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GEOPHYSICS

Landslides on the Eastern Slope of Sakhalin Island as Possible Tsunami Sources

B. V. Baranov[a], Corresponding Member of the RAS L. I. Lobkovskii[a], E. A. Kulikov[a], A. B. Rabinovich[a], Y. K. Jin[b], and K. A. Dozorova[a]

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An underwater landslide located in the central part of the eastern slope of Sakhalin Island was found and mapped during investigations under the auspices of the Korean–Russian Project Sakhalin Slope Gas Hydrates (SSGH) [1, 2]. The study region was confined to a depression oriented in the northeasterly direction (Fig. 1a). The research in this region [1–4] demonstrated that closed depressions with round and slightly elongated forms in the northeasterly direction are characteristic peculiarities of the morphology of this depression (Fig. 1b). The slope angles of their walls are 7°–10°, while the sizes are in the range between 600 m and 10 km. They are located at depths from 20 to 150 m. One of the largest depressions has a notable morphology. Its northern edge is quite flat (~7°), while the southern edge is steep (25°–30°). It consists of one or a few cliffs with a total height up to 100 m (Fig. 2).

Two types of the sedimentary sections were found within the study region. The first one is common. It is characterized by numerous reflecting levels that provide evidence about the layered structure of the sedimentary column. The second type of seismic section is observed only in the southernmost depression crossed by seismic profile LV56-03 (Fig. 2). Here, we distinguish a sedimentary body whose cover has a hilly structure, while the foot corresponding to a high-amplitude reflecting level cuts off the underlying reflectors. The body is acoustically transparent because there are no reflecting layers. Slope boundaries and diffracted reflections are seen on the high-resolution section of seismic profiler SES-2000DS, which is caused by the chaotic internal structure of this sedimentary body.

The above-mentioned peculiarities of the sedimentary cover structure together with the morphology of the depression give grounds to think that this sedimentary formation is a landslide. A section made using seismic profiler SES-2000DS with a resolution on the order of 10 cm [4] does not demonstrate that the roof of the landslide is covered with horizontally located sediments. Taking into account that the rate of sediment deposition in this region during the Holocene was 33 cm over 1000 years [2], the age of the landslide is less than 300 years. The break-off wall of the landslide is very steep (25°–30°). In some regions it consists of two cliffs. Its form is undulating, and its length is 22 km (Fig. 1b). The area occupied by the landslide is 42 km^2, and its volume is approximately 4 km^3.

Such a landslide would certainly cause a strong tsunami. The results of investigations and numerical modeling of landslide tsunamis in different regions of the ocean and, in particular, the catastrophic tsunami caused by a giant underwater landslide in the Newfoundland region (1929) [5] as well as numerous underwater landslides and related tsunamis in the regions of Alaska and British Columbia [6, 7] provide evidence that the landslide studied here could have caused a strong tsunami.

Avalanching of the underwater landslide is accompanied by wave generation at the sea surface immediately over the bottom region affected by the displacement of the sedimentary layers. The landslide body that moves down the slope entrains water masses in its trailing part and pushes water in the leading part (Fig. 3).

In order to estimate the characteristic tsunami waves caused by the underwater landslide on the continental shelf of Sakhalin Island, we used the method based, in particular, on the simplified analytical theory of solitary waves. This method was used to estimate the tsunami wave height in Kitimat Bay (British Columbia) [8] and also in the analysis of the landslide tsunami in Skagway port (southeastern Alaska) [6]. The

[a] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Nakhimovskii pr. 36, Moscow, 117997 Russia*
[b] *Korean Polar Research Institute, Get-pearl Tower, Sondo Techo Par 12 Gaetbeol-ro, Yeonsu-gu, Incheon, 406-840 Korea*
e-mail: llobkovsky@ocean.ru

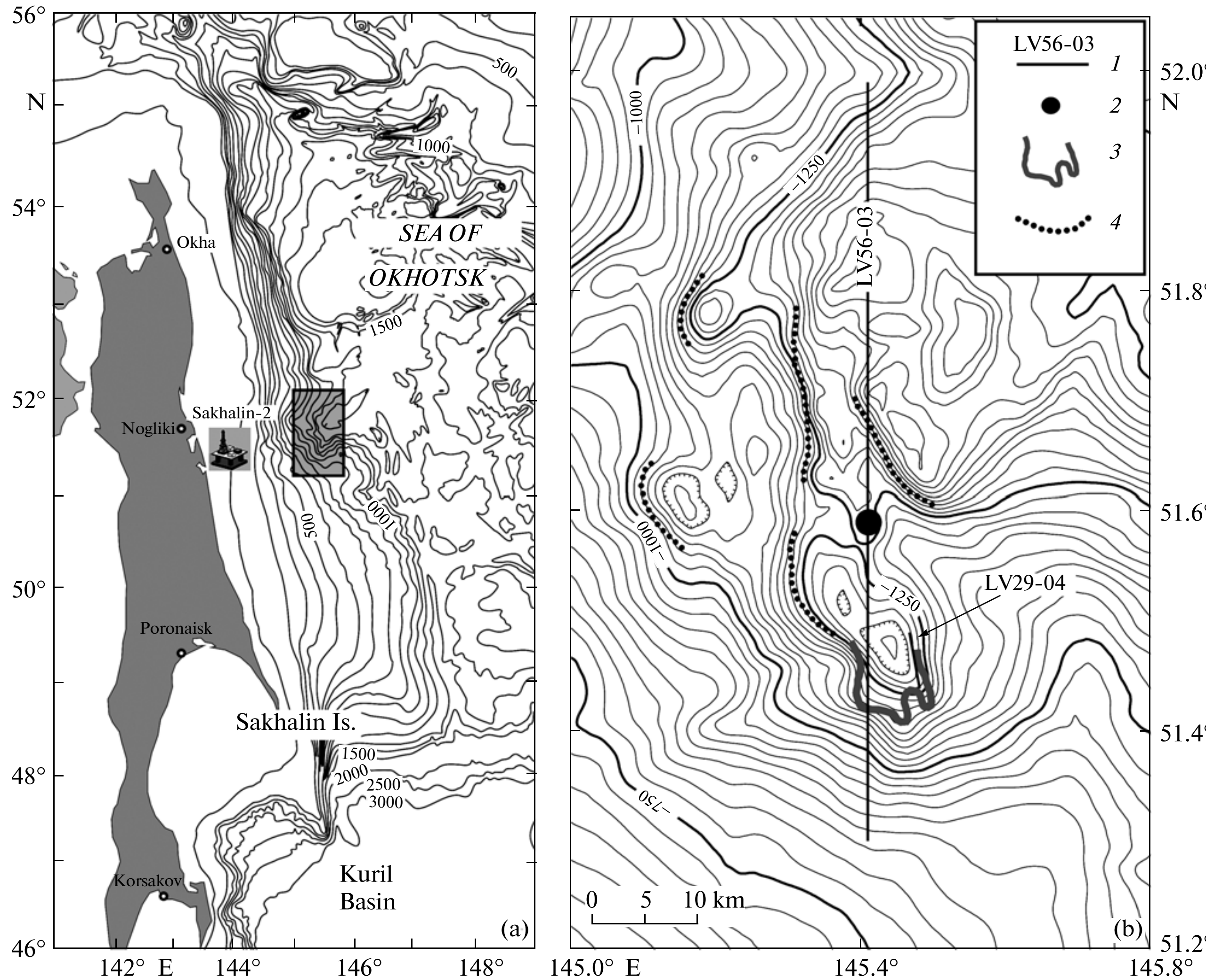

Fig. 1. (a) A bathymetric chart of the eastern slope of Sakhalin Island and location of the study region (rectangle); the isobaths are plotted with an interval of 100 m; on the slope of the Kuril Basin the interval is 500 m; (b) a bathymetric chart of the study region; the isobaths are plotted with an interval of 25 m; (*1*) seismic profiles and their numbers; (*2*) points of sediment sampling; (*3*) wall of the landslide separation; (*4*) regions of the slope favorable for landslide formation.

results of calculation reasonably agreed with the observed tsunami wave heights in these two basins. According to this method, the tsunami wave can be presented as

$$h = \frac{1}{D_0}\left[\left(\frac{8}{3}\right)^{1/2}\frac{\mu}{w}(\delta - 1)(D_0 - D_s)\right]^{2/3}, \quad (1)$$

where w is the mean thickness of the landslide body, l is its length, D_0 and D_s are the depths of the center of mass of the landslide body at the initial and final moments of the motion, δ is the landslide body density normalized by the fluid density, and μ is the relative share of the landslide potential energy that transferred to the energy of the tsunami waves generated.

According to the results of analysis for Kitimat Bay, the value of μ is not large; it is equal to ~0.01 [8]. The density of the sedimentary material of the landslide body can be estimated at ~0.8. The location of its mass center is $D_0 \approx 1350$ m. We assume that initially it was located at a depth of $D_s \approx 1100$ m. The mean thickness of the initial body is $w \approx 70$ m, and its length is $l \approx 5000$ m (see Fig. 3). The estimate based on relation (1) gives a value of the sea surface elevation equal to approximately 30 m. This initial perturbation divides into two main waves that move to the open sea and to the coast. Since the amplitude of the wave that moves to the coast is slightly smaller than the wave propagating to the deep sea, the height of the tsunami wave incident at the coast is less than half of the initial perturbation of the water surface ~10 m. We note that the characteristic size of the landslide $l \approx 5000$ m is much greater than the sea depth in this region. This means that the

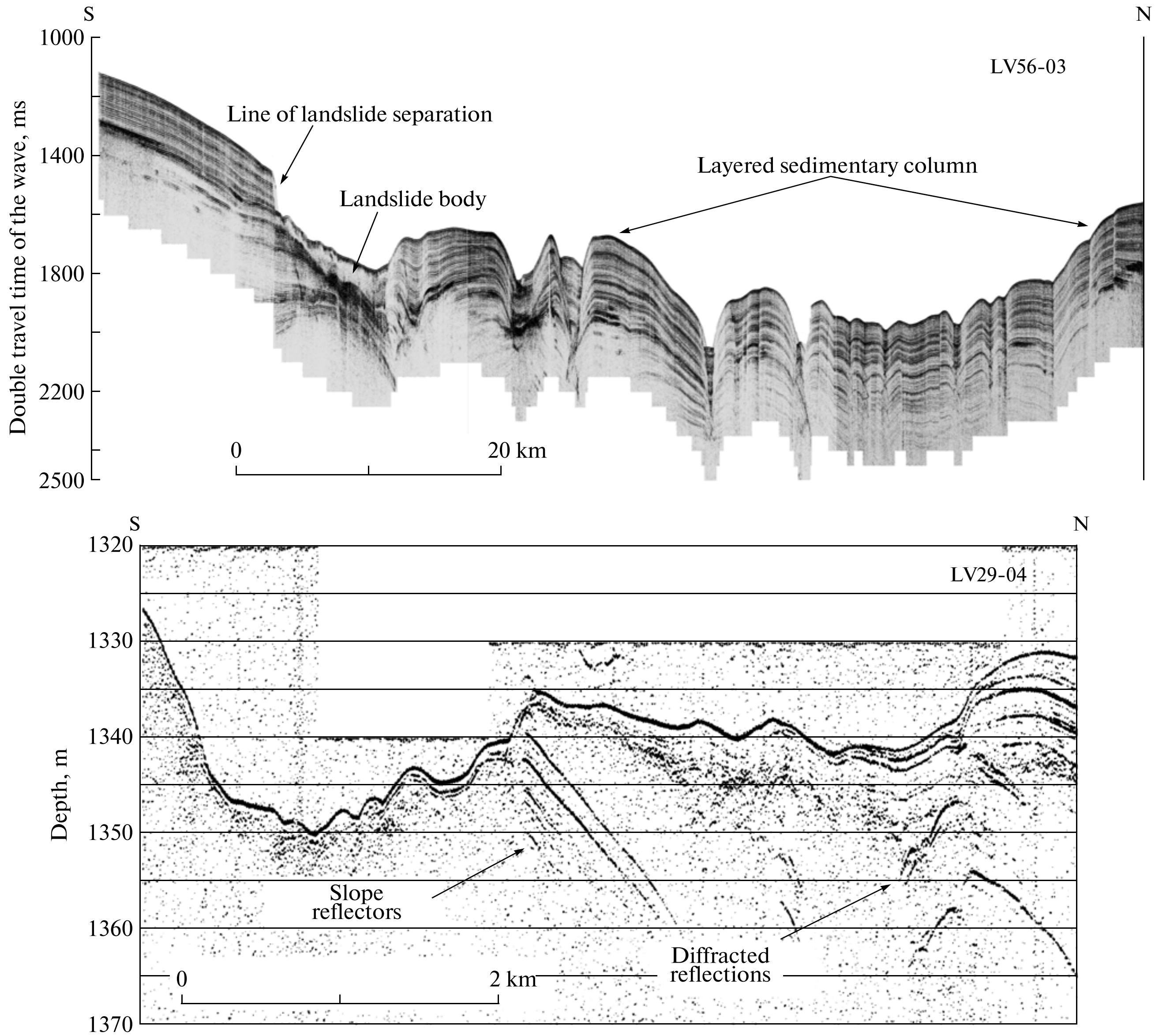

Fig. 2. Seismic profile LV56-03 (above) illustrating the structure of the upper part of the sedimentary cover in the study region [2]; the vertical scale is given in milliseconds of the double travel time of the wave in water (1000 ms corresponds to 750 m) in the upper part of the sediments: 1000 ms corresponds to ~900 m. Section LV29-04 (below) obtained by seismic profiler SES-2000DS [4], which demonstrates the sediment deformation in the landslide body. The locations of profiles are shown in Fig. 1b.

generated tsunami wave is related to the class of long waves. The dispersion of these waves is low, and their decay is characterized generally by the effect of horizontal diversion $h \sim \frac{1}{\sqrt{r}}$, where r is the distance from the source. Usually, the manifestation of the tsunami caused by underwater landslides is local. The events related to vast landslide processes, for example, the tsunami of 1929 in the northern part of Newfoundland are exceptions. Taking into account the size of the landslide analyzed here, we can suppose that the dangerous tsunami runup was pronounced over the coastline up to the first tens of kilometers long.

The peculiarities of the study region structure together with the expected seismic intensity of grade 8 [9] give grounds to suppose the probability of further destruction of the depression slopes (Fig. 1b) and formation of landslides of different volumes. In this case, the tsunami can be a hazard for the central part of the eastern coast of Sakhalin, where the infrastructure is currently intensively developed in relation to the prospecting of oil and gas resources within the Sakhalin–2 Project.

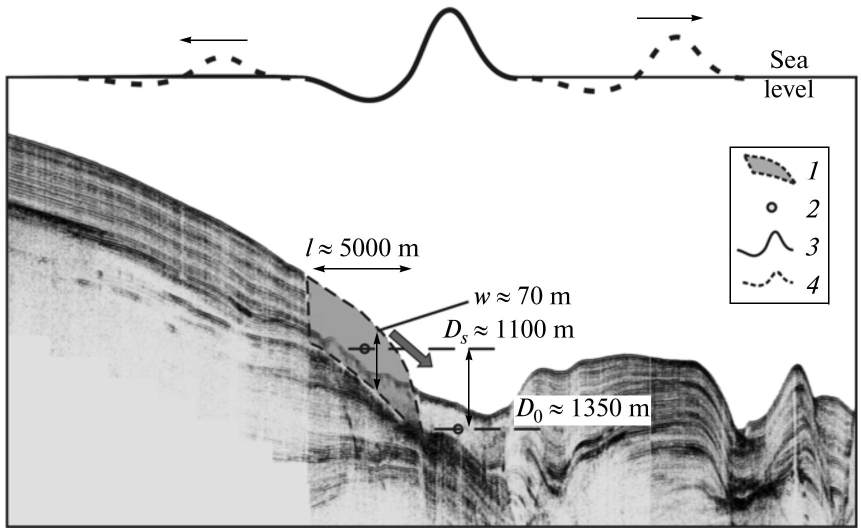

Fig. 3. A schematic of the tsunami wave generation as a result of underwater landslide: (*1*) the region corresponding to the initial location of the sediment mass of the landslide body; (*2*) approximate location of the mass center before (D_s) and after (D_0) the landslide of the sedimentary masses; (*3*) a typical wave profile formed at the sea surface immediately at the moment of land sliding; (*4*) profile of the waves propagating to the coast (left) and to the open sea (right).

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