kamchatkan region they appear each 75–160 km. They are between-blocks and stretch to the northwest for hundred of kilometers, divide the crust into blocks with vertical movements in different directions and have rather mobile southeastern ends in a transition zone between an ocean and a continent. Peninsulas represent the rising ends of blocks and the coastal gulfs represent the lowering ends of blocks. The scheme was determined from the south Japan to cape Dezhnyov. The both earthquakes occurred in the Vyvenka river-valley. Its northern valley side is a part of the Vyvenskiy deep northeastern fault and it is 12–20 km wide. The river-valley is represented by a depression. Its depth on a surface of Upper-Cretaceous basal complex is 3 km and in the Crystal basal complex comprises over 10 km. The length of the depression increases with the depth! The depression is located in the central part of a lowering block within Olyutorskiy gulf and is divided by lateral between-block faults: Paren'-Talovsko-Tilichkisky and Omolon-Kamensko-Olyutorsky. Along with the Vyvenskiy fault they "cut" from a mobile end of margin crust a "key" and that "key" splits off from the continent and "slides" into the ocean. Such a mechanism explains the earthquakes on the rest part of Chukotsky belt and supposes that the southeastern part of Koryakskiy highland may suffer the evolution of seismicity. It explains the presence also the gaps and zones of strong earthquakes for the Kurile-Kamchatkan island arc. They meet the width of a distance between the linear between-block faults. The zones of the major earthquakes and aftershocks near Kronotsky and Ozyorny peninsulas, Kunashir, Iturup and south Hokkaido islands justify this statement. *INDEX TERMS:* 1734 History of Geophysics: Seismology; 1744 History of Geophysics: Tectonophysics; 3040 Marine Geology and Geophysics: Plate tectonics; 7215 Seismology: Earthquake source observations; *KEYWORDS:* seismisity, tectonics, continental crust, Chukchi seismic belt.

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Introduction

[2] The southwestern Koryak Highland is characterized as a whole by relatively low seismic activity, which prohibits the linkage of the southwestern Chukchi seismic belt to seis-

mically active areas of Northeast Asia. However, the Koryak (1988), Khailino (8 March 1991) and Olyutorka (20 March 2006) earthquakes were recorded there. They permit the assessment of tectonic position of both deep structures' seismicity in the area and, probably, seismic activity of the Chukchi belt portion from the Dezhnev Cape to Kamchatka isthmus (60°N), as the area of interaction between the continent and hypothetical Bering Plate.

Geomorphologic Position of the Khailino and Olyutorka Earthquakes

[3] Foreshocks and aftershocks of the earthquakes occurred in the southwestern offsets of the Koryak Highland ranges that surround the Vyvenki River valley (description according to plane-table map of scale 1:500,000 "General Staff. Tilichiki", R-58-V, G (1977) and "General Staff. Pakhachi", R-59-V, G (1989).

[4] Distribution area of the earthquakes including their foreshocks and aftershocks forms a distinct rectangle extending from the Vetrovayam River in northeastward direction (50°) at 182 km to the Vakhavnitvayam River. The rectangle is slightly deformed being 74 km wide in the southwest and 66 km wide in the northeast. Its northern boundary begins from the Vetrovayam River (734 m a.s.l.) and passes along the major watershed of the highland to the Lyapganaivayam River (486 m a.s.l.). The northeastern boundary of the rectangle extends southeastward from the Lyapganaivayam River, through the Mt. Dvoinaya (1007 m a.s.l.) in the Vetvistaya River head to the point 345 m a.s.l. in the upper reaches of the Malyi Iyavyam River. The southern boundary of the rectangle stretches southwestward from the point 345 m a.s.l. through the Yavukuvayam River mouth (right tributary of the Pylgovayam River), approximately through Mts. Amva (689 m a.s.l.), Gainaluea (426 m a.s.l.), Olapail' (642 m a.s.l.) and terminates near the Village Olyutorka (the listed mounts are located about 3–5 km north of the boundary). The western boundary of the rectangle passes northwestward from the Olyutorka Village through the Village Korfovskaya MRS to the point 734 m a.s.l. nearby the Vetrovayam River head.

[5] The rectangle of the earthquake area is associated with three longitudinal orographic stripes. The northwestern one is represented by the Iygtyla, Ivtyl'avachum, and Seinav-Tunup mountains; south of the ranges occurs the Vyvenki River valley of width ranging from 20 km in the southwestern portion to 5–7 km in the northeastern part; the southeastern stripe is formed by the system of parallel ranges. These are the mounts Akhtynyn, Mamigai and the Ostantsovyi, Khai-Khokyn, and Maini-Kokyin ranges that are separated by the Av'yavayam and Tyltovayam narrow river valleys from the Ivtygin Range, the southernmost stripe of the Tilichin Ranges. The southern ranges are broken in the central part, opposite to the Vyvenki River valley, by stream valleys of the Egilvayam basin. The latters merge with the Vyvenki River valley widening it up to 32–35 km and form a rectangular lowland 32–35×45 km in size.

[6] The rectangle of the Khailino and Olyutorka earthquakes swarm is distinctly subdivided into five equal areas of northwestern extension, according to the shock clusters. The southwesternmost area, 44 km wide, occurs between the Vetrovayam River and the Tapel'vayam River low reaches. Its eastern boundary is traced to the Kultushnaya River head and further in the Govena Peninsula to Mt. Ustanap (1157 m a.s.l.). In the northwest it is traced to Mt. Ekynynai (822 m a.s.l.). The center of the area is the Village Vetvei in the Vetvei River mouth (right tributary of the Vyvenki River). The Village Tilichiki occurs in the southwestern angle of the area, which is given the corresponding name.

[7] Next in northeastward direction area has the eastern boundary along the Ogiranvayam River head (1132 m a.s.l.), western shore of the Nayuyu-Gytkhyn Lake, and is traced to the southwestern shore of the Potat-Gytkhyn Lake in the Govena Peninsula. Its center is the Village Khailino. It is named the Khailino area.

[8] Northeast of the latter the third, Uvalistaya area with the Uvalistye Mts. in the center, is located. Back of it the Inochvivayam area occurs, which gets its name from the Inochivivayam River. Finally the fifth area is situated in the basins of the Ayaonyvayam, Vakhavnitvayam, Vocheivayam, and Vulvyyakuyul rivers and is named the Vulvyyakuyul area. It is characterized by a single aftershock.

Position of the Khailino and Olyutorka Earthquakes Area in the General scheme of Tectonic Subdivision of the Southwestern Koryak Highland

[9] The discussed territory belongs to the Koryak-Kamchatka fold area located in northwestern segment of the Pacific mobile belt. The extreme northwestern part of the territory occurs in the Late Cretaceous Koryak tectonic zone (Koryak autochthon); further southeastwards it is associated successively with the Late Cretaceous Vyvenki uplift, Neogene–Quaternary Vyvenki depression, Paleogene–Neogene Tylgovayam synclinorium with local Tylgovayam and Korf depressions, and with the narrow northern stripe of the Pylgovayam anticlinorium [*Kravchenko and Razumnyi,* 2002; *Kravchenko et al.* 2000; *Litvinov,* 1999].

Characteristics of the Khailino and Olyutorka Earthquakes Swarm by Areas

[10] The common epicenter area of both earthquakes has well-defined boundaries. It is characterized by longitudinal zoning of the epicenters as revealed in five areas of northwestern extension. Among the most distinctly manifested are the northeastern swarm of the Olyutorka earthquake (182 km) and the transverse swarm of the Khailino earthquake (82 km). The former is distinctly subdivided into southern and northern halves, as is most evident in the Tilichiki area. In this area only shocks of the Olyu-

torka earthquake were recorded. The time period of 19–25 April 2006 was marked by the main shock and aftershocks ($M_b = 6.2$) in the stripe extending from the Village Tilichiki northeastwards (51°) up to 169°E. From 25 April to 15 May 2006, a series of aftershocks were clustered in 5–15 events in narrow stripes of northwestern extension (about 300°), the same as the entire area. Aftershocks of the Khailino earthquake are missing in the area.

[11] The Khailino area was completely covered by foreshocks, main shock and aftershocks of the Khailino earthquake. According to [*Lander et al.,* 1991], the common swarm, or the seismic focus zone extends northwestward (about 312–315°). The foci of the Khailino and Olyutorka earthquakes are commonly overlapped, which underlines their clustering and northwestward extension of seismic focuses. The Olyutorka earthquake event with $M_b = 6.2$ happened 55 km southeast of the Khailino Village, at the southeastward extension of the area to the Doubt Bay.

[12] The Uvalistaya area is characterized exclusively by epicenters of Olyutorka earthquake with the event of $M_w = 7.6$ east of the Nayuyu-Gykhtyn Lake.

[13] Epicenters of the Olyutorka earthquake with the event of $M_b = 5.8$ and one epicenter of the Khailino earthquake are recorded in the Inochvivayam area.

[14] The Vulvyyakuyul area is characterized by a single epicenter of the Olyutorka earthquake.

Estimation of Tectonic Position of the Khailino and Olyutorka Earthquakes

[15] The total epicenter area of both earthquakes represents the rectangle of northeastward extension as described above. It is mainly associated with riverheads of the Vyvenki River right tributaries within the Navkyrvayam and Ogiranvayam nappes of the Vyvenki uplift. The area is bounded on the north by the Vyvenki-Vatyn deep fault in its length between the Vetrovayam and Levtyrinvayam (Latyrinavayam) Rivers and the thrust faults that extend it northeastwards. On the southeast the uplift is bounded by the Vyvenki deep fault covered with soft deposits of the Vyvenki River valley [*Kravchenko et al.* 2000]. The central longitudinal axis of the common epicenter area is associated with that of the Vyvenki riftogenic depression manifested on the surface as the Vyvenki River valley. The southern half of the common epicenter area coincides with the Khailino graben filled with the Miocene coal-bearing molasse that begins at the Tapelvayam River mouth (right tributary of the Vyvenki River) on the southwest and extends to the Inibuvayam River (left tributary of the Tylgovayam River) on the southeast. The graben is bounded on the southeast by the fault of the Tapelvayam River of northwestward direction that is traced southeastward to the Govena Peninsula for the length of the Panetivayam River. The southern part of the Khailino graben is represented by marine molasse and is framed by riftogenic structures of the Tylgovayam depression [*Kravchenko and Razumnyi,* 2002].

[16] The Khailino earthquake happened 10 km east of the Khailino Village. It was preceded by 4 foreshocks and accompanied by 62 aftershocks. One and a half month after the main shock, the southwestward aftershocks associated with the southwestern wedge-out of the Tylgovayam riftogenic depression, increased. Different estimates of the focal depth [*Lander et al.,* 1991] range from 13 to 35–50 km, indicating likely crustal or transcrustal foci.

[17] The common swarm, i.e. the Khailino and Olyutorka earthquakes rectangle measures 182×6–8 km. It completely fits in with outlines of depressions recognized in the Vyvenki River valley according to MTZ records [*Moroz,* 1987]. The depression of the basement top along the 10-km isohypse is approximately superposed onto area between the Vetvei River mouth, Mt. Maini-Nayuyu, and the Nayuyu-Gytkhym Lake. It is just at the northern boundary of the basement 10-km isopach that the Vyvenki River channel discordantly changes its direction from southwestern to southeastern over a length of about 10 km and then again turns southwestward. The comparison of the earthquake clusters with the geologic map shows that northeastern boundaries of the areas are defined by transverse northwestern disturbances underlined by the channels of low reaches of the rivers Vetrovayam, Tapelvayam, Khatapvayam (extending at 85 km northwestward to the Unnaivayam River channel), Atalavayam (extending at 45 km northwestward to the Ev'einvayam River channel), and by the southeastward extension of the Enychavayam River channel. These disturbances are recorded in the Koryak flyschoid zone extending at 32–55 km northwestward (310°) from the boundary of the common swarm.

[18] The maximum depth of the Upper Cretaceous basement reaches 3 km and the 3-km isopach is associated with the Khailino earthquake area.

Keyboard Block Structure of the Earth's Crust

[19] The tectonic position of the common earthquake swarm can be revealed in the context of the keyboard block structure of the Earth's crust in active continental margins [*Yarotskii,* 1974, 1976, 2000]. The structure was formed by the system of transregional northwestern deep faults, transverse in relation to longitudinal regional structures of the region. The faults divide the crust into transcrustal blocks that embrace all three layers. They cut the continental margin from the Pacific coast across land and Sea of Okhotsk and grade into the system of longitudinal dislocations in Mesozoic structures of the Kolyma region. At the southeastern termination the blocks are in tense tectonic regime provided by processes in the continent-ocean transition zone. Certain blocks are in the state of emergence and are manifested in the shoreline configuration as peninsulas, others undergo subsidence (or slow emergence) and are represented by the bays. In transverse section the emerging blocks show up as deep wedges; the submerging, as deep trapeziums. Within the emerging blocks the granite metamorphic layer is presumably decreased with the overwhelming thickness of the basaltic one; in the downfaulted blocks the increased thick-

ness of the granite metamorphic layer is inferred. This conclusion is favored by emerging blocks of the southeastern Kamchatka capes, the Shipunskii, Kronotskii, Kamchatskii Mys, and Ozernyi Peninsulas, and complex of the Il'pinskii, Il'pyrskii, and Govena Peninsulas, which surface is mainly composed of basalts or andesite-basalts with portions of intermediate and acidic volcanites and which are characterized by carbonated ground water. The subsiding blocks are represented by the southeastern Kamchatka bays, Avachinskii and Kronotskii Gulfs, and by the southwestern Litke Strait; liparites, dacites, and rhyolites are mainly distributed on their surface. One further peculiarity of subsided blocks is the occurrence of manganese in geologic complexes of the Avachinskii and Kamchatskii Gulfs, Litke Strait, and in southeastern Koryak bays (Opukhi Bay), as well as the widespread nitric ground waters [*Yarotskii,* 2000].

[20] In the scheme of the keyboard block structure the discussed territory of the Khailino and Olyutorka earthquakes is associated with the subsiding block of the Olyutorskii Bay. The block is bounded in the southwest by the Paren'-Talov-Tilichiki transverse interblock fault; in the northeast, by the Omolon-Kamensk-Olyutorka fault. The area of the common earthquakes swarm is cut by the fault zone directed from the northwest along the Vetrovayam River through the Village Tilichiki and Skobeleva Harbor towards the southeastern coast of the Govena Peninsula. In the northeastern part of the block the fault goes from the Kamenskoe Village along the Belaya River, across the low reaches of the Naivalvayam River to the confluence of the Vyvenki River with the tributaries Vakhavinitapvayam and Irochivivayam Rivers. Between these faults the Tilichiki, Khailino, Uvalistaya, and Inochvivayam areas occur. The fifth area characterized by one aftershock is located outside the zone of the Omolon-Kamensk-Olyutorka fault, northeastward of it, in the adjacent emerged block of the Olyutorskii Peninsula. It is marked by lifted up margins of the blocks that show subvertical movements in different directions.

[21] The above-cited MTZ records [*Moroz,* 1987] on deep depressions at the top of the Upper Cretaceous basement within the riftogenic Vyvenki depression, provided the estimate of deep structures in the southeast of the Olyutorskii Bay block. It should be noted that the extent of the Vyvenki depression along the 6-km isopach (long axis) is four times greater than its length at the Upper Cretaceous top, i.e. the depression is widened with depth along both axes. This is just the evidence for trapezium-like deep transverse section of the subsiding block of the Olyutorskii Bay.

[22] The generation of transverse interblock faults was synchronous with initiation of the planetary regmatic net. The continental margin of the western Pacific mobile belt and the southern Cordilleras in the east are characterized by the presence of diagonal jointing net with the longitudinal northeastward and transverse northwestward directions. The distance between interblock faults is determined by the thickness of a deformed body with its extension [*Shafranovskii and Plotnikov,* 1975]. There is evidence that the Koryak continental margin was formed under stretching conditions. Maximum distances occur on relaxation of geodynamic stress at the boundaries of blocks with thick granite metamorphic layer, since there, according to the keyboard block concept, the greatest crust thickness is inferred, as observed in blocks of the southeastern Kamchatka bays, Avachinskii and Kronotskii Gulfs, southwestern Litke Strait, and Olyutorskii Bay. On relaxation of mechanical stress the faults are generated in all crustal layers of ultimate size, i.e. in structures of localized ideal homogeneous solid material; that is, the systems of transverse dislocations arise, similar to the deep ones but at shorter distances. In the discussed region, in upper structural storeys this system was recorded at the adjacent, west of the Olyutorskii Bay, emerging block of the Il'pinskii, Il'pyrskii, and Govena Peninsulas; it is manifested in the form of northwestern linear stripes of alternating various-amplitude blocks, i.e. local horsts and grabens. The stripes 15–20 km wide are oriented northwest (310–330°) and extend for tens of kilometers. On the adjacent territory southeast of the Khailino and Olyutorka earthquakes swarm, in the Machevna-Anivayam interfluve basin these structures are recorded as a series of linear intrusions stretched northwestward (310–315°). The analogous system of intracrustal faults shown up on the surface also occurs in the Vyvenki River valley in the form of faults separating five areas of the earthquakes epicenter clusters. These are the faults of the Vetvei, Levtyrinyvayam, Ogiranvayam, Navkyrvayam, Kailinovayam, and Maini-Lulovayam River valleys. They are followed on both sides of the Vyvenki River valley for tens of kilometers and some of them are traced by the river network, alteration of geologic complexes, and geophysical fields, and further in the adjacent structural-and-formational zones.

[23] Considering the position of the Khailino and Olyutorka earthquakes' common area in the keyboard block structure of the crust we should note that the northwestern faults of different depth represent planes of horizontal movements of adjacent blocks, which indicates their young age. However, they occurred at least from the Jurassic, so they are renewed and are active up to the present. There is evidence of probable horizontal shifting of adjacent blocks. For instance, the Vyvenki deep fault structure that plays a role of sutural zone, changed its extension from submeridional (40°) in the Anapka River valley to that of 60° in the Vetrovayam-Vetvei interfluve, in the area of the Vyvenki, Vakhavnitvayam, and Inochvivayam rivers confluence. The axis of the Koryak Range is shifted in the Vetrovayam-Vetvei interfluve. Examples of this sort, manifested in gravimetric and magnetic fields, in geomorphology and geology in the southwestern Koryak Highland, are quite common.

[24] The subsiding keyboard block of the Olyutorskii Bay in the active continental margin evidently tends to slip down to the ocean. At the boundary of the zone that corresponds to the Vyvenki deep fault depression representing an axis zone of both earthquakes' area, there arises a possibility of overhanging the oceanic bottom by the block's front in the form of four local blocks defined by peculiarities of Khailino and Olyutorka earthquakes clusters. The fifth block belongs to the adjacent emerging block of the Olyutorskii Peninsula and can be considered as a lifted up portion of two contiguous blocks. The weakest point at the block's termination is the Khailino block area, which is associated with the greatest troughs in the Upper Cretaceous and crystalline basements. It is precisely the area characterized by destruc-

tive earthquakes with densely concentrated foreshocks and aftershocks of both earthquakes.

[25] The proposed model of earthquake generation in the Vyvenki River basin at a distance of 65–90 km from the Bering Sea shore agrees with a tense fault tectonic regime in the continent-ocean transition zone of the Earth's crust. Major structural directions of seismic events are represented there by northeastern and northwestern plans. The northeastern plan is representative of the Earth's crust building up process at the active continental margin, with about 31-km-thick crust and relatively thick granite metamorphic layer. The northwestern plan is reflected in deep transverse dislocations that form the keyboard block of the Earth's crust as a whole [*Yarotskii,* 1976, 2000] and local keyboard blocks (as defined by [*Lobkovskii,* 1988]) of its upper storeys. The depth of the keyboard block base can be inferred from the depth of the Khailino earthquake [*Lander et al.,* 1991]. According to some estimates, it is 17 km, i.e. an intracrustal depth of decoupling of local keyboard blocks; according to another assessment, it constitutes 25–50 km, that is a transcrustal depth of spalling away of the whole subsiding Olyutorskii Bay block. The small depth (4 km) of the Olyutorka earthquake indicates its association with local keyboard blocks. The earthquake occurred in the region, adjacent on the west to the Khailino area that is characterized by the maximum downwarping of the Upper Cretaceous and crystalline basements.

[26] The earthquakes' initiation scheme inferred from the occurrence of keyboard blocks at the continental margin, was proposed in 1988 [*Lobkovskii,* 1988] and illuminates the generation of transverse epicenter areas of the Khailino and similar earthquakes. However, this scheme should be supplemented with the mechanism of participation in preparation and in the event, as such, of not single keyboard block but of several ones. This is apparent from the discussed tectonically related position of the Khailino and Olyutorka earthquakes' five epicenter areas considered as blocks. The scheme is also supplemented by the author's concept on keyboard block structure of the Earth's crust, which was formulated and developed since 1974 [*Yarotskii,* 1974, 1976, 2000]. On the other hand, the conception by [*Lobkovskii,* 1988] is a particular verification of our concept and their synthesis will provide the better insight into further events in the southwestern Chukchi seismic belt.

[27] The general conclusion of this paper is that the northeastern extension of the Khailino and Olyutorka earthquakes area marks the edge of the continent from which the key of the Olyutorskii Bay subsiding block is breaking off. The decoupling block includes local keys, namely, the blocks of northwestern extension that slide over intracrustal planes at the subsiding block margin. It is possible that sliding of the whole block is characterized by subcrustal earthquakes and that of its keyboard blocks, by the earthquakes in superficial thrust sheets. The development of observation network in the southwestern Koryak Highland will produce the evolving of more perfect models of intracontinental earthquakes.

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