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Beringia: Seismic Hazard and Fundamental Problems of Geotectonics

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Abstract—A brief review of the modern views concerning the geodynamics of Bering Plate is presented. The discussion covers the spatial distribution of seismicity in the Kamchatka-Aleutian-Alaskan region, the manifestations of tsunami, the active faults in the margins of the Komandor Basin known to date, the position of the collisional contact between the Kamchatka and Aleutian arcs, the probability of a catastrophic earthquake occuring on the western termination of the Aleutian arc, and the seismo- and tsunamigenic potential of Bering Plate.

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INTRODUCTION

The Bering Sea region is unique in terms of its tectonic position. It is limited by the Aleutian Islands in the south; the Alaskan coast forms its eastern boundary; Kamchatka, Koryakia, and Chukchi Peninsula border this region in the north and west. The region has long been an object of study by both Russian and American scientists; however, due to the geographical remoteness of this region and short history of instrumental geophysical and geodetic observations, there are still blind spots in the knowledge of this region. The seismic and tsunamigenic potential of the region is barely known. A series of questions regarding the character of junction between the Kuril-Kamchatka and Aleutian arcs at the southern boundary of the region and the strain regime of its western and northern continental framings still remain unclear. According to the present-day understanding, most of the territory of the region is occupied by the Bering Plate, which is located at the junction between the Pacific, North American, and Eurasian plates; however, as of now, not only the positions of its boundaries are uncertain but also its very existence is challenged. The present review summarizes the key modern views of the Beringian seismology and tectonics. We will also discuss the main problems whose solution appears to be vital both scientifically and from the standpoint of seismic and tsunami hazard assessment in the region.

THE SPATIAL DISTRIBUTION OF SEISMICITY IN THE REGION

Along its entire perimeter, the Bering Sea region is surrounded by seismic belts (Fig. 1). In the north, west, and south, earthquakes occur both on land and off the shore; the eastern (Alaskan) coast is almost aseismic. It is typically believed that the Bering Sea is completely accommodated within the rigid lithospheric Bering Plate (Lander et al., 1994; Cross and Freymueller, 2008; Mackey et al., 1997), and the seismicity is associated with the motions on its boundaries. However, two earthquakes with the magnitude of 6.5–6.7 with short aftershock series were detected during the past two decades in the central part of the Bering Sea. The region of these quakes is remote from all seismic networks and the recorded data are probably incomplete. Therefore, it is still unclear whether these earthquakes are parts of yet another seismic belt dividing the Bering Plate or they are isolated intraplate events. The earthquake epicenters located in the central Komandor Basin were identified based on the data from the early period of observations; they correspond to low magnitudes and are likely to fall in this region due to the observation errors.

The earthquakes in the western margin of the Bering Sea form the Koryak seismic belt stretching northwards from the junction between the Kuril-Kamchatka and Aleutian arcs and joining the Chukchi and Alaska seismic belts. The epicenters of most earthquakes in the southern part of the Koryak seismic belt are located on the eastern Kamchatka shelf; however, a few relatively strong events probably including the

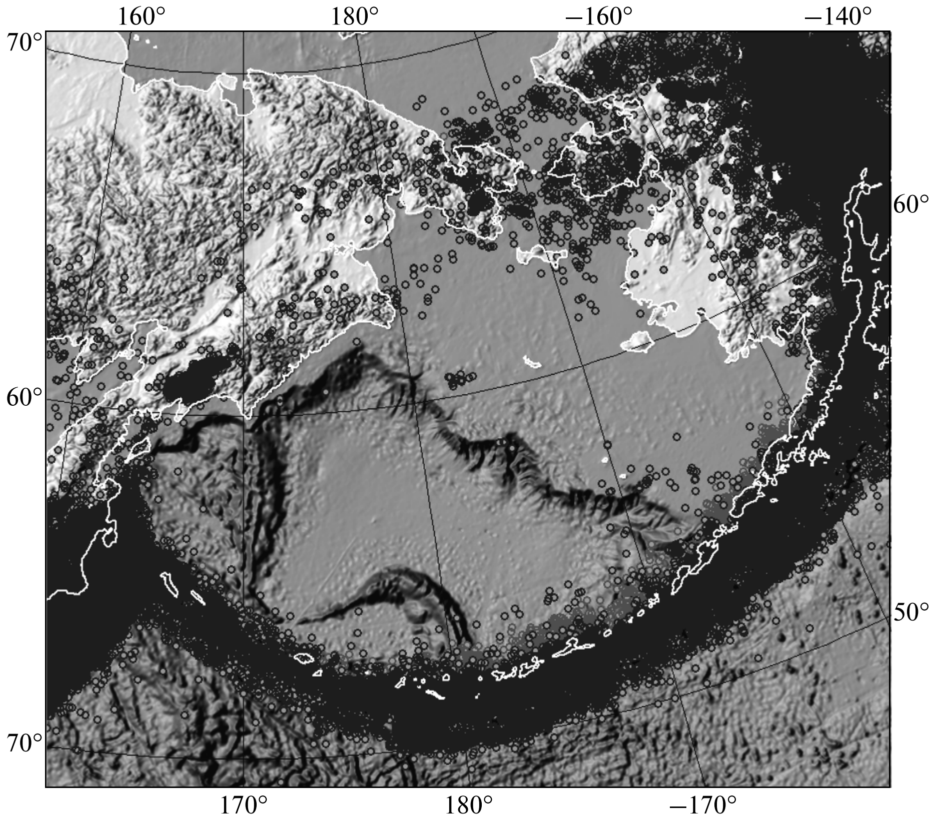

Fig. 1. The earthquakes in the Bering Sea region recorded during the period of 1962–2010, based on (*Kamchatka...* ; *Zemletryaseniya...*; *Alaska...*; *USGS...*; *Global...*,).

strongest Ozernovskoe earthquake of 1969 with $M = 7.8$ occurred at the base of the Kamchatka continental slope. Northwards, the seismicity of the Koryak belt is mainly concentrated on land, in the central parts of the Koryak Upland. However, several earthquakes are reported for the sea region off the Koryakia coast.

Most of the strong earthquakes in the region occur in the Aleutian arc, one of the most seismically active structures of the Earth. Tsunamigenic earthquakes with $M \geq 9$ have been recorded there. The events in the Aleutian arc can be spatially subdivided into two groups. The first group includes the events occurring at the subduction boundary of the Pacific Plate which passes into the transform boundary. It is this zone that accommodates the strongest events, whose epicenters are located in the Pacific Ocean; however, their large sources can partially extend beneath the Bering Sea at a depth of ~50 km. The second group includes the back-arc events with shallow-focus hypocenters in the Bering Sea. This seismicity is likely to be related to the transform displacements of the arc blocks along the strike of the arc (Lallemant and Oldow, 2000; Cross and Freymueller, 2008) by mostly strike-slip mechanisms. The magnitudes of the events recorded here reach 7.5. This group of the back-arc earthquakes also formally includes a few large events of the first half of the 20th century, which have even higher magnitudes (up to $M = 7.9$) but low hypocenter location accuracy (Gutenberg and Richter, 1949). It cannot be ruled out that these earthquakes have actually occurred in the subduction zone.

A small group of the earthquakes clustered at the junction zone between the Aleutian arc and Kamchatka has a distinct character. These events are related to the face collision between the Kamchatka and the westernmost segment of the arc—the Komandor Block (Gordeev et al., 2004, 2006; Geist and Scholl, 1994; Mackey et al., 2010). The seismicity of the Kamchatsky Peninsula has certain distinctions from either of the adjacent seismofocal zones and can be attributed to neither of them. In the region of the Kamchatka Peninsula, most earthquakes are shallow-focus and confined to the uppermost 50-km layer. The earthquakes in the Kamchatka Strait mainly cluster along the Bering, Pikezh, and Steller transform faults (Seliverstov, 2009). Westwards, at the transition to the Kamchatka shelf, this regularity is broken and the epicenters of the earthquakes occupy the entire frontal part of the Komandor block between its bordering faults and extend to the southern segment of the peninsula. The focal mechanisms of the Kamchatka earthquakes are dominated by reverse faults with the subhorizontal NW–SE compression axis (*Global CMT Catalog*).

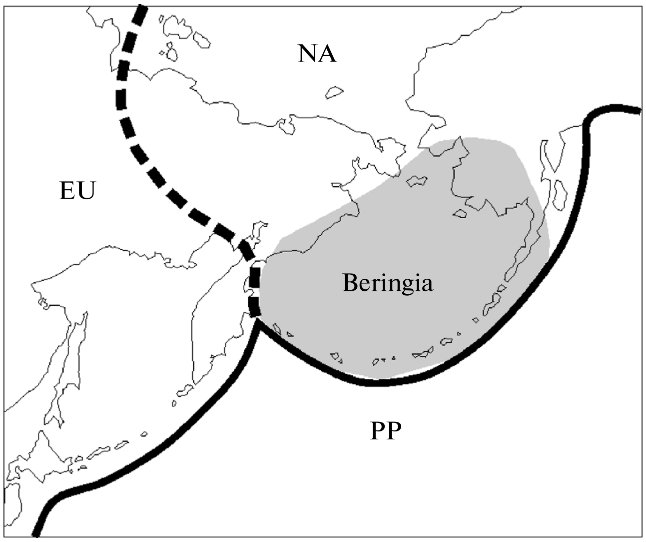

Fig. 2. Plate boundaries: PP, Pacific Plate; NA, North American; EU, Eurasian. The solid black lines denote the established boundaries; the dashed lines, the supposed boundaries. The position of the Bering microplate is marked in gray.

BERING LITHOSPHERIC PLATE

The existence of the Bering Plate has been debated up to the present (Lander et al., 1994; Kozhurin, 2012; Geist and Scholl, 1994). The key problem lies in the fact that Beringia is a loosely defined plate that does not have geologically clearly pronounced boundaries with the North American and Eurasian plates. Due to this, up to the present day, many researchers have considered the Bering Plate as part of the North American Plate (Fig. 2). It is supposed in (Scholl, 2007; Redfield et al., 2007) that the Bering Plate consists of quite a few independent blocks moving together in a common flow, which is driven by the extrusive squeezing of the rock masses of Alaska and Beringia material westwards or southwestwards. Although the existence of these blocks has not yet been proven, their motions relative to the North American Plate can be roughly described by a single rotation vector which, to a first approximation, can be considered as the rotation vector of the Bering Plate.

The motion parameters of the Bering Plate are still disputable. Their estimates are mainly based on two types of the data, namely, the focal mechanisms of the earthquakes and geodetic (GPS) measurements (Gordeev et al., 2001a, 2001b), which often contradict each other.

The rotation of Beringia as a whole can only account for the focal mechanisms of the earthquakes that occurred at the northern continental boundary of this plate. The relative displacement vectors on the southern (Aleutian) boundary are determined by the rapid motions of the Pacific Plate, and their directions barely change between different models of the slow rotation of the Bering Plate. In other words, within their accuracy, the focal mechanisms of the Aleutian earthquakes do not carry significant information on the Bering Plate motion. The main conclusions concerning the rotation of this plate follow from the regular changes in the focal mechanisms along the northwestern plate boundary: compression in southern Koryakia is changed by shearing in the Chukchi Peninsula and extension in northwestern Alaska (Fig. 3). This distribution of the focal mechanisms is consistent with the rotation of the Bering Plate relative to the North American Plate around the pole located northwest of their boundary. A more exact location of the pole can be obtained if we assume that the Bering Plate slides past the eastern segment of the Aleutian arc without displacing the subduction zone located in this zone (Fig. 3). It should be noted that the Beringian boundaries within Alaska still remains highly uncertain: in the configuration shown in Fig. 3, it runs transversely to the largest active strike-slip faults in Alaska (for example, across the Denali Fault).

GPS measurements in the region are complicated by the fact that almost all the Beringia regions located above sea level pertain to the tectonically unstable boundary zones of diffuse seismicity. Therefore, the local geodetic measurements could be highly sensitive to the motions of small blocks that are misaligned with the general plate motion. Nevertheless, the geodetic data obtained in northwestern Alaska (Cross and Freymueller, 2008) confirm the southward motion of this part of Beringia. However, for locating the pole of the Bering Plate rotation relative to the North American Plate, these authors also used the GPS measurements in Alaska, which are probably distorted by the deformations of the hanging wall of the subduction zone. As a result, the obtained rotation pole falls in the Amur Region, and the motion parameters contradict the focal mechanisms of the earthquakes in Koryakia. Due to this, the estimates of the Beringia rotation based on the GPS measurements cannot be regarded as acceptable as of now.

The northern boundary of the Bering Plate is drawn along the Koryak seismic belt (Lander et al., 1994; Mackey, 2010). A wide band of rare (disregarding the aftershocks) diffuse seismicity covers nearly the entire Koryak Upland continuing farther northwards across the Anadyr Bay and Chukchi Peninsula to Alaska, and southwards, along the Kamchatka shelf zone to the junction between Kamchatka and Aleutian arc. The great majority of the earthquakes in the belt occur within the continental margin and adjacent shelf. Only a few reliably determined epicenters of the earthquakes in the Koryak seismic belt are located within the oceanic basins of the Bering Sea.

TSUNAMI IN THE BERING SEA

Until recently it was believed that strong earthquakes and tsunamis are improbable in the Bering Sea. However, the events of November 12, 1969 (Ozernovskoe earthquake with $M = 7.8$) and April 21 (22),

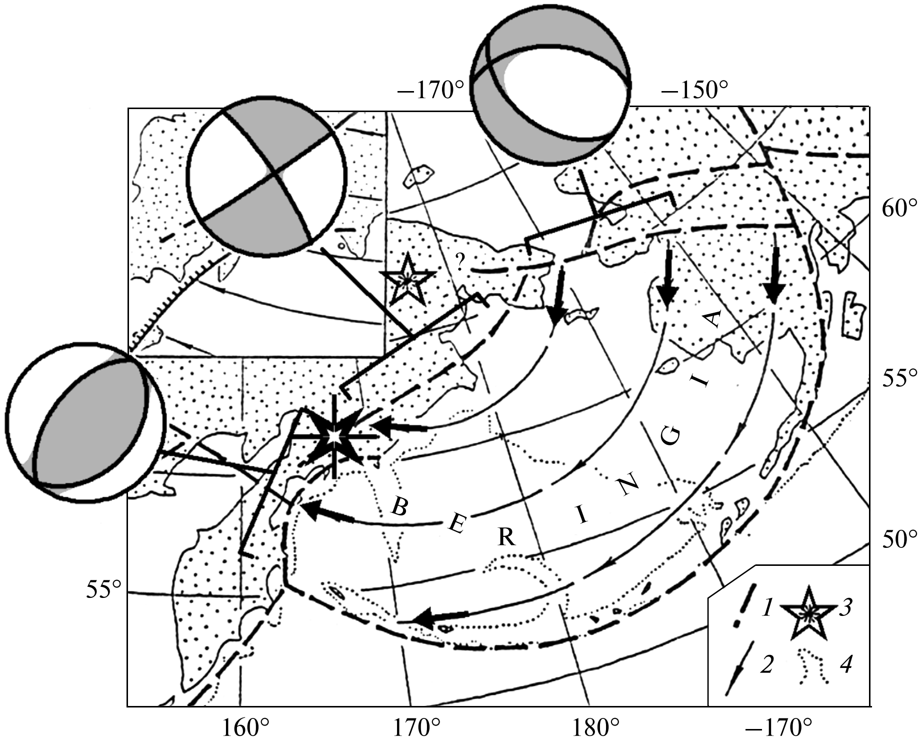

Fig. 3. The model of the Bering Plate rotation relative to the North American Plate, based on the focal mechanisms of the earthquakes, after (Lander et al., 1994). The rotation pole (gray star) is located at 67° N, 176° E; rotation velocity in not defined. The average focal mechanisms of the earthquakes demonstrate the gradual change of tectonic conditions on the northwestern boundary of the Bering Plate: from compression in southern Koryakia to shear in Chukotka, and extension in northwestern Alaska. The black star indicates the epicenter of the 2006 Olyutorskoe earthquake.

2006 (Olyutorskoe earthquake with $M = 7.6$) forced the scientific community to revise their ideas concerning the seismogenic and tsunamigenic potential of the region. At present, the possibility of tsunamigenic earthquakes in the Bering Sea region is not challenged; however, the exact locations of their sources are still unclear. Since the historical tsunami data are almost absent, the only way to solve this problem is to explore the tsunami deposits.

During the studies conducted since 1999, we reconstructed the parameters of a single historical tsunami of 1969 in a large coastal zone from the Kamchatka Peninsula and Bering Island in the south to Uka Bay and Karaginskii Island in the north (Martin et al., 2008; Pinegina and Kozhurin, 2011; Pinegina et al., 2013; Pinegina, 2014). Thus, we obtained the parameters of the tsunami height distribution along the entire coast affected by the tsunami waves higher than 3 m (Fig. 4). The tsunami of 1969 is a key event here because its intensity, magnitude, and extent of the affected coast enable approximate estimation of the same parameters for more ancient events.

To date, the field studies of tsunami deposits provided the data for 85 points of the Bering Sea coast of the Kamchatskii Peninsula and Karaginskii Island (Pinegina, 2014). At each point, the topographic profile was measured; the geological excavations were dug and documented; the heights, runup distances, and recurrence periods of paleotsunamis were calculated. For example, up to 14 tsunamigenic horizons were revealed in the southern part of the Ozernoi Bay for the last ~4500 years (Bourgeois et al., 2006). Five tsunamigenic horizons for the last ~1400–1800 years were identified on Karaginskii Island (Pinegina and Kozhurin, 2011). The uppermost of these horizons corresponds to the tsunami of 1969; however, it was only revealed in the southern part of the island.

Thus, it was found that the tsunamis from the earthquakes analogous to the event of 1969 do not generate large waves in the central and northern parts of the Litke Strait. Hence, the tsunami deposits here are associated with other seismic sources either in the Litke Strait itself or somewhere north of Karaginskii Island. At the same time, the tsunami deposits found on the southern Karaginskii Island, Ozernoi Peninsula, and Uka Bay can be related to the earthquake sources located either directly in the Litke Strait, or in the Ozernoi Bay or Komandor Basin. In the northern segment of Karaginskii Island, one or two horizons of tsunamigenic deposits dated to within the last ~1400–1800 years were found. Based on the obtained paleoseismic data, the recurrence of the tsunami with a height of >3–5 m was calculated for the western coast of the Bering Sea (Fig. 5).

The comparison between the reconstructed paleotsunami parameters and the 1969 tsunami shows that

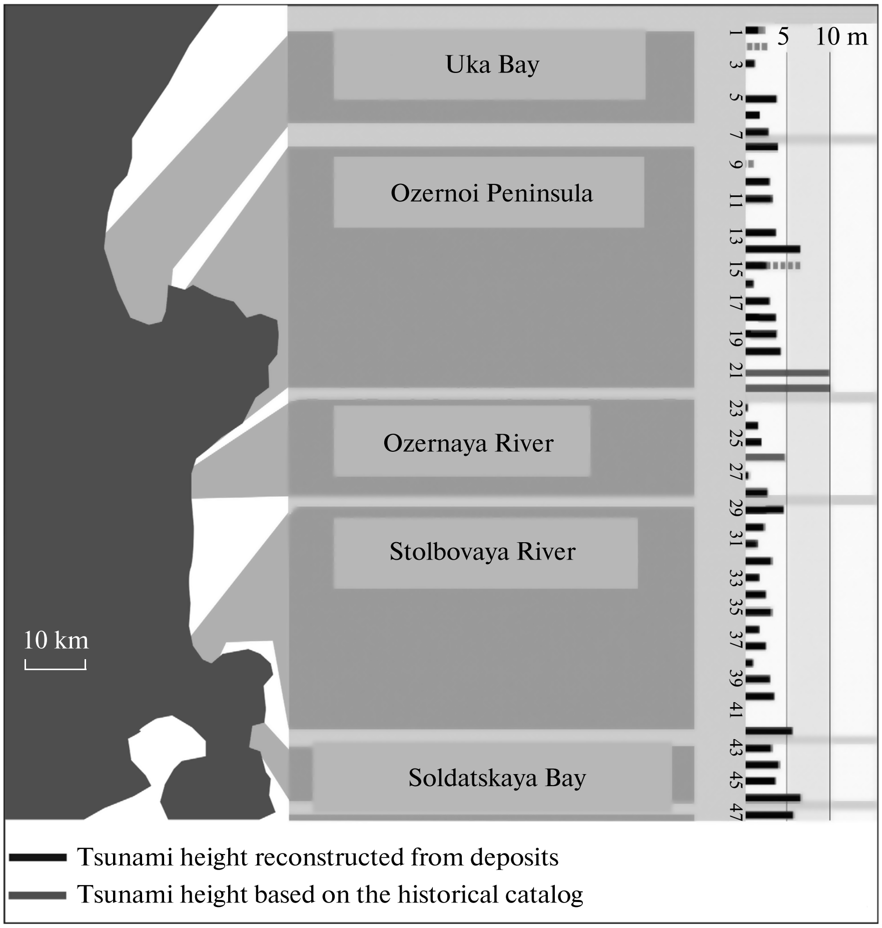

Fig. 4. The distribution of the 1969 tsunami runup height along the coastline reconstructed from the tsunami deposits, after (Martin et al., 2008).

during the last ~2000 years, the Bering Sea did not experience earthquakes with significantly higher magnitudes than the event of 1969 ($M_w = 7.8$).

The relatively short runup distances (a few hundreds of meters) and moderate runup heights (within 10 m) are the salient features of the Bering Sea tsunamis. However, these tsunamis constitute a real hazard for the population since most of the coastal settlements are situated on the narrow spits in the river mouths, at a height of 4–5 m above sea level.

ACTIVE SEISMOGENIC AND TSUNAMIGENIC FAULTS WITHIN THE FRAMING OF THE KOMANDOR BASIN OF THE BERING SEA

Recently, the studies of active faults have been started along the Bering Sea coast of Kamchatskii Peninsula, in Koryakia, and in the Kamchatka–Aleutian junction zone (Kamchatka Peninsula). Undoubtedly, the 2006 Olyutorskoe earthquake triggered a special interest in active tectonics of the region. As a result, the first scheme of active faults has been constructed to date (Fig. 6) (Kozhurin, 2012; Kozhurin and Pinegina, 2011). The new research updates, expands, and refines this scheme. Based on the obtained field data, the slip kinematics, recurrence intervals, mean slip amplitudes, and fault lengths were determined for a number of the faults, which then enabled the geophysicists to derive the focal mechanisms of the probable earthquakes, including the tsunamigenic events, and tentatively estimate the maximal lengths of the sources and magnitudes for these events. These data should be used when updating the seismic hazard maps and the schemes of seismic and tsunami zoning.

The studies (Kozhurin, 2012; Pinegina and Kozhurin, 2011) have shown that the recurrence period of a displacement on a single isolated fault within the Bering Sea margin varies from a few to about ten thousands of years. This explains why the active faults are not, most often, displayed in the instrumental seismicity. The recurrence of the tsunamis from the local regional sources is about 125–700 years. Thus, most of the active faults are located within the sea and have not yet been identified because the known faults, with their slip recurrence every few

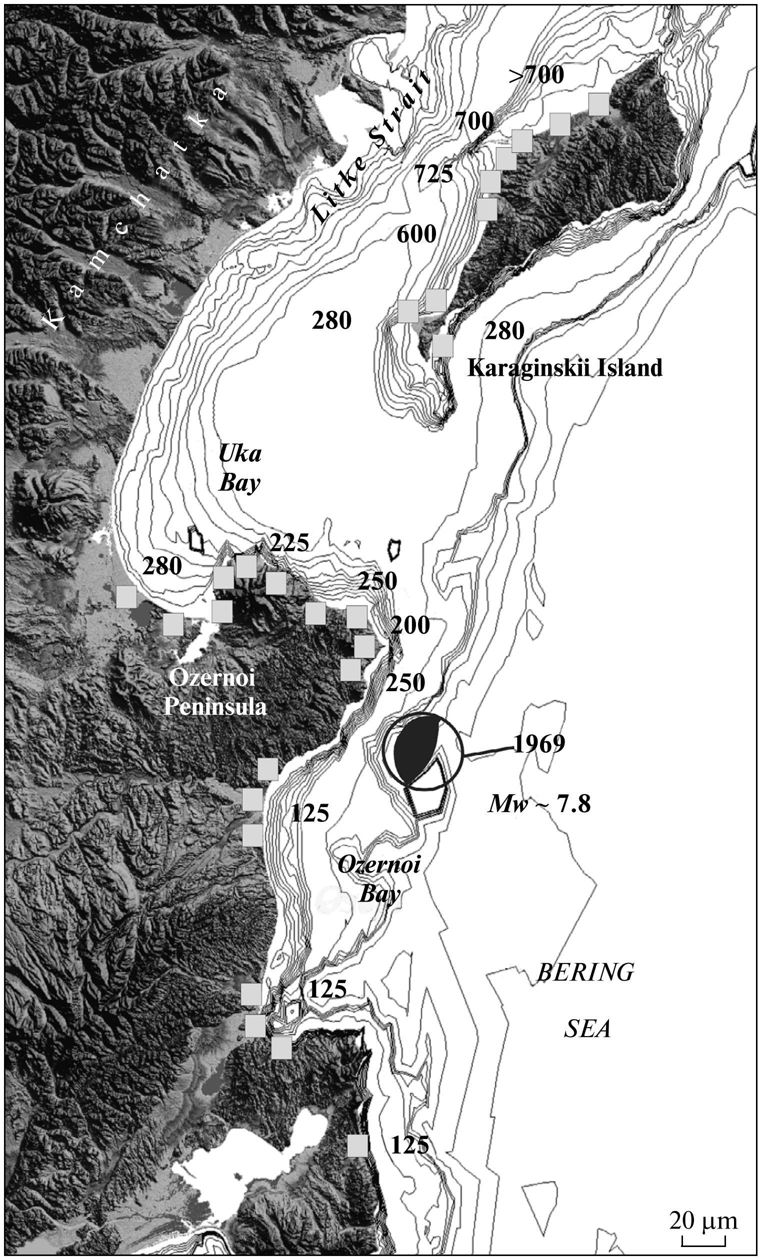

Fig. 5. The average recurrence period (years) of the tsunami with a height >3–5 m in the western sector of the Bering Sea for the last ~2000 years, based on the paleoseismic data (Pinegina and Kozhurin, 2011; Pinegina, 2014). The boxes denote the study regions, and the digits indicate the recurrence periods.

ka to tens of ka, cannot provide the tsunami recurrence of 125–700 yr).

WESTERN TERMINATION OF THE ALEUTIAN ARC

The Pacific Plate subducts beneath the Kamchatskii Peninsula at a rate of ~8 cm/yr, sliding along the right-lateral transform fault of the western (Komandor) segment of the Aleutian zone (Gordeev et al., 2001a). The Pacific Plate boundaries accommodate the strongest regional earthquakes. Therefore, the probability of catastrophic earthquakes with a magnitude of ~8.5–9 occurring in this region—the westernmost termination of the Aleutian arc—is an important question.

The existing data suggest the presence of a narrow elongated Komandor block (Komandor microplate) at the boundary between the Bering and Pacific plates (Apel et al., 2006). This block is bounded by the faults and it moves along the boundary with the velocity that is intermediate between the motion velocities of the confining plates. This leads to the emergence of the

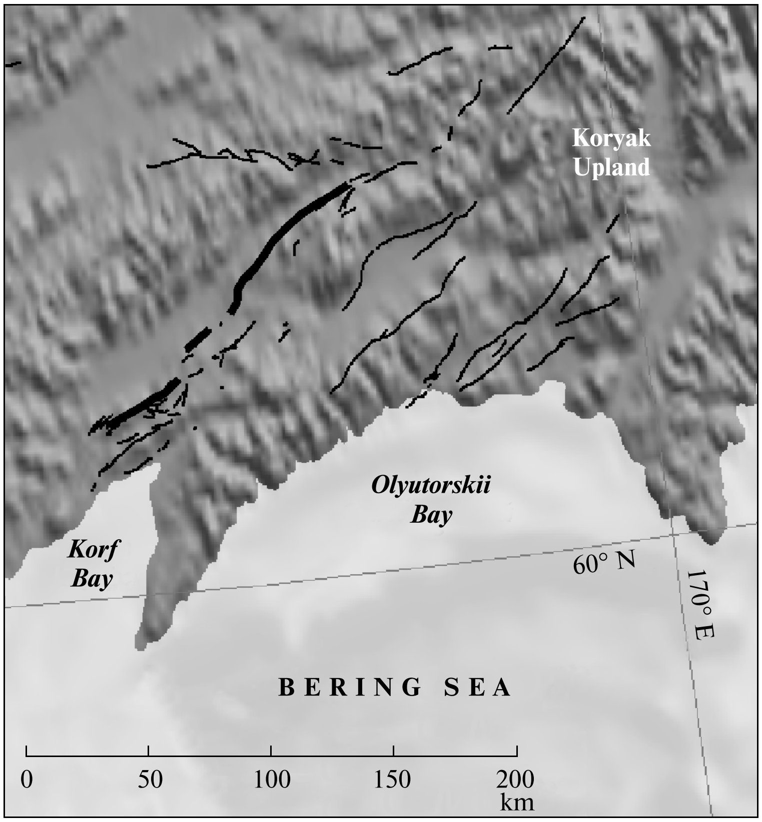

Fig. 6. Active faults (the black lines) in the northwestern margin of the Bering Sea. Part of these faults probably continue into the sea and are probably tsunamigenic. The rupture of the 2006 Olyutorskoe earthquake is shown by the thick line, after (Kozhurin, 2012).

oblique (relative to the main strike) dislocations between these blocks. This structure is well known in the regions of oblique subduction and sometimes referred to as a sliver. It results from the longitudinal sliding of the frontal blocks of the hanging wall along the main boundary due to the partial adhesion with the subducted plate. The most remarkable example of such a structure is the large Burma Plate (Fig. 7)—a sliver, whose slip had led to the catastrophic 2004 Sumatra–Andaman earthquake. The sliver of the Komandor microplate moving along the Aleutian trench towards Kamchatka could also cause the same event at some time. This hypothesis is particularly topical in view of the relative seismic quiescence observed during the past dozens of years on the southwestern boundary of the Komandor microplate, in contrast to the northeastern boundary which remains more active. A similar situation was observed prior to the 2004 Sumatra–Andaman earthquake.

As of now, the factual data supporting that such events occurred here in the past are absent. This problem requires detailed studies, including paleoseismological investigations.

THE JUNCTION BETWEEN THE KAMCHTKA AND ALEUTIAN ARCS

The region of the Kamchatka Peninsula, located on the continuation of the Komandor block, serves as a connecting link between the Aleutian and Kamchatka island arcs. Today, it is commonly accepted that deformation of the Kamchatka Peninsula was caused by the collisional interaction between the Aleutian and Kamchatka island arcs (Watson and Fujita, 1985; Geist and Scholl, 1994; Mackey et al., 1997; Apel et al., 2006). The Kamchatka Peninsula has long been studied by Russian and international research teams. However, the exact location of the collisional contact of the arcs and the kinematic parameters of the collision are still unclear. According to the existing models, the main collisional contact can be located in the Kamchtkan Strait, at the base of the eastern submarine slope of the Kamchatka Peninsula (Geist and Scholl, 1994), or within the southeastern Kamchatka margin, which in this case composes a single block with the Komandor part of the Aleutians (Freitag et al., 2001; Gaedicke et al., 2000; Baranov et al., 2010) (Fig. 8).

Yet another possible scenario suggests a relatively free motion of the Kamchatka Peninsula with respect

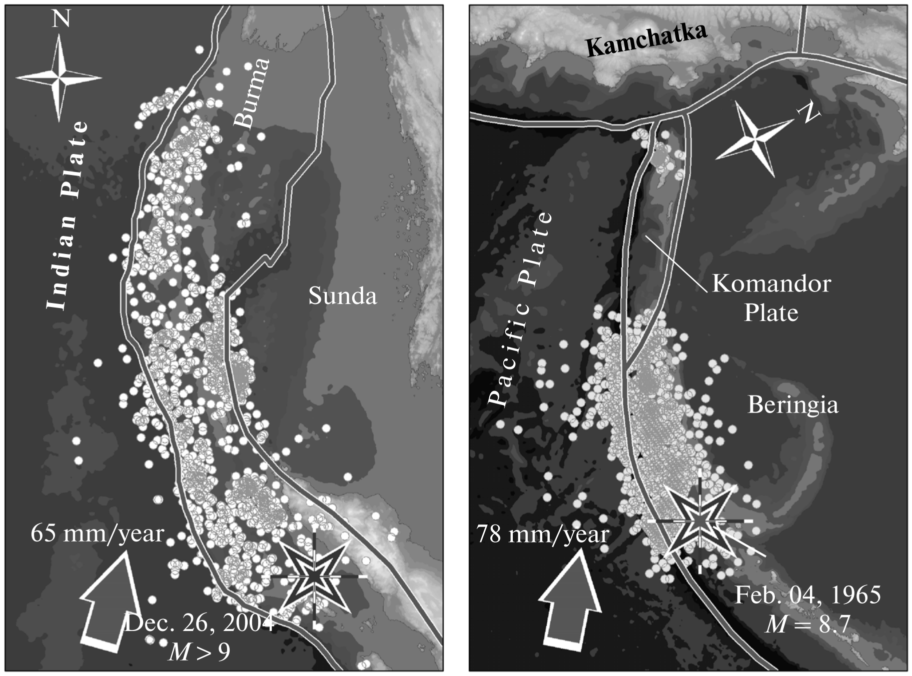

Fig. 7. Two slivers resulting from the oblique thrusting on different scales (Burma sliver is on the left, and the Komandor sliver, on the right). The arrows indicate the relative direction of motion of the subducting plate (Lander and Pinegina, 2010). The asterisks mark the epicenters of the two strongest earthquakes of 1965 and 2004, which occurred under similar geodynamic settings.

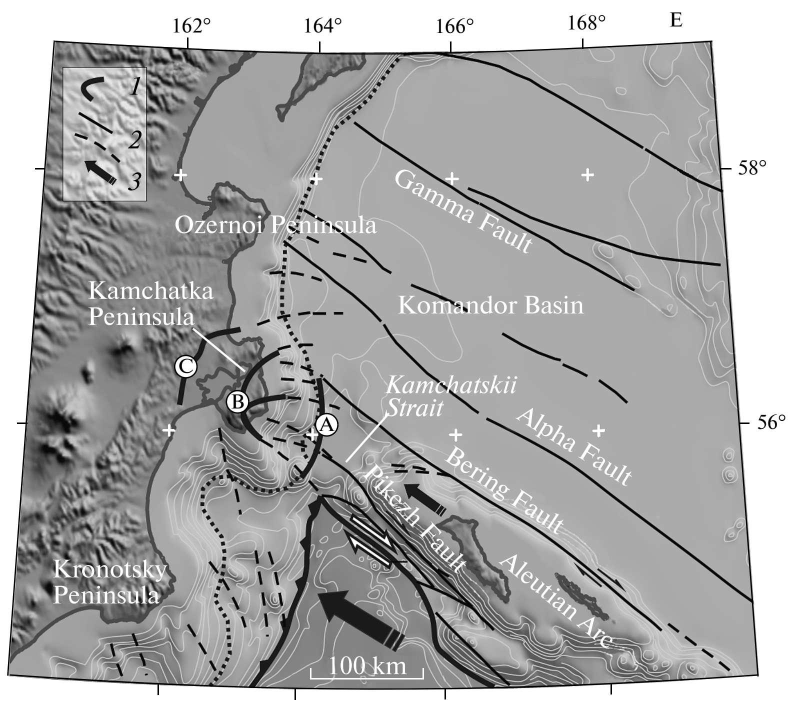

Fig. 8. The position of the collisional contact between the Aleutian and Kamchatka arcs, according to different authors: (A) (Geist and Scholl, 1994); (B) (Gaedicke et al., 2000; Freitag et al., 2001; Baranov et al., 2010); (C) (Kozhurin et al., 2010). The submarine faults (the dashed lines denote the supposed faults) are shown after (Seliverstov, 2009). The black arrows indicate the directions of relative motions of the Pacific Plate and the Komandor block.

to the Komandor block. This motion has a clockwise rotation component caused by nonuniform compression of this block from the arc-aligned blocks of the western Aleutians, whose motion speeds up with the approach of the Pacific Plate (Kozhurin, 2007). In this model, the western Aleutians, including the Kamchatka Peninsula, do not move as a single rigid block but, instead, as a set of relatively small blocks, which are more or less freely mobile relative to each other. It has been proven that there are active structures in the Kamchatka Peninsula, which can be considered to have resulted from the collisional interaction between the Kamchatka and Aleutian arcs (Kozhurin and Pinegina, 2011). The westernmost structure, which has a reverse fault/thrust kinematics, extends to the base of the eastern slope of the Kumroch Ridge, separates the Kamchatka itself from the Kamchatka Peninsula, and, in this sense, acts as the main collisional contact of two arcs (Fig. 8).

CONCLUSIONS

This brief review only covers the most general questions of tectonics and seismicity in the Kamchatka–Aleutian–Alaska region and their related natural hazards (earthquakes and tsunamis). The Bering Sea region has a complex tectonic structure, and the tectonic and seismic processes here are still largely unclear. In our opinion, further efforts should be focused on the following tasks:

(1) to prove or reject the existence of the Bering Plate and to define its boundaries;

(2) to obtain the data on the character of active crustal deformations in the continental margins of the Bering Sea;

(3) to specify the details of collisional interaction between the Aleutian and Kamchatka arcs (the type, distribution, and rates of collisional strains);

(4) to search for the traces of the previous mega-earthquakes on the western boundary of the Aleutian Arc, within the Komandor sliver;

(5) to determine the positions of the possible sources of the strong (including tsunamigenic) earthquakes in the Bering Sea and on its continental margins;

(6) to estimate the recurrence and magnitudes $M_{\max}$ of the earthquakes in the Bering Sea region and to refine the existing maps of the seismic and tsunami hazards and zoning.

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