EVALUATION OF TSUNAMI HAZARD FOR THE SOUTHERN KAMCHATKA COAST USING HISTORICAL AND PALEOTSUNAMI DATA

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Abstract. An example of solution of the problem of quantitative evaluation of the tsunami hazard is considered using tsunami data for the Kamchatka coast. This approach is based on the probability model of the Poisson type for tsunami process, with parameters calculated using geophysical data. The quality of the model used for tsunami risk estimation depends on the tsunami incidence frequency f and characteristic tsunami height H^*. The parameters f and H^* are not stationary and we refer them to their evolution as dispersion.

Three models using different tsunami data sets were considered: a homogeneous model based on a 50-year data set, a second model using the same set with additional 15-meter run-up data on Khalaktyrka coast in eastern Kamchatka caused by the 1841 tsunami, and a third model using the additional paleotsunami data from Khalaktyrka lake.

The comparison between them allows to conclude, that using the paleotsunami data for an elected point combined with the historical data makes the dispersion of the tsunami process parameters f and H^* much less.

1. Tsunamis on the Kamchatka coast

Tsunami on the Kamchatka coast are dangerous events. The catastrophic 1952 tsunami destroyed almost fully the Severo-Kurilsk city on the Paramushir Island and several settlements on the Southern Kamchatka coast. Since then, the run-up of two tsunamis was more than 7 meters, while the run-up of the 1969 tsunami reached 15 meter [1-6]. Hence quantitative evaluation of the tsunami risk on the Kamchatka coast is an important problem. Unfortunately, all the catalogues and articles [3-6] contain data only for period 250 years while only data sets related to 6 strong and moderate tsunamis occurring during the last 50 years are of sufficient quality. There are single data for other tsunamis. Tsunami data sets for the last 50 years are given in the Table.1 and incidence is shown in Figure 1.

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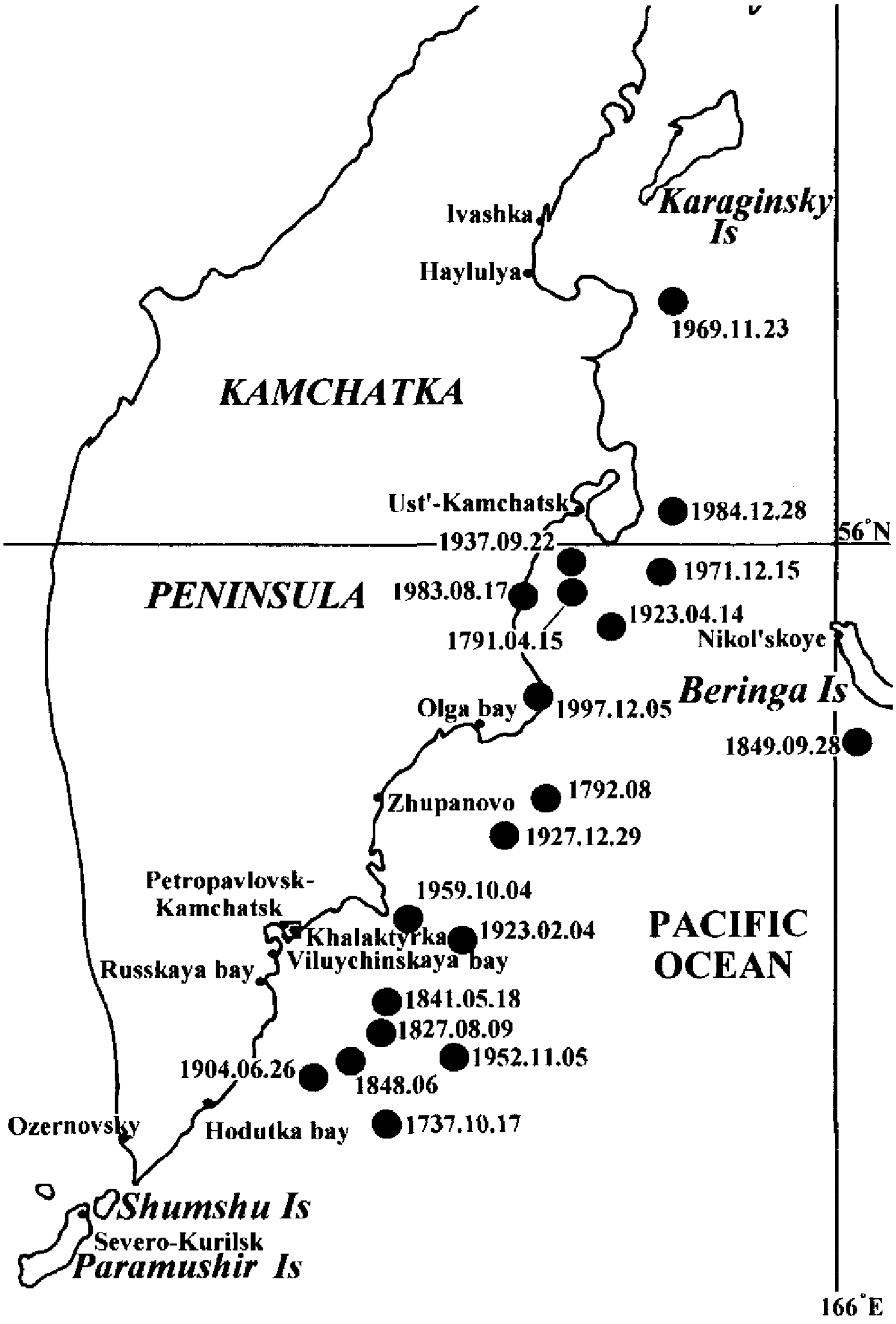

Figure 1. Tsunami sources distribution around Kamchatka

TABLE 1. Maximal tsunami run-up's for Kamchatka peninsula coast and the nearest Islands for the time period since 1952

Point	Tsunami data (year. month. day)												
	1952	1959	1960	1963	1964	1965	1969	1971	1973	1983	1984	1985	1997
	11.05	05.04	05.04	10.13	03.27	02.04	11.23	12.15	02.28	08.13	12.28	03.05	12.05
Lavrova bay							2.0						
Ivashka							7.0						
Haylulya							7.0						
Ozernoy cape							5.0						
Olhovaya riv.							15.0						
Ozernaya bay							3.0						
Ozernoy riv.							7.0						
Ust'Kamchatsk (town))	0.1		0.55				0.2	0.45		0.02	0.02	0.03	
Ust'Kamch.(sea coast)	0.5		4.0					2.0					
Olga bay	13.0		4.0										1.0
Zhupanovo	5.0		4.0										0.5
Morzhovaya bay	8.0	2.0	7.0										
Shipunsky cape	12.0		3.0										
Nalychevo	7.0												
Khalaktyrka	5.0		2.0										
Bezymyanny cape	5.0												
Rokovaya bay	3.0												
Petropavlovsk.Kamch.	1.2	0.13	0.6	0.07	0.07	0.09	0.04	0.06				0.02	0.02
Tarya bay	3.0		1.0										
Mayachny bay	5.7		2.0										
Vilyuchinskaya bay	8.0		5.0										
Sarannaya bay	7.0												
Zhirovaya bay	8.0												
Russkaya bay	7.0		7.0										
Povorotny bay	10.0												
Asacha bay	7.0												
Hodutka bay			3.0										
Utashud Is.	8.6												
Lopatka cape (East)	9.5		2.0										
Lopatka cape (West)	5.0												
Ozernovsky	5.0												
SeveroKurilsk	15.0		4.7		0.8	0.1		0.1	0.76				
Medny Is.			1.0										
Nikolskoye	2.0		3.5				2.5				0.17		

2. Paleotsunami data at Khalaktyrka.

Because of bad situation with historical tsunami data geological deposits related to paleotsunami were investigated near Khalaktyrka beach. Two profiles in this region were investigated (Fig.2). 11 sections 309-320 were made along the profile PR-1 and 8 sections 301-308 were made along the profile PR-2. The sandy layers found in the sections were considered as tsunami traces [7-13]. Thickness of tsunami layers was 0.5 – 20 cm. and decreased along along the profile for big distance from the coast. Special tephrastratigraphy sections 2001 – 2007 were made near Khalaktyrka lake far from the coastal area.

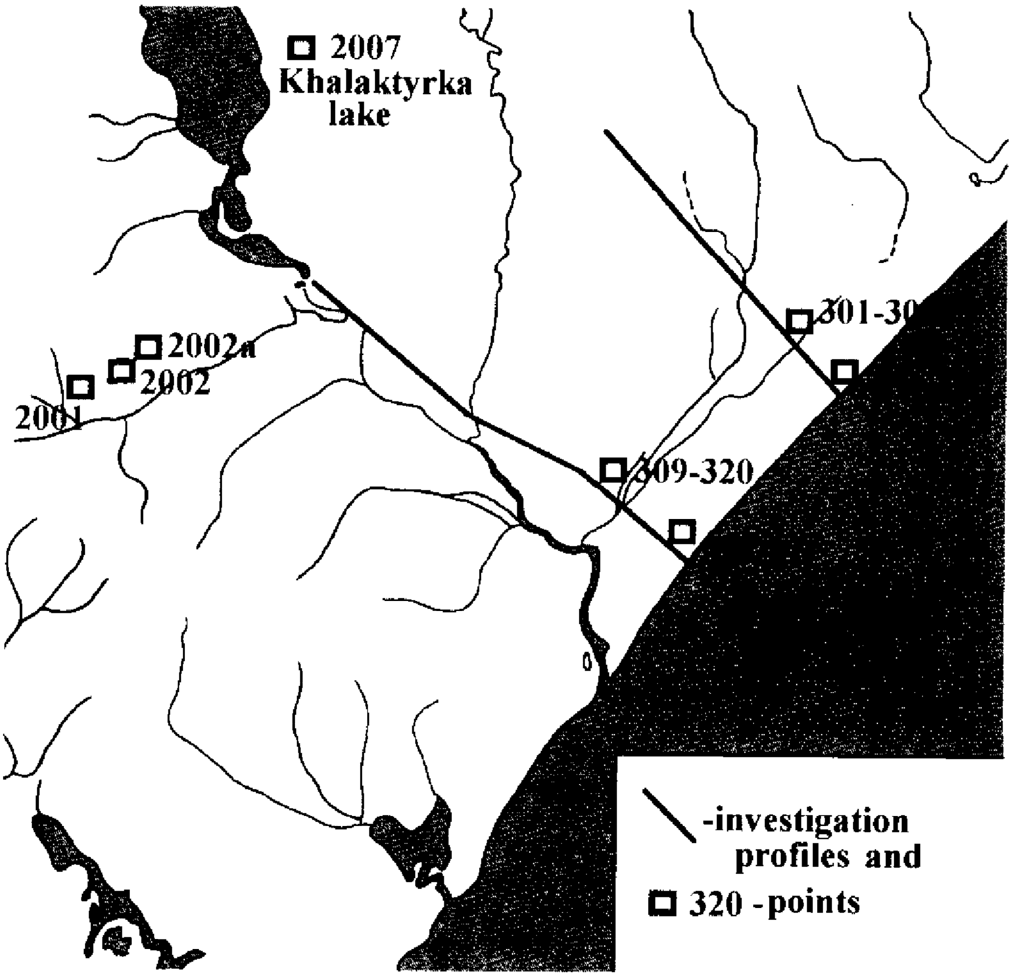

Figure 2. Investigation area near Khalaktyrka beach.

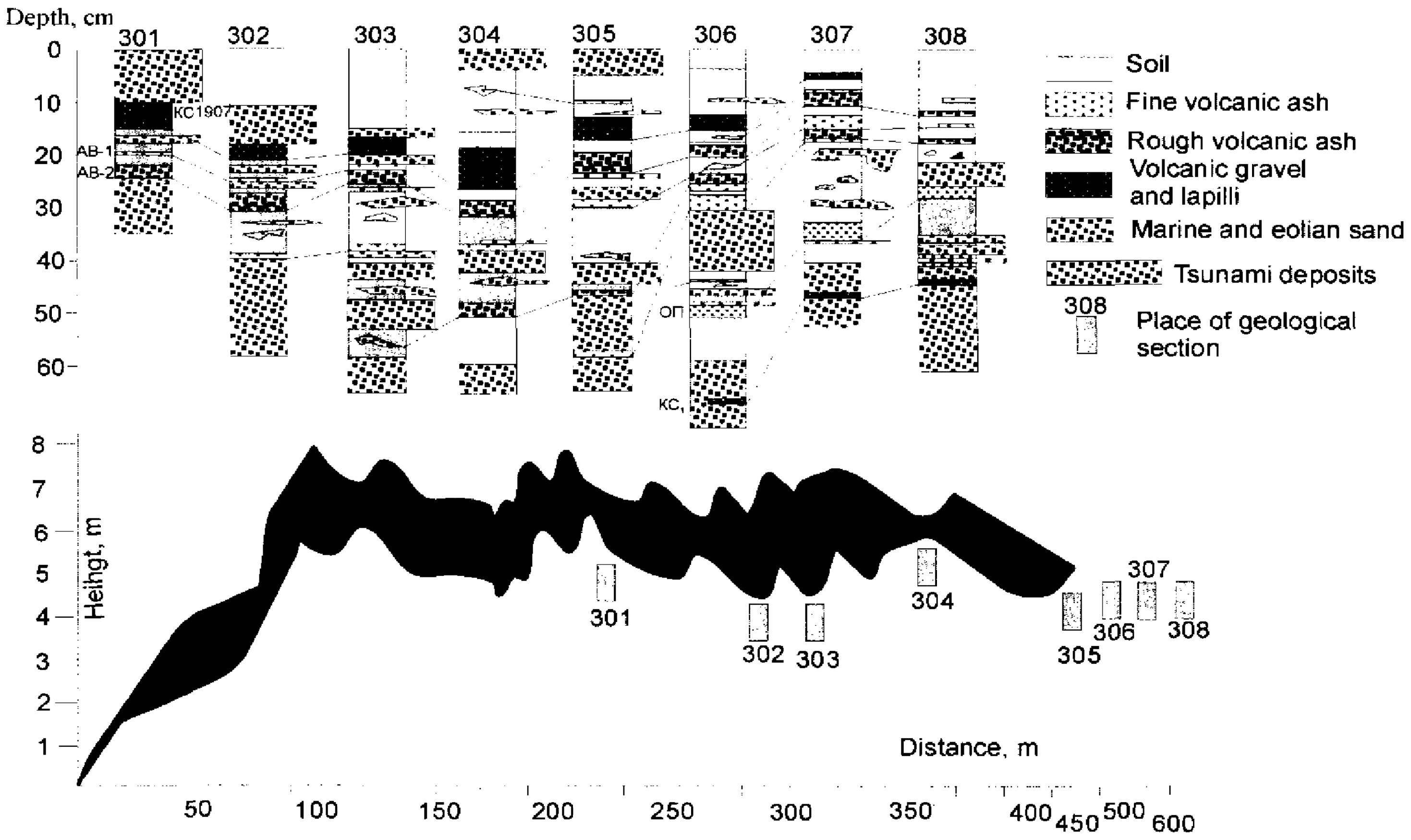

Figure 3. The section structures along the profile N 2

Several layers contained organic woody material used for ^{14}C dating. The age of the most tsunami deposit layers was estimated by tephrastratigraphy and tephrachronology methods using the tephra layers related to good investigated volcano eruptions [14]. The section structures along the profile PR-2 are shown on the Fig.3. The general synthesis related 13 tsunamis using all the geological sections after correlation of tsunami and tephra layers, as follows.

The two upper tsunami layers are related to the good known events at 1952 and 1959 (1960 ?).

According to position between two key-marker tephra layers dated 1855 (Avacha) and 1907 (Ksudach), the third tsunami layer should be the trace of the 1904 tsunami. 4-th and 5-th tsunami layers are located between two tephra layers of the Avacha volcano dated 1855 and 1779 and can be related to tsunami events at 1841 and 1792 (1827 ?). 6-th, 7-th and 8-th tsunami layers are located between two tephra layers dated 1779 (Avacha volcano) and 606 (Opala volcano). Upper tsunami trace can be from the great 1737 tsunami. Its description made by Krasheninnikov was the first tsunami description in the Russian history [6]. All the others tsunami layers do not seem related to any historical events. 9-th, 10-th and 11-th tsunami layers are located between two tephra layers dated 606 (Opala volcano) and 236 (Ksudach volcano). That layers are distinct on the distance to 700-750 m from the recent shoreline. 12-th and 13-th tsunami layers are located between two tephra layers dated 236 year (Ksudach volcano) and 3500 years ago (Avacha volcano). That layers are distinct on the distance to 900 m from the recent shoreline.

The most recent height of the coastal ridge is about 8 m over the sea level and we have to consider all the found tsunami having the wave height more than 8 m.

3. Probability model for tsunami process

The problem of quantitative evaluation of the tsunami risk can be addressed with the probability model of the Poisson type for tsunami process, and parameters of this model can be calculated using the geophysical data.

So, probability to have n tsunamis with height more than h_0 at a selected location is given by the following formula [15]:

$$P_n(h \ge h_0) = \frac{[\varphi(h_0)\cdot T]^n}{n!}\cdot e^{-\varphi(h_0)\cdot T} \qquad (1)$$

where T is the observation time interval, $\varphi(h_0)$ is the mean frequency of tsunamis with height more then the "threshold" h_0. The last function is the recurrence function. The asymptotes of the tsunami recurrence function for extreme tsunami heights should be in accordance with good known extreme statistics suggesting on exponential approximation for an empirical recurrence function,

$$\varphi(h) = f(x)\cdot e^{-\frac{h}{H^*(x)}} \qquad (2)$$

which is in accordance with a double negative exponential law for extreme values [16-17]. The parameter H^* is the calibrated (characteristic) tsunami height and depends on the coastal point x of tsunami observation, and f is tsunami incidence frequency. The tsunami incidence frequency is regional one varying very slowly along the coast. Hence it can be considered as a constant value for all points of Southern Kamchatka region.

In practice the functions $\varphi(h)$ are inferred from the tsunami catalogues, and they do not often contain sufficient data. The weighted least square method [3] allows the estimation of the tsunami activity parameters H^* and f. The average tsunami incidence frequencies related to the ordered tsunami heights $h_1 > h_2 > h_3 > \ldots h_k$ and their dispersions are presented by formulae in [15], as follows

$$\overline{\ln \varphi(h_k)} = \sum_{s=1}^{k-1} \frac{1}{s} - 0.577 - \ln T \qquad (3)$$

$$\sigma(\ln \varphi(h_k)) = \sqrt{\frac{\pi^2}{6} - \sum_{s=1}^{k-1} \frac{1}{s^2}} \qquad (4)$$

Clearly, Eq. 4 shows that the dispersion of logarithm of tsunami recurrence function is decreasing function of the number k of ordered tsunami run-up and incidence related to the maximal tsunami height h_1. The weighted least square method can be used to estimate the parameters H^* (for many points) and f (a single value for all region) of the empirical recurrence function with its dispersions (a priori errors) [18].

Only 6 strong and moderate tsunamis occurred during the last 50 years have been well described in catalogues (see Table 1). There are single data for other tsunamis.

The frequency f of strong tsunamis should be a stable regional parameter, and its a priori error can be considered as a general indicator of data quality. The standard deviation σ of the parameter $\ln(f)$ can be considered with a relative a priori error $\sigma(\ln(f)) \approx \frac{\sigma(f)}{f}$ for the tsunami incidence frequency.

4. Historical and paleotsunami data analysis.

The homogeneous probability model (1) *for the Southern Kamchatka coast based on the* 50-year data sets (see Table 1) gives the following parameters: f=0.07 1/y, $\sigma(\ln(f))$=0.2 (regional) and calibrated tsunami heights H^* and its standard deviations H^*=0.7 m, $\sigma(1/H^*)H^*$=0.6 for Petropavlovsk-Kamchatsky and H^*=2.8 m, $\sigma(1/H^*)H^*$=0.6, for Khalaktyrka, where σ is standard deviation.

The product $\sigma(1/H^*) \cdot H^* \approx \frac{\sigma(H^*)}{H^*}$ can be considered as a relative a priori error of parameters H^* and its values (see Table.2) shows that having historical data do not allow calculation of needed parameters with good accuracy.

The second model uses the same set but adds the 15-meter run-up measurement on the Khalaktyrka coast caused by the 1841 tsunami. The second model gives following parameters: f=0.07 1/y, $\sigma(\ln(f))$=0.2 and H^*=0.8 m, $\sigma(1/H^*)H^*$=0.6 (Petropavlovsk) and H^*=4.5 m, $\sigma(1/H^*)H^*$=0.4 (Khalaktyrka). So, using a single addition of historical measurement for Khalaktyrka changes the H^* for this point in the frames ($\pm\sigma$) of the model 1 and makes the relative error less for the same point only, while it does not change the parameters for all the others points.

To improve the model, in Autumn 2000, the traces of paleotsunami on Khalaktyrka coast were investigated. During this expedition, 13 tsunami deposits were found on the 8-meter terrace.

The model 3 uses the initial 50-year data sets and the additional 1841 tsunami date and paleotsunami data set for Khalaktyrka, results into the following parameters: f=0.07 1/y,

$\sigma(\ln(f))=0.2$ and $H^*=0.8$ m, $\sigma(1/H^*)H^*=0.6$ (Petropavlovsk) and $H^* = 4.2$ m, $\sigma(1/H^*)H^*=0.15$ (Khalaktyrka). Using a good additional set of paleotsunami data for Khalaktyrka changes the H^* for this point from in the Model two and makes the relative error much less for the same point only while not changing the other parameters.
Corresponding results are shown on the Figure 4 and Table 2.

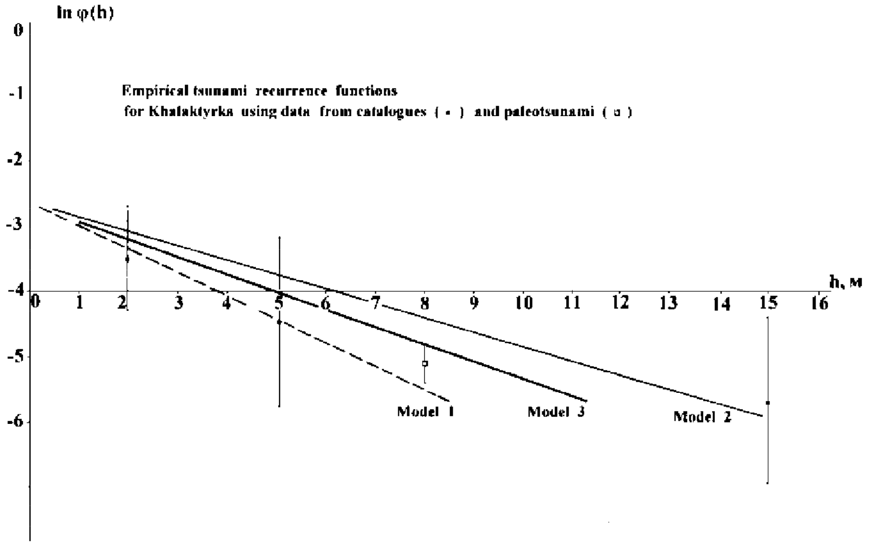

Figure 4. Empirical tsunami recurrence function for Khalaktyrka for three different models.

The most essential details on this picture are standard deviations related to different kinds of tsunami data. Tsunami heights 5 m (1952) and 15 m are (1841) are maximal values for corresponding periods and have maximal standard deviations. This fact explains the advantage of paleotsunami data. Tsunamis with a great run-up are rare events but many tsunami traces can be found for the long pre-historic period.

TABLE 2. Tsunami activity parameters *f* and H^* of three probability models for the Kamchatka coast and the nearest Islands.

Points	Model 1 Based on historical data for period 1952-2000 $\ln(f)=-2.65$, $f=0.07$ 1/year, $\sigma(\ln(f))=0.2$		Model 2 Based on historical data for period 1952-2000 with 15-meter run-up for Khalaktyrka (1841) $\ln(f)=-2.68$, $f=0.07$ 1/year, $\sigma(\ln(f))=0.2$		Model 3 Based on historical data for period 1952-2000 with 15 meter run-up for Khalaktyrka (1841) and paleotsunami data $\ln(f)=-2.68$, $f=0.07$ 1/year, $\sigma(\ln(f))=0.2$	
	H^*, m	$\sigma(H^*)/H^*$	H^*, m	$\sigma(H^*)/H^*$	H^*, m	$\sigma(H^*)/H^*$
Ust'Kamchatsk (town)	0.5	0.7	0.52	0.73	0.53	0.73
Ust'Kamch. (sea coast)	2.35	0.61	2.41	0.62	2.42	0.63
Olga bay	6.67	0.61	6.83	0.62	6.85	0.63
Zhupanovo	3.86	0.64	3.96	0.65	3.98	0.66
Morzhovaya bay	6.79	0.65	7.00	0.67	7.03	0.67
Shipunsky cape	6.14	0.63	6.26	0.64	6.28	0.64
Nalychevo	3.95	0.73	4.01	0.74	4.02	0.75
Khalaktyrka	**2.75**	**0.62**	**4.52**	**0.37**	**4.17**	**0.16**
Bezymyanny cape	2.82	0.73	2.86	0.74	2.87	0.74
Rokovaya bay	1.69	0.73	1.71	0.74	1.72	0.74
Petropavlovsk-Kamch.	0.72	0.63	0.75	0.65	0.75	0.65
Tarya bay	1.58	0.62	1.61	0.63	1.62	0.63
Mayachny bay	3.04	0.62	3.10	0.63	3.11	0.63
Vilyuchinskaya bay	5.32	0.63	5.44	0.64	5.46	0.64
Sarannaya bay	3.95	0.73	4.01	0.74	4.02	0.75
Zhirovaya bay	4.51	0.73	4.58	0.74	4.59	0.74
Russkaya bay	6.64	0.67	6.81	0.69	6.83	0.69
Povorotny cape	5.64	0.73	5.73	0.74	5.74	0.75
Asacha bay	3.95	0.73	4.01	0.74	4.02	0.75
Hodutka bay	3.87	1.07	4.01	1.11	4.03	1.11
Utashud Is.	4.85	0.73	4.93	0.74	4.94	0.75
Lopatka cape (East)	4.84	0.64	4.93	0.65	4.94	0.65
Lopatka cape (West)	2.82	0.73	2.86	0.74	2.87	0.74
Ozernovsky	2.82	0.73	2.86	0.74	2.87	0.74
Severo-Kurilsk	7.87	0.63	8.07	0.64	8.11	0.64
Medny Is.	1.3	1.07	1.34	1.11	1.35	1.12
Nikolskoye	3.35	0.7	3.47	0.72	3.49	0.73

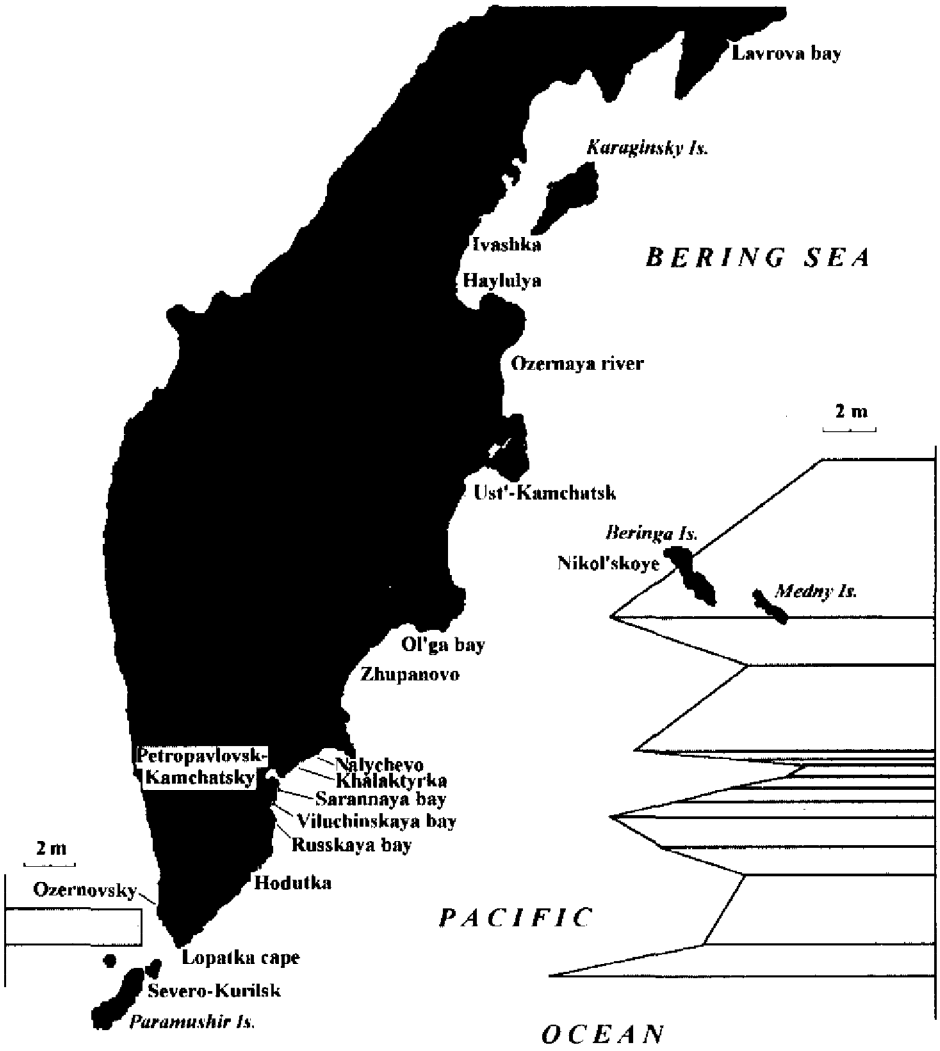

Figure 5. The observing tsunami h_{100}-zoning scheme for the Southern Kamchatka coast and the nearest Islands

Having the tsunami activity parameters f and H^*, we can estimate the tsunami hazard for any selected locale. For example the average maximal tsunami height with recurrence period t can be calculated by formula [15]:

$$h_t = H^* \cdot \ln(f \cdot t) \qquad (5).$$

Observed tsunami zoning scheme for the Southern Kamchatka coast can be created using Model three as given in the Table 3. The results are shown in the Figure 5 for average maximal tsunami height with recurrence period of 100 years.

5. Conclusions.

Historical and paleotsunami data for the Kamchatka coast were analysed and applied to estimating tsunami hazards using a probabilistic model.

The quality of probability model used for tsunami risk estimation depends on the quality and quantity of geophysical data used for its creation. Using the good set of paleotsunami data for any selected point makes the relative error of the tsunami activity parameters less compared to calculations using just data available in catalogue

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