Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Sections, Vol. 348, No. 4, 1996, pp. 693–699.
Translated from Doklady Akademii Nauk, Vol. 348, No. 4, 1996, pp. 532–538.

GEOPHYSICS

The Shikotan Tsunami of October 5, 1994

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Presented by Academician V.I. Keilis-Borok December 1, 1994

Received March 1, 1995

INTRODUCTION

A powerful earthquake with a magnitude of $M_S = 8.0$ on the Richter scale occurred in the South Kuril Islands on October 5, 1994 at 00h 23 min local time (October 4, 13h 23 min GMT). Its intensity was as follows (according to the 12-point scale MSK-64): 8–9 on the island of Shikotan, 7–8 on the other islands of the South Kurils and on Kunashir, 6–7 on Iturup and Hokkaido, up to 5–6 in the north of Honcu, and 2–4 in the north of the Kurils and on the major part of Sakhalin. This earthquake was most disastrous on the Southern Kurils. 13.4 thousand people suffered from its consequences, including 11 who perished, 32 who were badly wounded, and 210 who were lightly wounded; 7700 people were left homeless. It completely destroyed 111 houses and more than 250 houses partially; more than 800 objects were damaged and destroyed. According to preliminary estimations, the total material damage was about 600 billion rubles.

The earthquake caused considerable tsunami waves on the South Kurils coast; noticeable waves were register on Sakhalin and at many places along the shores of the Pacific (Japan, U. S., Chili, and other countries). Fortunately, there were no casualties caused by the tsunami, because it occurred during night. However, the material damage was quite substantial.

One of the most important consequences of the earthquake was the total tectonic subsidence of Shikotan by 0.5–0.7 m.

A brief analysis of the Shikotan tsunami on 5 October based on available operational data and field observations from the South Kurils is given below.

SEISMIC DATA

Both long-term [1] and medium-term [2] forecasts predicted a powerful earthquake of $M_S > 7.5$ in the South Kurils during the 1993–1997 period. However, short-term forecast were not performed since March 1994 due to financial problems, and all seismic observations in the South Kurils including the tsunami warning service, had ceased. They were resumed only 1–2 weeks after the earthquake of October 5. Therefore, the source zone characteristic is given according to the data from distant seismic stations and the nearest local network of the Hokkaido University.

The main shock occurred under the Pacific ocean bottom, 50 km to the east of Shikotan (Fig. 1). Epicenter coordinates and source depth (Table 1) are determined by joint processing of data from Russian, Japanese, and American stations within a ±15 km error limit. During the following month, more than 1500 aftershocks with $M_S > 3.0$ took place. Aftershocks of the first week allow us to clearly outline the source zone within an area of about 200 × 80 km. It is extended along the islands and partially overlaps the sources of previous powerful tsunamis in this area. With the exception of the main aftershock of October 9 with $M_S = 7.4$, powerful aftershocks with $M_S > 6.8$ occurred within the narrow zone transverse to the deep trough and only during the first 6 hours

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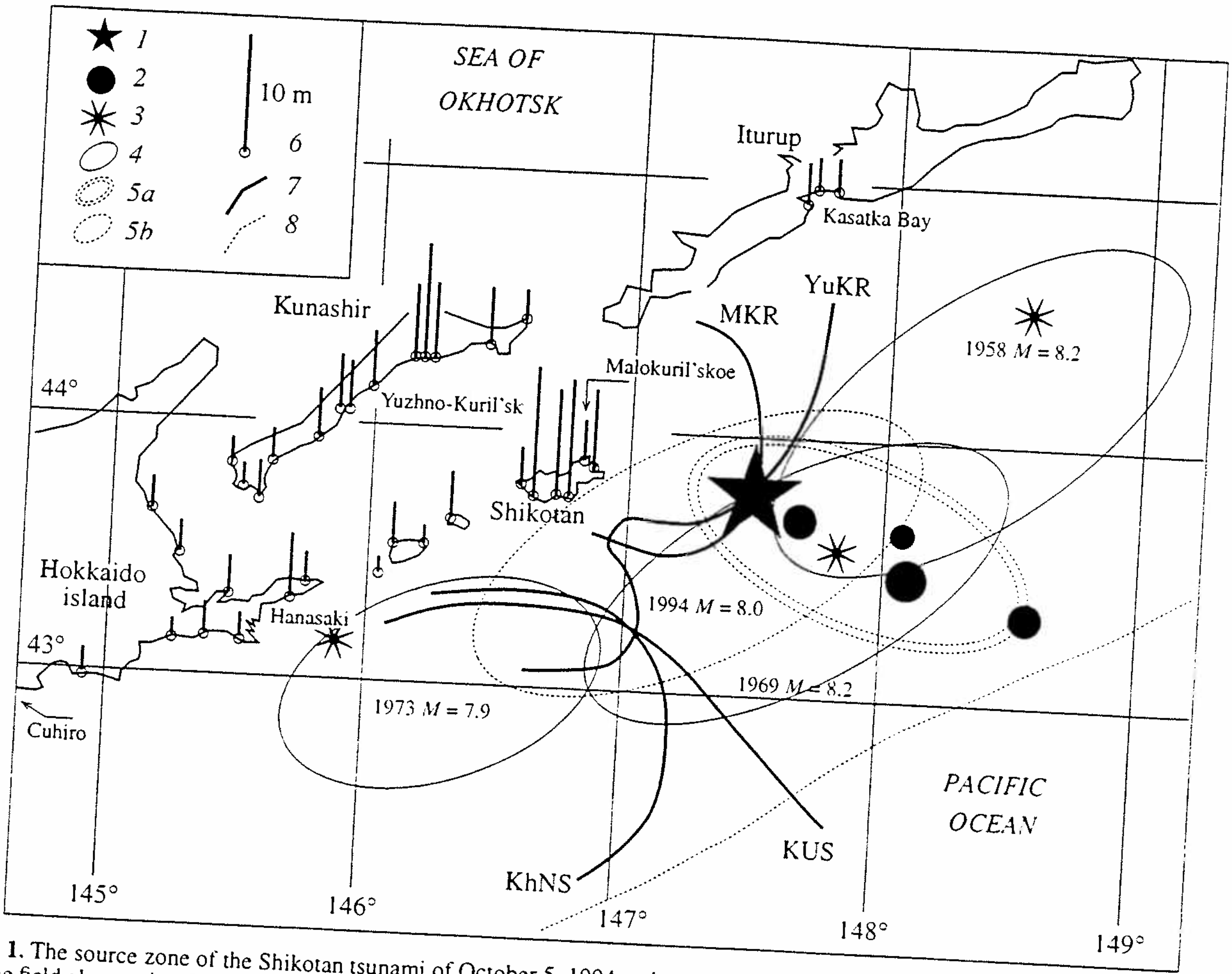

Fig. 1. The source zone of the Shikotan tsunami of October 5, 1994 and maximal observed tsunami heights at the coast (according to the field observations). Epicenters of: (*1*) the main shock of October 5, 1994; (*2*) aftershocks with $M_S > 6.8$ during the first 6 hours after the main shock; (*3*) for most powerful historical earthquakes (year and magnitude of earthquakes are cited); contours of tsunami: (*4*) powerful historical tsunamis; the tsunami of October 5, 1994: (*5a*) according to the most powerful aftershocks during the first 6 hours, (*5b*) according to the aftershock zone during the first week; (*6*) inverse isochrones of the tsunami runup plotted for the coastal sites; (*7*) the coastal sites and maximal tsunami heights; (*8*) the deep trough axis.

after the main shock. This suggests the possibility of the source zone having a different orientation (Fig. 1). On the whole, in its seismic parameters ($M_S > 8$), the earthquake of October 5 is a typical event (Table 1 and Fig. 1) for subduction zones such as the area of the South Kurils. But it differs from previous events in the following features: (a) proximity of the source zone to Shikotan; (b) the rather great value of the sourc's seismic moment (M_0) for the event with $M_S = 8.0$; and (c) the considerable value of the shear displacement component in the source. The substantial macroseismic effect caused by this earthquake and the high intensity of the associated tsunami which accompanied it, to a certain extent can be attributed to these source features.

Table 1. Basic parameters of the most powerful earthquakes and tsunamis in the area of the South Kurils according to [3–8]

Date	Time in the source			Coordinates of the hypocenter, degrees		H, km	M_s	M_0, H_m	Rupture plane in the source, degrees			Parameters of the tsunami	
	h	min	s	N	E				Str.	Dip	Slip	i_0	H_m, m
06.11.58	22	58	09	44.53	148.54	40	8.2	4.4	46	58	97	+2.0	5
11.08.69	21	27	36	43.58	147.82	40	8.2	2.2	50	70	98	+1.5	5
17.06.73	03	55	02	43.15	145.88	55	7.9	0.67	43	67	81	+1.0	1.5
04.10.94	13	23	01	43.8	147.5	30	8.0	2.9–3.7	58	69	142	+2.0	10.8

Note: Str.—strike, Dip—dip angle of rupture plane in the source, Slip—slip angle within the rupture plane, i_0—tsunami intensity in the source, H_m—maximal recorded tsunami height at the coast.

ACTIVITIES OF THE TSUNAMI WARNING SERVICE

The seismic sections of the service was based during the earthquake on the work of only one Yuzhno-Sakhalinsk seismic station (observations at the Kuril'sk and Shikotan tsunami stations stopped in March 1994). The tsunami alarm signal was given by the station 8 min after the beginning of the earthquake registration (standard time 10 min); the tsunami warning was cabled to Kuril'sk (on the island of Iturup) in 15 min, but to Yuzhno-Kuril'sk (Island Kunashir) only 7 h after the alarm had been announced, as the earthquake had extensively damaged telecommunication equipment and upset the link with Yuzhno-Kuril'sk. In fact, the population of Kunashir, Shikotan, and other islands of the South Kurils had been notified about the tsunami hazard not by the responsible service but by N. A. Pokidin, Mayor of Yuzhno-Kuril'sk, on the basis of a powerful earthquake. The alarm retreat signal was communicated to the South Kurils 8.5 h after the earthquake when further changes of the ocean level were no longer considered dangerous to the population. It should be admited that the operative tsunami warning service failed to fulfill its duties because of its extremely poor technical equipment for observations and communication.

FIELD INVESTIGATION OF THE TSUNAMI CONSEQUENCES

In the ten days after the earthquake, a group of geophysicists and oceanographers from a number of Russian academic institutes, Sakhalingidromet, and two U. S. universities left for the South Kurils to collect field data on tsunami manifestations. The field work was carried out during a fortnight through visual inspections, photography, and geodetic and aerial surveys. The most detailed investigations were performed on the coast of Shikotan and Kunashir islands on the sides facing the tsunami source. The tsunami run up height and flooding distances on the coast were measured without any particular difficulties since they were carried out using fresh evidence. In most cases the flooding boundary could be clearly distinguished by seaweed deposits and, debris, by the upper edge of grass cover affected by saline sea water, or by other signs. Using the aerial survey in certain coastal areas allowed researches to estimate the flooding boundary immediately throughout the whole area and approximately estimate (based the topographic data) wave heights. Later, these data were used to choose the sites for accurate measurements of runup heights using geodetic methods. The measurement results for individual sites are presented in Table 2; in Fig. 1, the data are supplemented by observations of our japanese colleagues for the island of Hokkaido.

The greatest material damage from the tsunami was observed in the old part of Yuzhno-Kuril'sk situated on the gently-sloping coast. Here the flooding distance was on the average 200–250 m, whereas in the floodplain it was about 900 m. Practically all buildings in the flooding zone were damaged, and some entirely destroyed. The tsunami wave washed away three houses, one of which was pulled from its foundation and carried upstream 300 m. Many light

Table 2. Measured maximal height of the tsunami wave runups on October 5, 1994 above the theoretical zero depth (according to field observations)

Measurement site	Coordinates of the measurement site		Tsunami height, m	Measurement site	Coordinates of the measurement site		Tsunami height, m
	N	E			N	E	
The South Kurils				The Kurils			
Shikotan				Kunashir			
Dimitrov Bay	43°46′	146°34′	6.3–10.8	From Krugloe L. to Filatova R.			4.0–5.0
Krabovaya Bay	43 52	146 42	3.2–3.4	Ilyushina R	44°10′	145°57′	6.3–9.8
Malokuril'sk Bay	43 54	146 48	2.9–3.7	Kosmodem'yanskaya Bay	44 07	145 52	4.6
Tserkovnaya Bay	43 16	146 40	6.0–8.9	Yuzhno-Kuril'sk	44 04	145 50	4.0–4.8
Zelenyi				Izmena Gulf,	43 44	145 30	2.0–2.6
Southeast coast,	43 29	146 06′	1.5*	Iturup			
Polonsk				Kastka Gulf	44 54′	147 40	3.4
Chasovnya Bay,	43 41	146 18	4.0*	Sakhalin			
Yurii				Katangli			0.2**
Bahlanii Cape	43 26	146 06	3.5*	Poronaisk	49 13	143 06	0.3**
Shirokaya Bay	43 25	146 05	1.5*	Starodubskoe	47 25	142 51	0.3**

Note: One asterisk denotes visual evaluations, two asterisks indicate mareograph records.

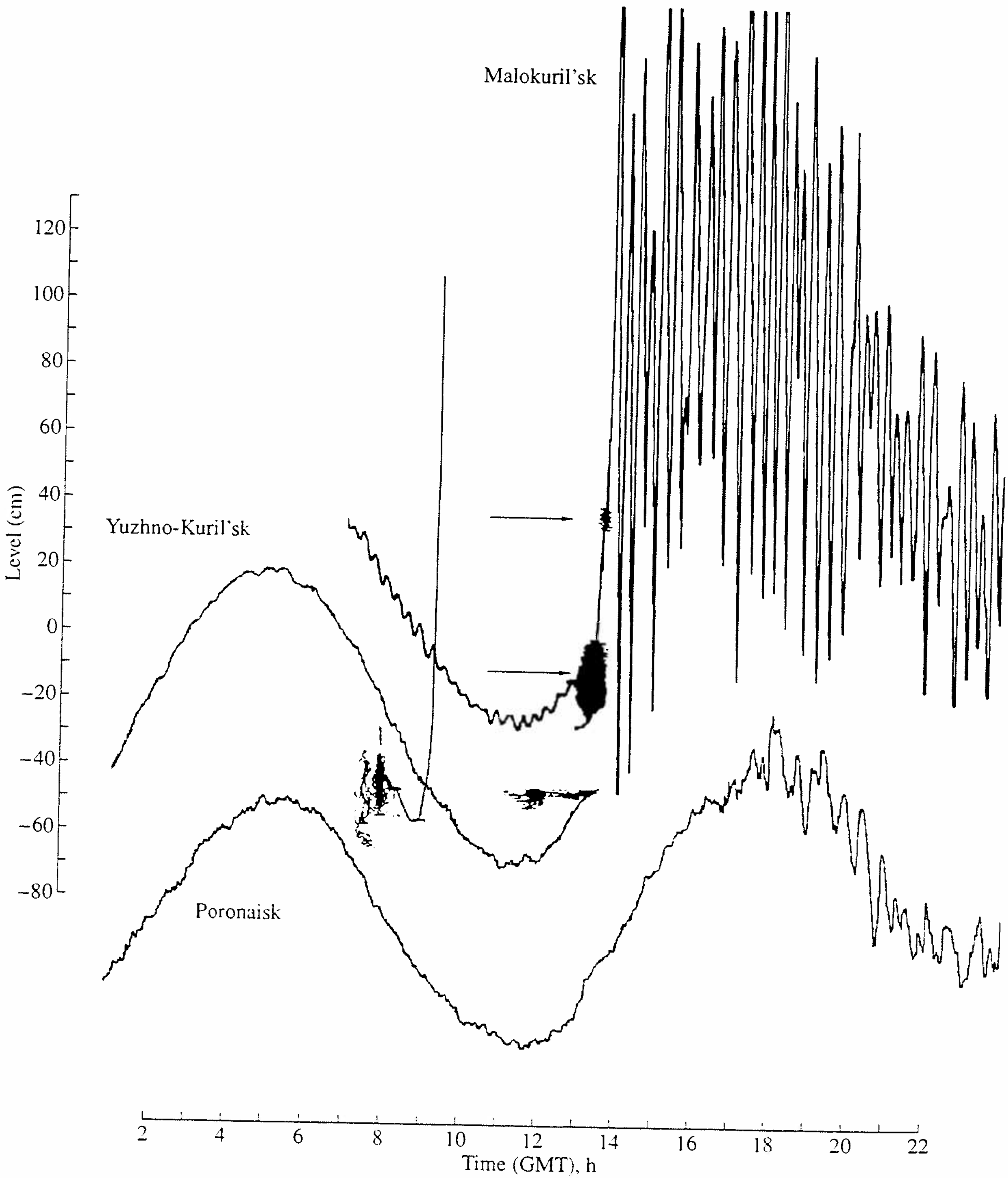

Fig. 2. Records of sea-level oscillations caused by the tsunami of October 5, 1994 in Malokuril'sk (Shikotan I.), Yuzhno-Kuril'sk (Kunashir I.), Poronaisk (Sakhalin I.). Arrows show the main shock moment and recorder pen position which documented the sea-level variation preceding the wave arrival.

structures were washed away tens of meters. The tsunami destroyed and damaged the moorage and parts of industrial buildings in the port. Two vessels sank, seven flat-bottomed barges and a passenger boat were cast up on the shore, and several vessels that had been cast up on the shore by the preceding typhoon were carried by the tsunami wave further into the land distances of from 30 to 200 m. On the island of Shikotan, in Malokuril'sk Bay, the tsunami manifested itself as resonance seiche oscillations with an amplitude up to 2 m and period about 20 min. Here moorages and moored vessels were severely damaged.

Table 3. Comparison of the observed and calculated tsunami heights in reference sites for different models of the source

Model	Source dimensions, km	Wave period, min	Amplitude of the initial disturbance, m	Mean H_0/H_c
1	130×40	4	+2.7/–0	1.5 ± 0.5
2 (Fig. 1, *5a*)	$\sim 160 \times 70$	12	+1.5/–1.5	1.3 ± 0.4
3 (Fig. 1, *5b*)	$\sim 180 \times 80$	12	+1.8/–0.7	1.1 ± 0.3

One of the most important field observations, established using geodetic and depth measurements, suggests that Shikotan Island subsided by 0.5–0.7 m because of the earthquake. Information from local inhabitants about the subsidence of Anuchin and Plonskii, as well as the southern (Izmena Gulf) and central (Stolbchatyi Cape) part of Kunashir, after the earthquake has not yet been confirmed by instrumental measurements. The subsidence of islands does not contradict the data on the main shock mechanism but requires detailed investigations in the future.

Interesting information was received from eyewitnesses who, while their vessels were at sea, happened to be near the epicenter during the earthquake. The "seaquake", as has already been noted [9, 10], was felt by many people as a most powerful impact on the vessel's body followed by prolonged (several tens of

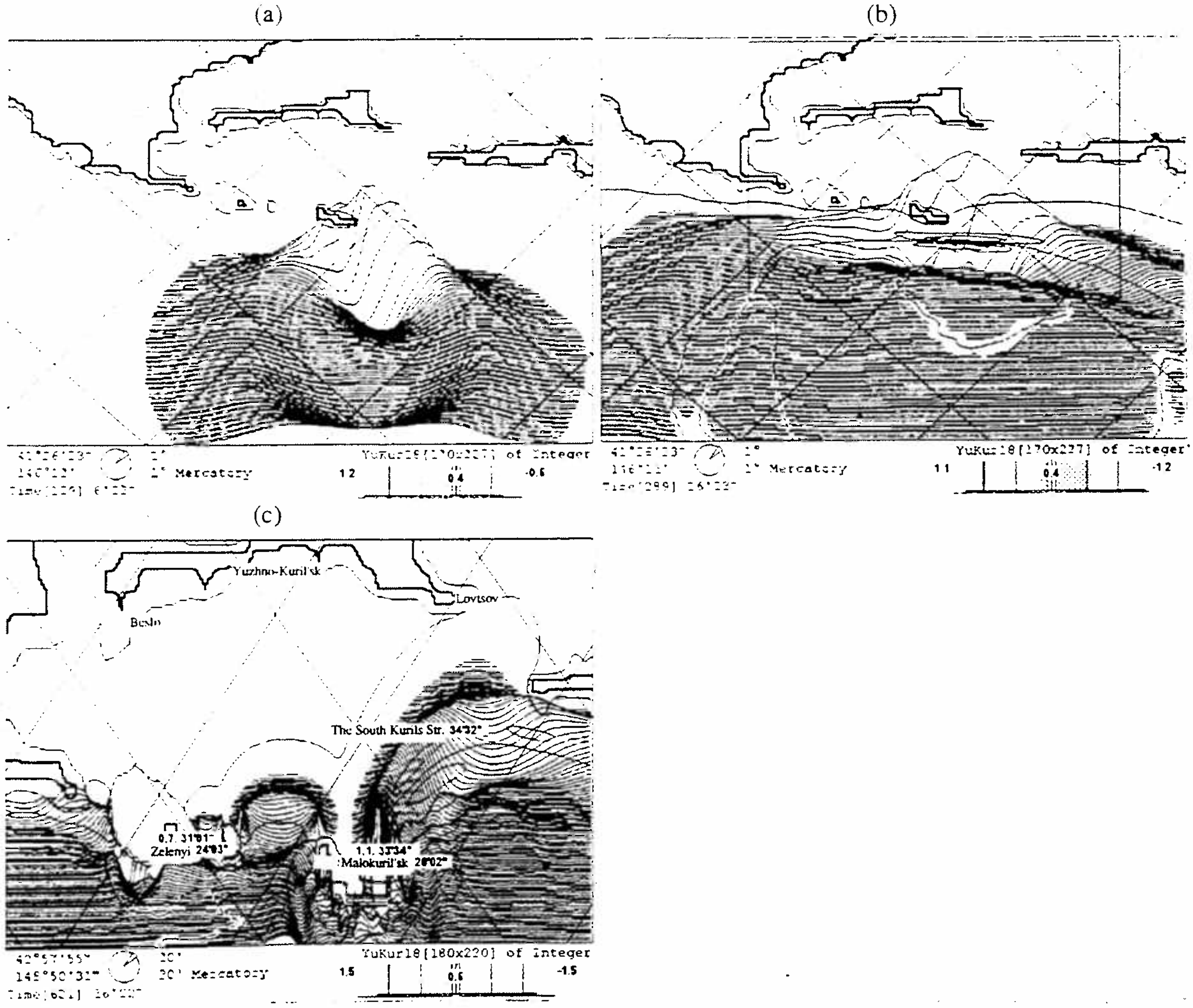

Fig. 3. Numerical modelling results for the Shikotan tsunami of October 5, 1994 in the area of the South Kurils: (a) the configuration of ocean disturbance source 6 min after the earthquake, maximal height in the source 1.7 m; (b) transition from the general calculated bathymetry with a step of 1.8 km to the more detailed one (1 km); the area of South Kurils Strait is shown in the frame; (c) arrival of the first tsunami wave into the South Kurils Str. The off-figure data denote coordinates of the bottom left network corner, the form of cartographic projection, time from the start of the earthquake (h, min, s), and sea-level height gradations which serve as a scale.

seconds) vibration. In [11] it is shown that these effects can be explained by the action of a shock wave induced in the watermass by a powerful earthquake.

INSTRUMENTAL RECORDING OF THE TSUNAMI

The wave records were obtained by many coastal automatic sea-level recorders not only in Russia and Japan, but also at distant stations Hawaii, Alaska, etc.). The records from the four mareographs nearest to the source (in Malokuril'sk, Shikotan Island; Yuzhno-Kuril'sk, Kunashir Island; Hanasaki and Cushiro, on Hokkaido), are most interesting (Fig. 2). The record from Yuzhnokuril'sk is practically unsuitable for studying the tsunami wave characteristics because the recorder pen jumped back along the time axis during the shock and was hooked by the paper edge after the arrival of the tsunami wave. It can be seen that approximately 30 min after the shock a small ebb of 10 cm took place and was followed 30 min later by an abrupt sea-level rise. According to the information received from eyewitnesses, the tsunami in Yuzhno-Kuril'sk started with an ebb that occurred 30–60 min after the main shock. Then followed three great waves with a period of about 15 min. The Malokuril'sk recorder clearly shows the trace from the main shock as a thick ink blot, subsequent rapid sea-level elevation, and seiche oscillations with a period of about 20 min. Comparison of the observed tide with the predicted one points to coast subsidence resulting from the carthquake in the area of Malokuril'sk Bay by about 0.6 m. Spasmodic level variations caused by residual surface deformation during the earthquake are also observed to a lesser extent on the mareograph records in Hanasaki and Cushiro. These four records allowed researcher to determine run times of the tsunami from the source plot inverse run time isochrones (Fig. 1), and specify the source boundary on the island slope side. This boundary probably corresponds to the overthrusted oceanic limb of the fault in the source zone (Table 1) that induced the most intensive tsunami waves.

NUMERICAL MODELLING OF THE TSUNAMI

Calculation of expected tsunami heights based on seismic data is just being introduced into the operative tsunami warning service. For the first time in the Russian service, such calculations were performed for the tsunami of October 5, 1994. Calculations were based on the operative data obtained in the Sakhalingidromet Tsunami Center. They were carried out in accordance with the scheme implementing the equations for long waves in shallow water and by observing the approximation criteria for the rated wave period [12]. An example of one such calculation is given in Fig. 3, and Table 3 shows generalized results of comparisons between observed and calculated tsunami heights at 5–6 coastal reference sites for 3 models of the source whose characteristics were refined as new seismic and mareographic data were obtained. On the average, the agreement between observed and calculated data should be considered satisfactory even for the first source model, which had been set, rather inaccurately, by empirical formulas using the operative evaluation $M_S = 7.7$ and the first determination of the epicenter coordinates. For the third variant which, evidently, gives the closest approximation of the real source the calculated data give a tsunami height distribution which agrees well with the field observations.

In conclusion, it should be noted that the operative field investigation of the consequences of such rare natural catastrophes as the Shikotan tsunami of October 5, 1994, which was among the most powerful in the area in this century, is extremely important. The recurrence of such an event is estimated to occurapproximately every fifty years [13]. Investigation materials combined with numerical modelling would allow researchers to scrutinize the available theoretical models of tsunami waves and improve operative and long-term tsunami predictions.

ACKNOWLEDGMENTS

The authors thank the administration of the Yuzhno-Kuril'sk district for their assistance in our investigation, N.S. Terent'ev (Informgeotsentr GP Vostokgeologiya, Yuzhno-Sakhalinsk) for the aerial survey materials, and our Japanese colleagues, Dr. M. Kasahara from Hokkaido University, Sapporo, and Prof. Shuto from Tohoku University, Sendai, for the presented data on the earthquake aftershocks and tsunami heights on Hokkaido. This work was supported by the Presidium of the Far East Division, Russian Academy of Sciences, and by the Russian Foundation for Basic Research, projects nos. 93-05-8073, 93-05-8110, 93-05-14499, and 94-05-16722.

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