Using the paleotsunami data for the tsunami hazard assessment

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Abstract. The article is focused on the development of statistical methods of the tsunami recurrence evaluation using paleotsunami data. The new key moment is the creation of a model to quantify the preservation potential of paleotsunami deposits. The article includes a brief overview of the results of studies of the variability and preservation of tsunami deposits. The model was tested on materials about paleotsunami on the coast in the Khalaktyrka area (a village within the city of Petropavlovsk-Kamchatsky), obtained earlier, for four time intervals set by the key-marker volcanic tephra layers in Kamchatka (Ksudach in 1907, Avachinsky in 1855 and 1779, Opala in 606). The maximum likelihood estimates of the number of tsunamigenic horizons for the indicated time intervals are given. The restrictions of the considered model are analyzed.

1. Introduction. Geological tsunami traces on the coasts

Tsunami is a dangerous natural phenomenon, at times attacking the Far East coast of Russia. Therefore, hazard and risk assessments are necessary for planning the development of tsunami-prone coasts and urban planning in the coastal zone [1]. However, the lack of data in the catalogs [2–3] of historical tsunamis does not allow to quantify the tsunami hazard with an acceptable accuracy of the order of 5–10 %. This requires 250–500 years of tsunami registration without gaps. The only alternative to this expectation is the use of paleotsunami data.

Research, started independently in different countries, has shown that strong tsunamis leave geological traces on the attacked coasts.

Figure 1 shows that tsunami deposits the most beach material in the “middle third” of the inundated coastal area. Near the shore, the material is weakly deposited from the high-speed flow, and in the zone of maximum run-up height, a little material remains in the flow.

Figure 1. Schematic position of the zones of erosion and accumulation of material in the area affected by the direct tsunami flow [4].
Fresh deposits of tsunami can be traced almost to the boundary of inundation zone, but in the case of paleotsunami deposits, the situation is complicated by the incomplete preservation of thin layers.

The aim of this work is to create a method for obtaining the tsunami recurrence assessments using the data on paleotsunami deposits, taking into account their preservation potential.

2. Deposits of modern tsunamis and paleotsunami, their formation and preservation
When interpreting data on paleotsunami sediments on the Far East coast of Russia, the results of studying the features of sedimentation associated with modern large historical tsunamis of the 20th and early 21st centuries are of great importance [5–9].

Tsunami deposits on slopes are usually washed away by atmospheric precipitation over time, but in the conditions of coastal peatlands, the slopes are very small, and the beach material deposited by the tsunami is fixed with vegetation over the years. In the long-term process of fixation, tsunami deposits are deformed by plants growing from below and roots of a new vegetation cover, as well as by insects living in this environment (bioturbation). One of the urgent tasks in the study of tsunami deposits is the analysis of their preservation potential on the scale of geological time.

For several years, authors [10–12] traced the dynamics of deposits of the largest recent tsunamis in relation to their preservation potential. The most important factor was the initial thickness of the sediments. The probability of preservation of deposits less than 10 cm thick is quite small, but deposits with a thickness of more than 10 cm were well preserved. In a number of regions, anthropogenic impact turned out to be an important factor. The final conclusion drawn in the cited papers is following: the data on tsunami deposits require correction for variability and preservation.

3. Features of statistical accounting of data on paleotsunami on the example of the Khalaktyrka region, Kamchatka
For a long time, the main type of natural materials used by tsunami specialists were data on maximum tsunami run-up heights collected in catalogs [2–3]. The main feature of such material is the data on the heights that were reached by the tsunami waves. The presence of paleotsunami deposits found at a certain level above the ocean indicates that the tsunami has exceeded this level. What the maximum run-up height was in this case, is unknown.

The method of joint analysis of data on historical tsunamis and paleotsunami deposits is considered on the example of the coast in the Khalaktyrka region, Kamchatka (figure 2).

Figure 2 shows typical features of paleo tsunami layers. As a rule, tsunami deposits at wave heights of less than 10 m are located in spots. Surface processes reduce the preservation of the layers, and as a result, each section contains its own set of deposits, with partial overlapping sets from adjacent sections. As can be seen from figure 2, volcanic tephra deposits can be traced along the profile much more clearly and reliably.

Accordingly, for the correlation and dating of the paleotsunami deposits, the tephrostratigraphy and tephrochronology method was used [13], based on the previously studied Holocene key-marker tephra layers in Kamchatka. This approach made it possible to determine the stratigraphic position, relative and absolute age of tsunamiogenic layers in geological sections. In the study area on the coast of the Khalaktyrka beach, 13 tsunamiogenic horizons (Ts1–Ts13) were identified [14]. Tsunami deposits are usually represented by thin (0.5 to 20 cm) layers of dark gray sea sands.

It is obvious that the formation of deposits of various tsunamis took place in different conditions. Therefore, the average probability of sediment preservation should be used in conditions that are close to homogeneous.

For this purpose, the entire time interval in which tsunamiogenic layers were identified is divided into four intervals of shorter duration (k = 1, 2, 3, 4), within which the conditions for the formation of deposits are more uniform. For this, clear time boundaries were used, set by the deposits of key-marker tephra layers associated with the eruptions of the volcanoes such as Ksudach in 1907 (Ks-1907), Avachinsky in 1855 (Av-1) and in 1779 (Av-2), Opal in 606 (Op), Ksudach in 236 (Ks1)
(figure 2). For the same purpose, a two compact groups of sections in the "middle" parts of profiles 1 and 2 were studied (figure 2). There are sections 302–306 (at a distance of 270–500 m from the shoreline) and 309–313 (at a distance of 250–440 m from the shoreline) [14].

![Figure 2](image)

**Figure 2.** Paleotsunami study area on the Pacific coast of Kamchatka and the location of profiles and sections. Geomorphological profile 2 and section diagrams [14].

The data on the number of tsunamigenic layers in each of the studied sections that fall within the time interval between the horizons of key-marker volcanic ash are summarized in Table 1.

The positions of sections 302–306 and 309–313 are of different heights. However, the height of the beach ridge \( h = 8 \) m is associated with tsunami deposits in these sections, since the tsunami reached them, having overcome the high beach ridge (figure 2).

Assume that there were \( N \) paleotsunamis at some coastal location during the time period \( T \), with the deposits of which the height \( h \) above the sea level is associated. It is known that the sequence of large tsunamis is close to Poissonian one [15]. Therefore, the probability of such an event is given by formula:

\[
P_N = e^{-\varphi(h) \cdot T} \frac{[\varphi(h) \cdot T]^N}{N!},
\]

where the parameter \( \varphi(h) \), depending on the threshold height \( h \), is the average frequency of tsunami manifestations, which is called the tsunami recurrence function (RF).

According to the definition, tsunami recurrence function (RF) is the average frequency of tsunami occurrence in a given place \( x \), with maximum run-up height being equal to or more than the threshold height \( h \)

\[
\varphi(h) \equiv \langle \frac{N(\text{run-up height} \geq h)}{T} \rangle,
\]

where \( N(\text{run-up height} \geq h) \) is the number of tsunamis with maximum height \( \geq h \) occurring during the time period \( T \).
Table 1. The number of tsunamigenic interlayers in the sections related to a considered time interval and an estimate of the probability of their preservation.

| Number of section | Time interval (years) | Today – 1907, \( k = 1, T_1 = 113 \) years | 1907 – 1855, \( k = 2, T_2 = 52 \) years | 1855 – 1779, \( k = 3, T_3 = 76 \) years | 1779 – 606, \( k = 4, T_4 = 1173 \) years |
|-------------------|-----------------------|--------------------------------------------|--------------------------------------------|--------------------------------------------|--------------------------------------------|
| 302               | 1                     | 1                                         | 1                                         | 0                                         | 0                                         |
| 303               | 1                     | 1                                         | 0                                         | 0                                         | 0                                         |
| 304               | 2                     | 0                                         | 0                                         | 0                                         | 0                                         |
| 305               | 2                     | 0                                         | 0                                         | 0                                         | 0                                         |
| 306               | 1                     | 0                                         | 0                                         | 0                                         | 0                                         |
| 309               | 2                     | 0                                         | 1                                         | 3                                         | 3                                         |
| 310               | 0                     | 0                                         | 0                                         | 0                                         | 0                                         |
| 311               | 1                     | 0                                         | 0                                         | 0                                         | 0                                         |
| 312               | 1                     | 0                                         | 0                                         | 2                                         | 2                                         |
| 313               | 1                     | 0                                         | 2                                         | 2                                         | 2                                         |

Tsunamigenic interlayers

- Ts1–Ts2
- Ts3
- Ts4–Ts5
- Ts6–Ts8

Maximum likelihood estimates of the tsunamigenic interlayers numbers, \( N \):
- Uncertain \( \geq 2 \)
- Uncertain \( \geq 3 \)

Probability of the tsunami deposits preservation, \( p_k \):
- 0.6
- 0.2
- \( \leq 0.2 \)
- \( \leq 0.33 \)

Moreover, the exponential approximation of the tsunami recurrence function is acceptable for large tsunami heights \( h \geq 0.5 \) m [16]:

\[
\phi(h) = f \cdot \exp \left[ - \frac{h}{H^*} \right]. \tag{3}
\]

Parameter \( f \) is the asymptotic frequency of large tsunamis in the region, which generally slowly changes along the coast and can be considered to be a regional constant. Parameter \( H^* \) is the characteristic tsunami height for selected location \( x \), which is proportional to the average coefficient \( K(x) \) of the tsunami height transformation (amplification) from the open ocean to the coastal location \( x \).

Tsunami activity parameters \( f \) and \( H^* \) must be determined from historical tsunamis and paleotsunami data. Accordingly, substituting the values of these parameters into formulae (3) and (1), we can estimate all the necessary probabilistic values of hazard and risk associated with a tsunami.

In fact, we cannot be sure that the identified \( n \) deposits of paleotsunami are all paleotsunami \( N \), because not all traces of paleotsunami are preserved. Let us assume, that the \( i \)-th section contains \( n_{ik} \) deposits from \( N_k \) paleotsunami that actually took place during the \( k \)-th time interval. The corresponding probability \( P_{ik} \) \( (n_{ik}) \) can be estimated by the binomial distribution [17]:

\[
P_{ik}(n_{ik}) = C_{n_{ik}}^{n_{ik}} P_{ik}^{n_{ik}} q_{ik}^{N_k-n_{ik}}, \tag{4}
\]

where \( q_{ik} = 1 - p_k \) is the probability of “erasing” the paleotsunami traces.

The likelihood function for the \( k \)-th time interval is equal to the product of the probabilities related to each \( i \)-th section [17]:

\[
L_k = \prod_i P_{ik}(n_{ik}) = \prod_i \frac{N_k!}{n_{ik}!(N_k-n_{ik})!} P_{ik}^{n_{ik}} q_{ik}^{N_k-n_{ik}} = \prod_i \frac{N_k!q_{ik}^{N_k}}{n_{ik}!(N_k-n_{ik})!} \left( \frac{p_k}{q_k} \right)^{n_{ik}}. \tag{5}
\]
For the $k$-th time interval, the values of the number of paleotsunami $N_k$ and probability $p_k$ that maximize the value of the likelihood function $L_k$ should be used as the maximum likelihood estimates. According to (5), these maximum likelihood values are related by a simple analytical formula:

$$p_k = \frac{\sum m n_{ik}}{m N_k},$$

where $m$ is the number of sections. The value of the maximum likelihood estimates of paleotsunami interlayers $N_k$ is found by a numerical method. The obtained values of the estimates of the number of tsunami deposits $N_k$ and probability $p_k$ of their preservation in the given time intervals, obtained by maximizing the likelihood function, are included in Table 1.

The analysis of the likelihood function (5) showed that the amount of actually identified deposits Ts1, Ts2 and Ts3 for the time intervals 2020–1907 and 1907–1855 is consistent with their distribution in 10 sections and are maximally probable. It is interesting that the estimates of the probability of preservation of tsunamigenic interlayers for these time intervals, $p_1 = 0.6$ and $p_2 = 0.2$, characterizing the conditions of their formation and preservation, differ significantly. This probability is less for the more ancient events of the period 1907–1855.

For the other two time intervals 1855–1779 and 1779–1856, the numbers of identified paleotsunami interlayers Ts4–Ts5 and Ts6–Ts8 does not agree with their distribution in 10 sections, and the maximum of the likelihood function does not correspond to these quantities. There may be several reasons for this discrepancy. It is possible that 10 investigated sections are not enough to statistically compensate for the low probability of the preservation of traces of some ancient tsunamis. It is also possible that the conditions for the formation of tsunamigenic deposits during these longer periods of time could change significantly, which violates the requirement of uniformity of the conditions assumed in the model.

As an example, figure 3 shows the joint function of the recurrence of tsunami heights for Khalaktyrka, constructed earlier [18] by the least squares method based on the data on the historical tsunamis of 1841, 1952, and 1960, and 11 paleotsunami identified in [14] for all considered sections for the period starting from 236 BC.

Figure 3 demonstrates the significance of the paleotsunami data: exactly 11 paleotsunami correspond to one value of the recurrence function with the smallest value of the standard deviation (apriori error), compared with large standard deviations for (total) 3 large historical tsunamis.

4. Conclusion
Data on paleotsunami are very important for obtaining estimates of tsunami hazard (recurrence and possible heights) and risk with acceptable accuracy, which is necessary both for solving purely scientific problems and for planning the development of the coastal zone. However, the direct use of data on paleotsunami can lead to underestimations of the recurrence frequency, and therefore it is necessary to take into account the peculiarities of their formation and changes that occur in tsunami sediments prior to their fixation.

Using the maximum likelihood method, a model was built to estimate the real number $N$ of paleotsunami during a certain time period $T$ (which characterizes the frequency of tsunamis) and the
Probability $p$ of the preservation of their traces based on data on the number of paleotsunami deposits in several sections associated with the same height $h$ above ocean level.

The model was tested on data on paleotsunami on the coast near Khalaktyrka, for four time intervals set by clear deposits of key-marker volcanic tephra layers. Estimates of the number of tsunamigenic horizons for time intervals after 1855 are the most probable. For older events prior to 1855, the number of identified paleotsunami interlayers does not agree with their distribution in 10 sections, and the maximum likelihood function does not correspond to these quantities. This is explained both by the limitations of the constructed model, associated with the conditions assumed in it, and by the low probability of preserving traces of some tsunamis.

Despite some limitations of the considered method, the developed quantitative approach to assessments of the formation parameters of tsunamigenic deposits can be successfully used as a starting point for obtaining adequate quantitative assessments of tsunami hazard and risk.

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