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GEOPHYSICS

The Sakhalin Earthquake on August 17(18), 2006, and the First Realization of Integrated Forecast

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The paper describes an experiment in which we established for the first time a scheme of integrated earthquake forecast based on long-term forecast with determination of the region of earthquake preparation, its magnitude, depth, and operative forecast on the basis of hydroacoustic data obtained during field measurements in the region of the expected event. We used a mobile field station, which simultaneously detects hydroacoustic and seismic signals in the region of large earthquake preparation.

On August 18, 2006, at 02:20 (Sakhalin time), an earthquake occurred with a magnitude of 5.6 near the Shebunino Settlement in the Kholmsk region of Sakhalin (Fig. 1). The earthquake occurred at the boundary of a seismic quiescence zone. According to the digital network of seismic stations of the Sakhalin Branch of the Geoseismic Service of the Russian Academy of Sciences, this earthquake had the following parameters: time at the source t_0 = 2:20:37.8; geographical coordinates of the epicenter $\varphi = 46.45°$ N, $\lambda = 142.11°$ E; depth of the source h = 8 km; magnitude $M_s = 5.6$ (according to the USGS data, $M_b = 5.6$, h = 32.6 km).

While analyzing the spatiotemporal distribution in the southern part of Sakhalin in 2005 [5], seismic gaps of first kind (based on large earthquakes) and second kind (based on weak events) were found in the Kholmsk region (Fig. 2). These precursors became the basis for presenting a long-term forecast of a large earthquake in the Kholmsk region to the Russian Council of Experts on Seismic Hazard and Risk (RCE) on December 22, 2005. The forecasted parameters were as follows: the beginning and end of the hazard January 2006–July 2013; magnitude 6.0–7.2; and depth 0–30 km. Thus, the forecast predicted a possible interval of the event within 7.5 yr and the RCE formulated a positive resolution based on this forecast.

However, an operative forecast a few hours before the event is needed to warn the local population and

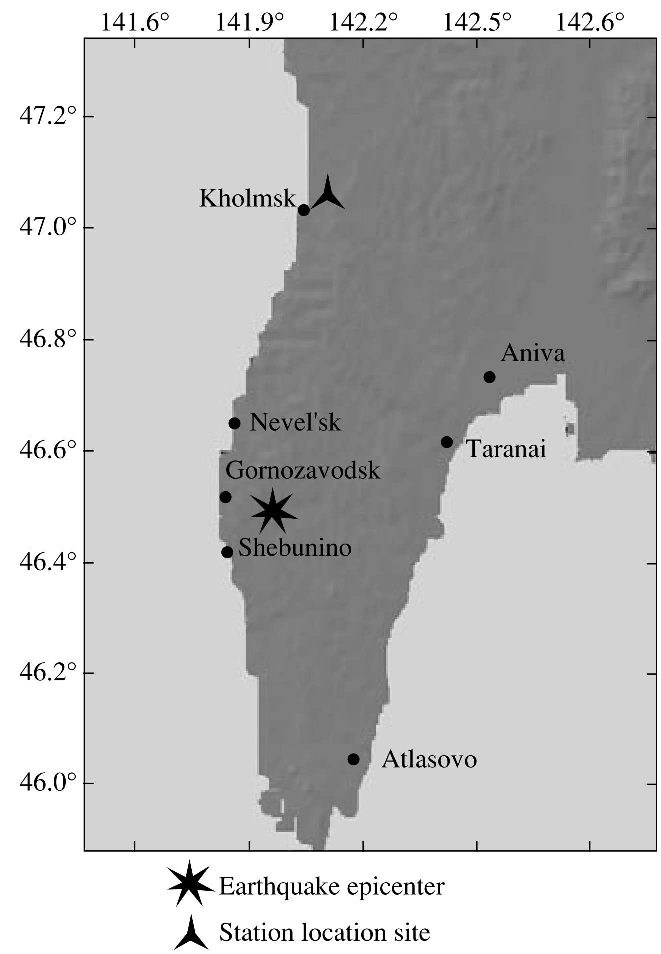

Fig. 1. Chart of southwestern Sakhalin. The earthquake epicenter and location of the seismic hydroacoustic station are indicated.

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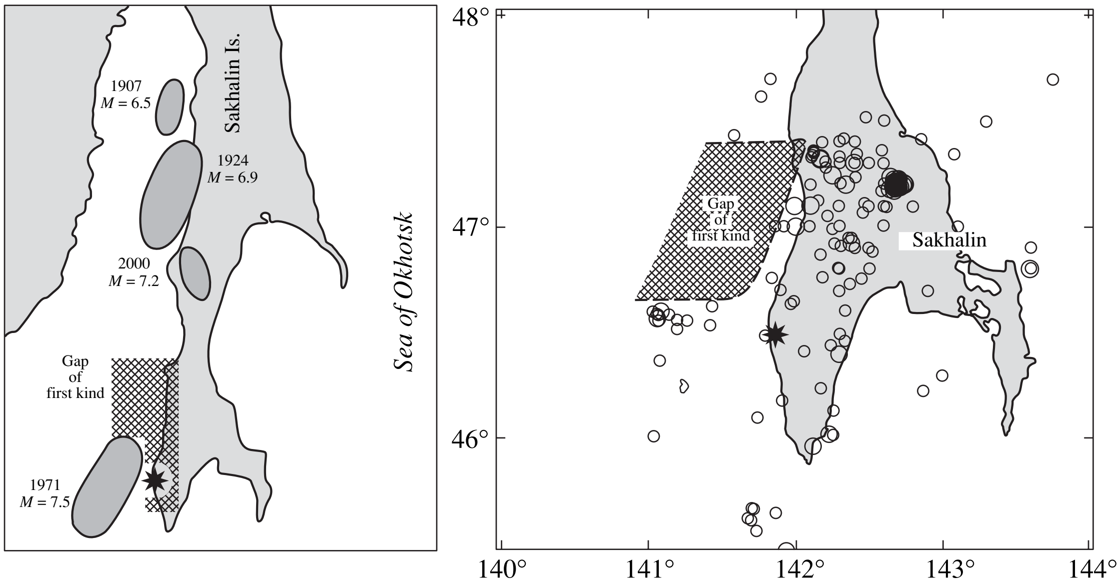

Fig. 2. Location of the seismic gap of first kind (shaded area) and second kind (limited by a dashed line on the right). Asterisk denotes the epicenter of August 18, 2006, earthquake with $M_s = 5.6$. Sources of known large earthquakes are shown (ellipses). Epicenters of crustal earthquakes with $M_s \geq 3.0$ from 1993 to 2005 based on the data of the IRIS-2 system and the Datamark network of seismic stations are shown on the right.

interact with the Ministry of Extraordinary Situations of the Russian Federation. Thus, it is necessary to determine the beginning of the critical stage of earthquake preparation. It is shown in [1] that a surface zone of dilatancy is formed in the course of earthquake preparation. This zone is located above the source area immediately adjacent to the upper boundary of the solid medium, in which small cracks are formed preceding the main rupture. It is shown in [4, 6] that high-frequency acoustic signals appearing during the formation of small cracks in the surface zone of dilatancy attenuate rapidly and cannot be recorded by land-based stations. However, they can be recorded by hydroacoustic receivers in the water column a few hours before the main shock. Similar results (in other frequency ranges) were obtained in [2, 3].

Hydroacoustic receivers located in water reservoirs on land (lakes, pools) receive the signal not from the source area of the future earthquake but directly from the rocks surrounding the reservoir, where intense cracks are formed. According to a number of estimates, the size of such a region of earthquake preparation can be as large as 400 km.

Taking into account the long-term forecast of an earthquake in the Kholmsk region and manifestation of short-term indicators (gas release and activation of a mud volcano in the southern part of Sakhalin) in mid-August 2006, a mobile station of simultaneous recording of seismic and hydroacoustic signals was deployed in a closed water reservoir near Kholmsk (Malka River region) in order to distinguish the pulses generated during the critical stage of earthquake preparation within a few hours before the main shock. Hydroacoustic receivers were located in the reservoir and connected by a cable to the data acquisition system, which was located on land together with the seismic subsystem. The coordinates of the station were 47.117° N and 142.096° E. The station was located in a securely guarded zone, and the probability of generation of anthropogenic signals is insignificant. The distance to the station from the epicenter of the earthquake was 61 km.

The seismic hydroacoustic station was designed at the Institute of Marine Geology and Geophysics (Yuzhno-Sakhalinsk), the Special Design Office for Automation of Marine Research (Yuzhno-Sakhalinsk), Shirshov Institute of Oceanology (Moscow), and Geopribor Open Joint-Stock Co. (Moscow). The station includes seismic and hydroacoustic subsystems and a common data acquisition system. The seismic subsystem is realized on the basis of a SME 4011 molecular electronic seismometer designed and developed at the Moscow Institute of Physics and Technology.

The hydroacoustic system developed at the Special Design Office for Automation of Marine Research (Yuzhno-Sakhalinsk) includes two hydrophones of all-round vision (with a spacing of 25 m) and an amplifier. The data acquisition system is based on an E440 module (L-Card Closed Joint-Stock Co., Moscow). This system was designed as a mobile field station, which can be deployed at the points with expected earthquake preparation and used for operative forecast.

The seismic module of the system can permanently record in three (two horizontal and one vertical) channels; the frequency range of the recorded signal is 0.017–20 Hz; and the sampling frequency is 200 Hz.

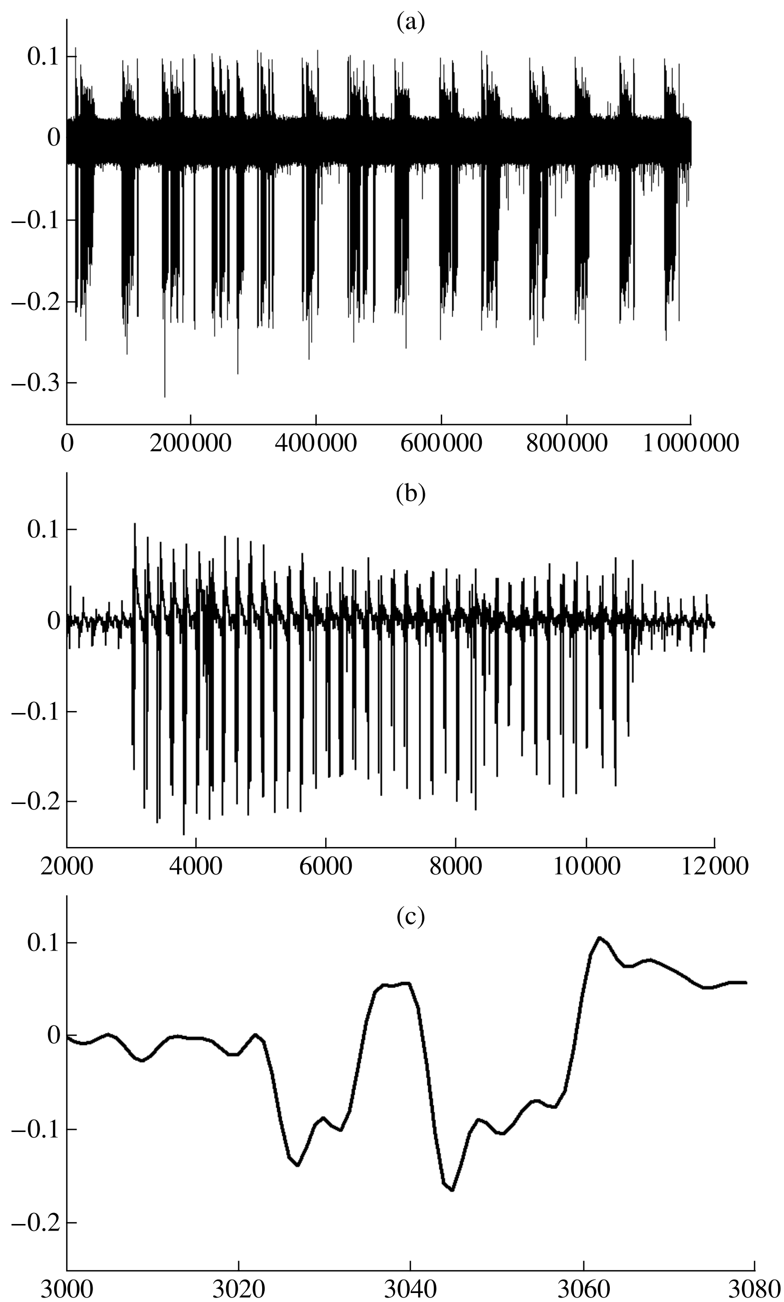

Fig. 3. Series of signal trains recorded by the first hydroacoustic channel of the station (a); one signal train from the presented series (b); one signal from the leading part of the signal train (c). Number of counts is shown along the horizontal axis for all fragments (duration of the counts is 0.005 s). Amplitude of the signal is shown along the vertical axis (in mV). The example is from the record on August 17, 2006. The beginning of the record is at 01:30:00 GMT; the beginning of the fragment is at 01:30:00, and its duration is 2 h 53 min 20 s.

During the experiment described here, the hydroacoustic module of the system included two hydrophones with the frequency range 1–70 Hz. The sampling frequency was 200 Hz. The seismic and hydroacoustic channels were synchronized. The records were made over 5 channels in total. The duration of one record was 6 h, and the volume of information was 41.2 MB. Each channel of records contained 4 320 000 counts.

A check of both subsystems and permanent operation were started on August 11. The number of hydroacoustic channels and the distance between hydrophones were increased in the course of the experiment to detect the source of the signal (three channels located at the vertices of an equilateral triangle with a side of 100 m).

Starting from the record on August 16, 2006, from 03:30:00 to 19:30:00 (hereafter, GMT), series of simi-

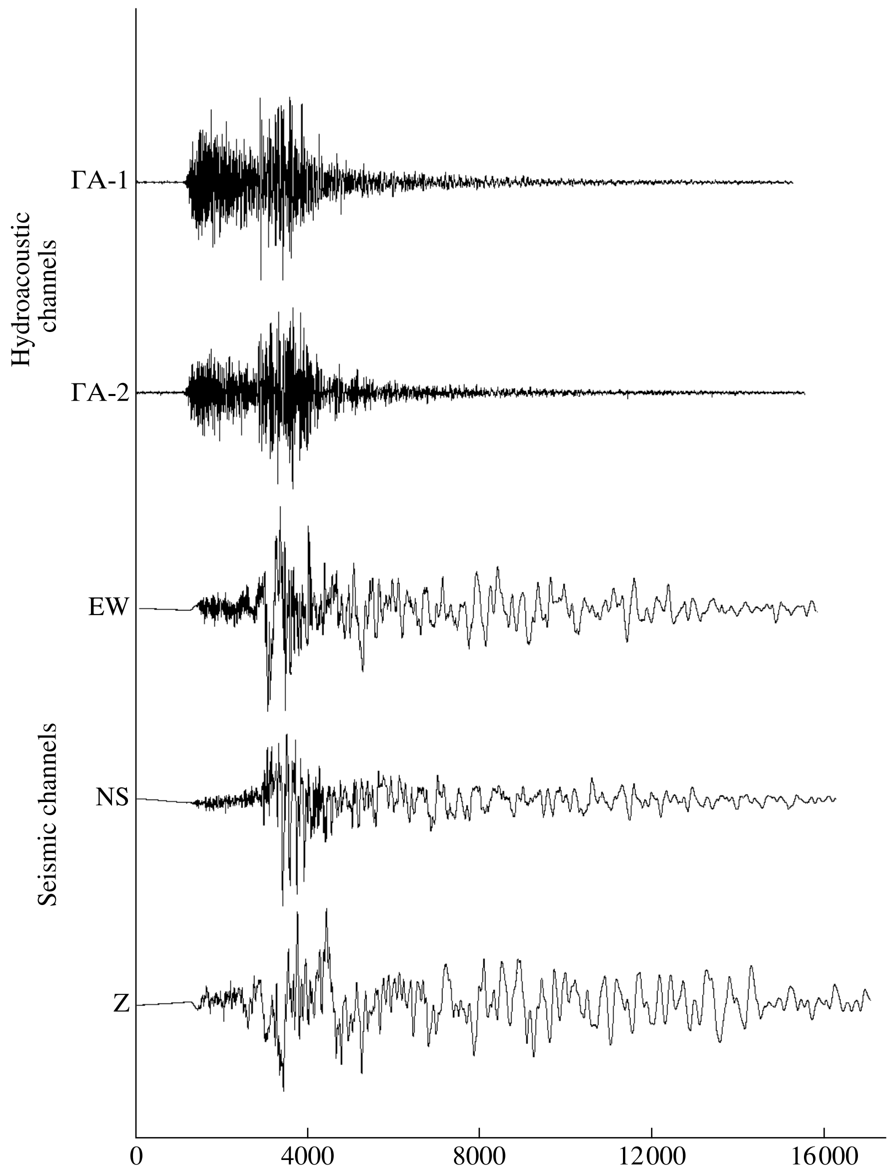

Fig. 4. Earthquake near the Shebunino Settlement (Kholmsk region, Sakhalin) on August 17, 2006, recorded at 16:20:08 by all channels of the seismic hydroacoustic station (beginning of the record is at 13:30:00). Magnitude $M_b = 5.6$, coordinates of the epicenter 46.45° N and 142.11° E, source depth 12 km. Seismic signals are compressed 100 times (decreased signal amplitude); hydroacoustic signals, 10 times.

lar signals (trains) appeared in hydroacoustic channels. The first train appeared at 18:57:05.5, i.e., 21 h 22 min and 40 s before the beginning of the earthquake. A total of 13 trains were distinguished in this record. In the subsequent records, 243 trains of similar signals were distinguished. No significant changes in the signal were found in the seismic channels.

Figure 3a shows a characteristic segment of the compressed record with a series of signal trains (record on August 17, 2006; beginning of the segment at 01:30:30 and end at 04:23:50; duration of the record 2 h 53 min 20 s). Figure 3b shows one train of signals from the presented series (beginning of the fragment at 01:30:40; duration 50 s). One signal from this train is separated (Fig. 3c). The beginning of this fragment is at 01:30:45 (duration 0.4 s).

The number of signals in the train showed a wide range (from 7 to 130). The time interval between the two neighboring trains also changed from one to a few minutes. At the same time, the location of signals within the train was sufficiently stable. It is interesting to note that the time interval between signals shows an insignificant variation range (0.796 ± 0.05 s) similarly to the amplitude and duration of the signals. By the end of the train, the amplitude of the signals became somewhat weaker and their shape was not sharply delineated. The first signals in each train exceeded the background amplitude significantly (3–7 times). Thus, they can easily be distinguished from the record (using hardware or software methods). In the calm state, the background amplitude is sufficiently stable.

We can consider, based on comparative analysis of two hydroacoustic channels, that all signals within one train were generated in one region (one source), while the signals in different trains appeared from different sources. Sometimes, long trains appear as the result of superposition of two series of signals. Three hydrophones located at the vertices of the equilateral triangle with a side of 100 m would make it possible to solve the problem of the exact location of the signal source.

The character of an individual signal (Fig. 3c) points to the fact that high-frequency components of the signal were filtered out. Using this record, we cannot determine certain characteristics of the source of microdestructions such as depth, size of the radiating source, and its energetic characteristic (magnitude).

After 05:13:04 on August 17 (11 h 6 min before the main shock), signals of such a type were not recorded. Such signals were detected neither after the earthquake nor after the aftershocks (four records, each 6 h long, were analyzed). Figure 4 shows signals of the earthquake recorded by all channels of the station. The record of aftershocks at the station has a similar shape. Trains of signals were not observed before aftershocks. In such cases, the preparation period of the seismic event is short and surface zones of dilatancy are possibly not formed.

The authors of [2] recorded signals of a similar character in Kamchatka a few tens of hours (sometimes even more than one day) before the seismic event. These signals disappeared a few hours before the main shock. The authors of [6] suggested a hierarchic scheme of the evolution of acoustic signals in the earthquake preparation zone. First, signals from microdestructions in the medium appear owing to an increase in the mechanical load up to the critical value. They appear over a large area (depending on the magnitude of the prepared event) tens of hours before the main shock. Both the beginning and the end of the record of such signals can indicate that earthquake preparation is in the critical stage. The end of the signal record indicates that an earthquake is possible within a few hours, and the earthquake preparation zone narrows to the epicenter zone so that cracks of a larger scale appear there. In the case of the Kholmsk earthquake, the entire zone around the reservoir belonged to the earthquake preparation region. When the preparation region narrowed to the size of the epicenter zone, records of signals in the reservoir terminated. In order to refine the system of operative forecast of earthquakes, it is expedient to deploy in the future a number of stations of such a type in the supposed region of seismic event preparation.

ACKNOWLEDGMENTS

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