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A millennial-scale record of Holocene tsunamis on the Kronotskiy Bay coast, Kamchatka, Russia

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Abstract

Deposits from as many as 50 large tsunamis during the last 7000 years are preserved on the Pacific coast of the Kamchatka Peninsula near the mouth of the Zhupanova River, southern Kronotskiy Bay. These deposits are dated and correlated using Holocene marker tephra layers. The combined, preserved record of tsunami deposits and of numerous marker tephras on Kamchatka offers an unprecedented opportunity to study tsunami frequency. For example, from the stratigraphy along southern Kronotskiy Bay, we estimate frequency of large tsunamis (>5 m runup). In the last 3000 years, the minimum frequency is about one large tsunami per 100 years, and the maximum about one large tsunami per 30 years; the latter frequency occurred from about 0 to 1000 A.D. This time interval corresponds to a period of increased seismicity and volcanic activity that appears to be recorded in many places on the Kamchatka Peninsula.
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Introduction

The Kamchatka Peninsula (Fig. 1) is one of the most tectonically active regions of the world and has historically experienced a number of large tsunamis generated along the Kamchatka–Kuril subduction zone (Zayakin and Luchinina, 1987; Zayakin, 1996). The two largest occurred in November 1952 and in October 1737; the latter is the oldest documented tsunami on Kamchatka. Cataloguing and assessment of tsunami records are important for long-term tsunami prediction and for tsunami-hazard mapping. In the case of Kamchatka, however, as well as a number of other tsunami-susceptible coastlines, historical records of tsunamis are too short to develop a predictive chronology of events using only historical data. The way to obtain long-term data is to study prehistoric tsunami deposits.

Paleotsunami research became an active field of investigation in the late 1980s. Evidence of strong modern and prehistoric earthquakes and tsunamis has been found and studied in Japan, North America, and a number of other localities. On Kamchatka, studies of tsunami deposits began in about 1990 (e.g., Melekestsev et al., 1994; Minoura et al., 1996; Pinegina et al., 1997). In the course of these studies, techniques have been developed for identifying paleotsunami deposits, but none, to our knowledge, has generated statistics for millennial-scale paleotsunami distribution and frequency.

In most studied regions, long-term statistics are unobtainable because there are too few recorded events or there is a scarcity of reliably dated events or a lack of means for correlation of events in different localities. On a time scale of centuries, Minoura and Nakaya (1991; Minoura et al., 1994) studied a number of tsunami deposits in northern Japan and attempted to correlate them with Japan's long historical tsunami catalog. Also, based principally on buried soils, recurrence analysis of paleoearthquakes in Cascadia has been attempted (Atwater and Hemphill-Haley, 1997; Clague and Bobrowsky, 1994; Hutchinson et al., 1997).

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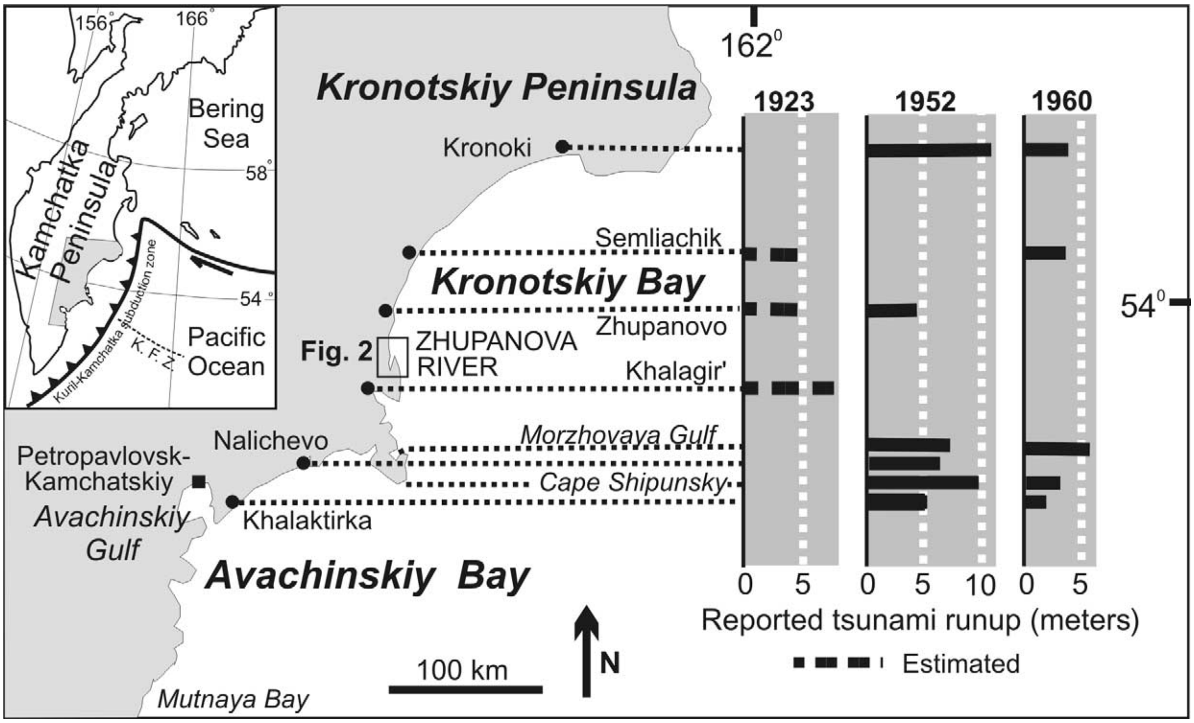

Fig. 1. Map of southeastern Kamchatka showing location of field area (small box labeled "Zhupanova River" and "Fig. 2") and other localities mentioned in the text. (Upper left inset). Tectonic setting of Kamchatka, showing the Kuril–Kamchatka subduction zone and the Kruzenstern fracture zone (K.F.Z.). Three bar graphs to the right show tsunami runup from large 20th-century tsunamis affecting this part of Kamchatka—4 February 1923 Kamchatka, 5 November 1952 Kamchatka, and 24 May 1960 (local time) from Chile.

The eastern coast of Kamchatka, downwind of one of the most active volcanic arcs in the world, offers a superb opportunity to examine millennial-scale records of tsunami history. The tephras from these volcanoes have been studied for the last 50 years (e.g., Braitseva et al., 1997), and widespread occurrence of marker tephra layers permits dating and correlation of sections bearing tsunami deposits. Because no one section will preserve all tsunami deposits or tephra layers, multiple excavations and correlations are the key to establishing a long-term tsunami history.

The purpose of this study was to find and to date as many tsunami deposits as possible, so as to obtain statistically significant data. We focused on south Kronotskiy Bay, near the mouth of the Zhupanova River (Fig. 2), for the following reasons: (1) the region is characterized by high seismicity and has a historic record of tsunamis; (2) the 1952 tsunami left an identifiable deposit, which can be used as a benchmark; (3) marshes on this coast preserve tsunami deposits well due to a high rate of peat accumulation; and (4) there are many well-studied tephra layers, so terraces and tsunami deposits may be dated and correlated.

This paper is concerned primarily with overall stratigraphy and statistics of these deposits. More details about the deposits, additional measured sections, and some preliminary analysis are presented in Pinegina et al. (2000).

Background and field methods

Setting of the Zhupanova River mouth

Excavations were made at about 30 sites north and south of the Zhupanova River mouth (Fig. 2). Additional excavations were made up to 10 km upriver from the coast. The Zhupanova River drains into the southern part of Kronotskiy Bay, north of Cape Shipunskiy, about 100 km north of Petropavlovsk-Kamchatskiy, the only city on Kamchatka (Fig. 1). Cape Shipunskiy lies approximately in the middle of the Kamchatka portion of the Kuril–Kamchatka subduction zone (Fig. 1) where this subduction zone intersects the Kruzenstern Fracture Zone (Gorbatov et al., 1997). Along this portion of the subduction zone, Pacific Ocean crust about 92 million years old (at the trench) is subducting more or less orthogonally beneath Eurasia at a dip angle of approximately 55° and a convergence rate of about 7.5–7.6 cm/yr (Gorbatov et al., 1997).

The north and south sides of the Zhupanova River mouth (Fig. 2) differ in geomorphology, with the southern side indicating uplift and the northern side being relatively stable. The area south of the river mouth is occupied by a chain of low, terraced bedrock hills and a series of Late Pleistocene terraces 15, 25, and 30–40 m high. The north side of the river mouth is an accretionary coastal plain, about 5 m

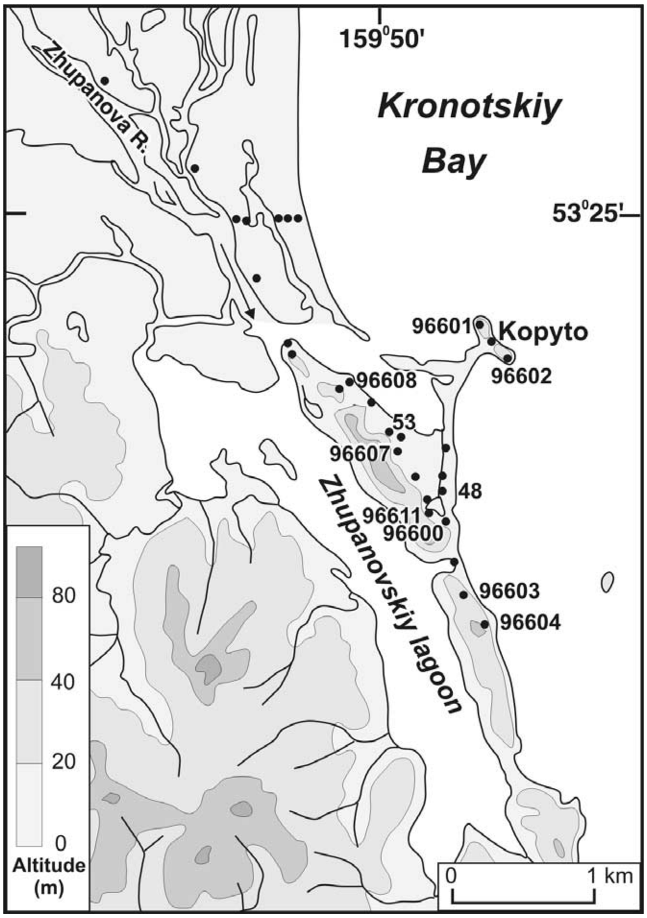

Fig. 2. Map of field area (Zhupanova River mouth), with locations of logged excavations (dots). Excavations are numbered if illustrated (Figs. 3 and 7) or mentioned in the text.

above sea level, comprising marine and alluvial sediments; this coastal plain extends as much as 30 km inland. Most sites lower than about 5 m altitude both north and south of the river mouth are either marshes or bogs. The peat in these wetlands is 1 to 2.5 m thick (depending on age) and typically overlies lagoonal mud or nearshore marine sand. The bogs and marshes are separated from the ocean by a series of beach ridges. Recent beach ridges range in height from about 3 to 5 m, and the present beach is 30–50 m wide. Older beach ridges are preserved as chains of hummocks 1 to 3 m high.

The modern Zhupanova River delta developed about 5000 to 6000 years ago, as indicated in excavations by the transition from marine to nonmarine facies and based on the presence of marker tephra layers (Table 1). The lowest marker tephra in the nonmarine facies on the delta is AV_3 (~4500 ^{14}C yr B.P.; Table 1), some tens of centimeters above the transition. North of the river mouth, the coastal plain has prograded from west to east since that time. Near the river mouth, a barrier formed about 4000 years ago (oldest tephra in beach ridge excavations is AV_1, about 3500 ^{14}C yr B.P.); since then, the lagoon behind has been filling with peat.

South of the river mouth, fluvial processes are not as important. There, a barrier (a tombolo between the coastal hills and Kopyto hill, Fig. 2) formed 4500 to 5000 years ago; a lagoon behind later filled with peat, from the margins toward the center. Excavations on this barrier contain AV_3 (4500 ^{14}C yr B.P.) and some older tephras but not AV_4; the oldest peat at the margin of this lagoon contains AV_3, and peat is prograding into this lagoon. The youngest sections contain only AV 400 (Table 1). The shoreline both north and south of the mouth is accreting.

Tephra stratigraphy

The paleotsunami deposits are assigned ages principally on the basis of their position with reference to known and dated volcanic ash horizons (marker tephras; Table 1). On Kamchatka, more than 24 Holocene marker tephra layers are related to 11 volcanic centers (Braitseva et al., 1997). These dated tephra layers provide a record of the most voluminous explosive events in Kamchatka. Each marker tephra has been traced for tens to hundreds of kilometers away from its source volcano and characterized by stratigraphic position, area of dispersal, radiocarbon age, typical grain-size distribution, and chemical and mineral composition (Braitseva et al., 1997).

Regional marker tephras other than those in Braitseva et al., (1997), as well as more local marker ash layers, were also used in the Zhupanova region study (Table 1). From known sources, these tephras include ash from the 1963 Karymsky (KM) eruption (described in Masurenkov, 1980) and ash layers from Avachinsky volcano eruptions (AV) dated to 3000, 7150, and about 1000 ^{14}C yr B.P. (O.A. Braitseva, L.I. Bazanova, I.V. Melekestsev, and L.D. Sulerzhitsky, unpublished data). Tephras from unknown sources include “black ash” (BA) from about 2000 ^{14}C yr B.P. and from Avachinsky(?) about 400 ^{14}C yr B.P. (AV 400).

Tephra layers were described and identified in the field, with identifications checked by examining samples in the laboratory and by consulting isopach maps of marker tephras. Marker tephra layers were traced up the Zhupanova River to check thickness trends. Local bulk peat samples were dated by radiocarbon to help evaluate stratigraphy (Fig. 3; Table 2). However, we place more reliance on marker-tephra identification, primarily because most tephras are distinctive and well-studied, at least down to AV_1, a distinctly basaltic tephra from Avachinsky volcano. In general, local radiocarbon ages from peat are younger than ages assigned by marker tephras (e.g., sections 96611, 96608, Fig. 3). Bulk peat samples generally give young ages due to younger roots growing down into older peat. Moreover, we are finding that wetter peats in our coastal sections can have ages up to about 500 years younger than expected, and we are examining this problem.

Table 1
Holocene marker tephras present at Zhupanova site, southern Kronotskiy Bay

Code	Source of tephra	Average age[a] ^{14}C yr B.P.	Assigned age (A.D./B.C.) used in this paper[b]	Ash volume (km^3) where known	References, source of information
KM 1963	Karymsky	Historical	1963 A.D.	<0.1	Masurenkov, 1980
KS 1907 (KSht3)	Ksudach, Styubel cone	Historical	1907 A.D.	1,5–2	Braitseva et al., 1995, 1997
AV 400	Avachinsky?	377 ± 87 (3)	1500 A.D.	?	This paper
AV 1000	Avachinsky	1000[c]	1000 A.D.	?	Bazanova et al., unpubl.[c]
OP	Baraniy Amfiteatr subcaldera (Opala)	1478 ± 18 (11)	600 A.D.	9∼10	Braitseva et al., 1995, 1997
KS1	Ksudach, caldera 5	1806 ± 16 (15)	230 A.D.	14∼15 18∼19	Braitseva et al., 1995, 1997 Volynets et al., 1999
BA	Unknown (black ash)	2000[c]	0 (A.D./B.C.)	?	Bazanova et al., unpubl.[c] and this paper
AV 3000	Avachinsky	3000[c]	1300 B.C.	?	Bazanova et al., unpubl.[c]
AV1	Avachinsky	3512 ± 18 (10)	1800 B.C.	∼2	Braitseva et al., 1995, 1997
AV3	Avachinsky	4481 ± 24 (7)	3000 B.C.	∼1.5	Braitseva et al., 1995, 1997
AV4	Avachinsky	5489 ± 27 (7)	4300 B.C.	∼4	Braitseva et al., 1995, 1997
AV5	Avachinsky	5602 ± 40 (2)	4500 B.C.	∼0.5	Braitseva et al., 1995, 1997
AV 7150	Avachinsky	7150[c]	6000 B.C.	?	Bazanova et al., unpubl.[c]
KO	Kuril Lake–Ilinsky caldera	7666 ± 19 (12)	ca. 6400 B.C.	100–120	Braitseva et al., 1995, 1997
KRM	Karymsky caldera	7889 ± 67 (4)	ca. 6600 B.C.	8∼10	Braitseva et al., 1995, 1997

[a] ^{14}C ages are averages based on number of dates in parentheses; all ages are from the Laboratory of Geochronology, Moscow Geological Institute, Russian Academy of Sciences, L.D. Sulerzhitsky, Director.
[b] Calendar ages assigned are approximate, based on calibration using CALIB 4.3 (Stuiver et al., 1998).
[c] Unpublished data from L.I. Bazanova, O.A. Braitseva, I.V. Melekestsev, and L.D. Sulerzhitsky.

Field methods and criteria for tsunami deposits

Our results are based primarily on two field seasons and about 40 stratigraphic sections from excavated trenches (Figs. 2 and 3; Pinegina et al., 2000); for each, altitude and distance from the coast were noted. Each section was measured and described stratigraphically, and sand and volcanic ash layers were sampled for granulometric and mineralogical analysis. In general, microfossils are neither common nor well preserved in these deposits. Most excavations were well beyond and above places where sand could be transported by mechanisms other than a tsunami. Pits dug in hollows between beach ridges were not very useful because they were too sandy, the sand being mostly transported from the beach by wind and by storm waves, as well as by tsunamis.

In the last 10 years, deposits from a number of recent and historical tsunamis have been described (e.g., Clague et al., 1994; Sato et al., 1995; Nishimura and Miyaji, 1995; Minoura et al., 1996; Bourgeois et al., 1999): These observations have contributed to a general understanding of the nature of tsunami deposits and criteria for their recognition. In general, tsunami deposits are sheetlike and comprise sediment eroded from adjacent beaches or other unvegetated surfaces. Locally they can be patchy and will not be present over the entire inundated surface (Fig. 4; Nishimura and Miyaji, 1995; Hemphill-Haley, 1995). Tsunamis can also erode, particularly in proximal or unvegetated areas.

Tsunami deposits are not uniquely identifiable, and other kinds of deposits may share some of their characteristics, but in general they will not share all. Storm deposits most closely resemble tsunami deposits, but storm waves will not penetrate the distance of a long wave such as a tsunami. Moreover, on Kamchatka, cyclones are weaker than those in Japan; there, tsunami deposits have been described, to the exclusion of storm deposits, at altitudes of <3 m (e.g., Minoura et al., 1994). Compared to tsunami and storm deposits, eolian sands are typically very well-sorted, very fine sand and form thicker, wedge-shaped layers; silt and very fine eolian sand are also disseminated in the peat. Flood deposits are typically brown and may be muddy, with more angular grains than beach sand; most of our Zhupanova localities are not susceptible to river flooding. Colluvium, present near the base of hills, is poorly sorted and has angular grains.

Our sections are principally located on coastal peat bogs

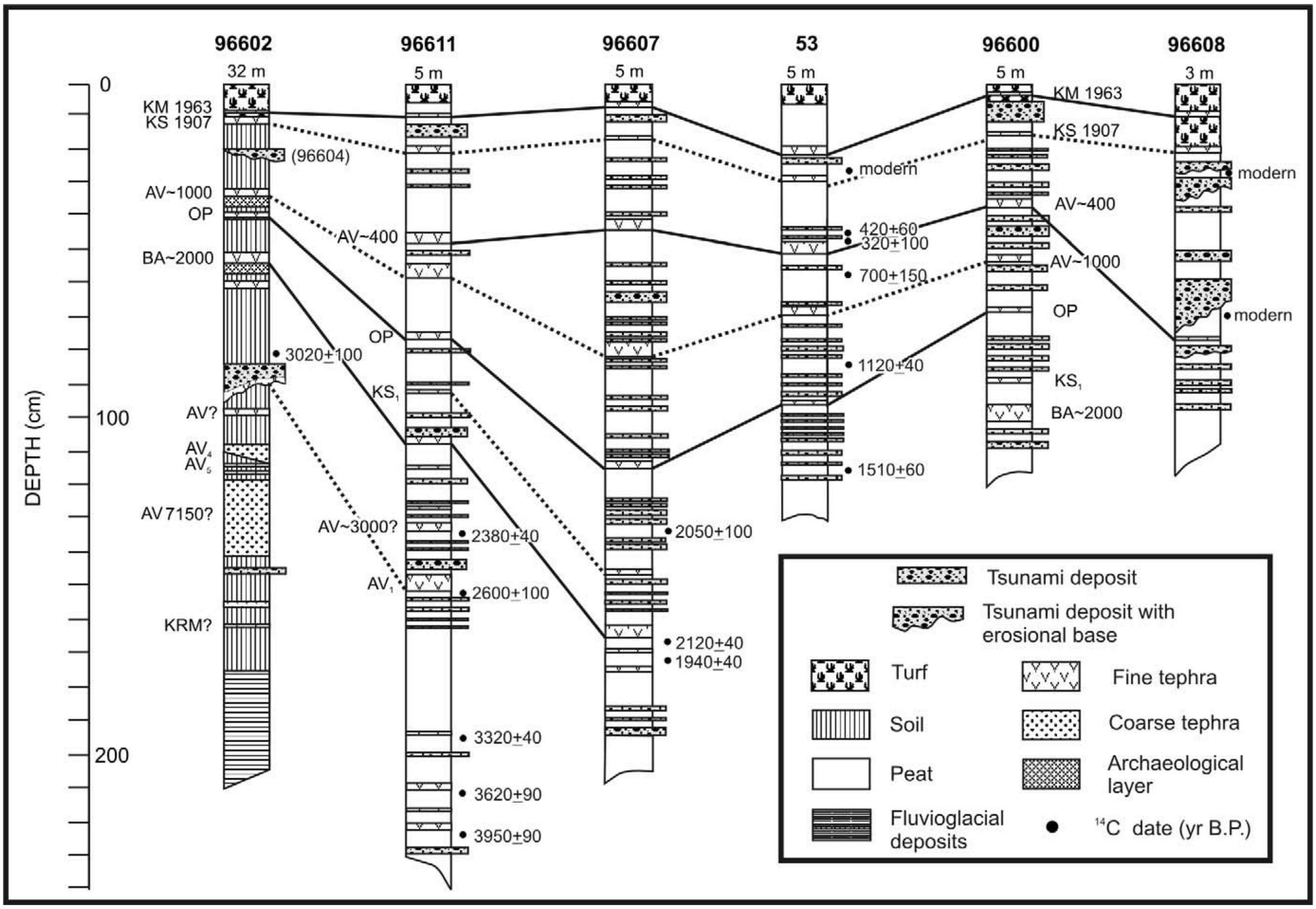

Fig. 3. Stratigraphy of six of the most informative excavations at the Zhupanova site, arranged by elevation and correlated using marker tephras (e.g., KM 1963, AV_1, see Table 1 for abbreviations); see Fig. 2 for excavation locations. Local radiocarbon ages are plotted (Table 2). Tsunami deposits are shown as wider boxes in columns for the purpose of readability. In the case of excavation 96602, there is some generalization from excavations at this terrace level; in particular, we show a tsunami deposit observed at site 96604.

and terraces, 5 m or more above sea level (Fig. 5) and more than 200 m from the shore. The source of tsunami sediment for these sites is primarily beach sand eroded from the shoreline and deposited across vegetated surfaces (Fig. 5). Sand layers in the peat sections are interpreted to be tsunami deposits based on the following characteristics: First, the sand layers are found beyond storm-wave influence; lack of storm-wave influence is identified by changes in vegetation from beach grasses to less tolerant plants, by elevation and distance from the shoreline, generally farther than 250 m and higher than 5 m, and by the presence of (sand-poor) peat. Second, interpreted tsunami sands are similar to local beach sand, comprising generally well-sorted and well-rounded particles; these deposits tend to become finer away from the coastline. Third, layers are sheetlike, with typical thicknesses of a few millimeters to a few centimeters, and generally thin away from the shoreline. Finally, the sand layers have a stratigraphic return period of decades to hundreds of years, as expected for tsunamis on a subduction-zone coastline.

Character of tsunami deposits at Zhupanova site

The interpreted tsunami deposits occur as laminae or thin beds (but locally up to 15 cm thick) of black or grayish sand and locally include gravel (clasts up to 5 cm in diameter) and wood fragments. Thin beds typically show the best sorting. Deposits tend to fine and thin in the landward direction. Tsunami deposits differ in distribution and character north and south of the river mouth. To the south, deposits are limited to the seaward side of a chain of hills, about 1 km from the river. In excavations at the seaward base of this hill (e.g., 96608, Fig. 2) there are several relatively thick (up to 15 cm) beds of poorly sorted sandy sediment, which we infer to be deposits rapidly dropped by tsunamis when they broke against the hill. North of the river mouth, where the terrain is low and relatively flat, correlative tsunami deposits are thin, well-sorted, and in rare cases extend inland as far as 5–10 km upriver (orthogonally 3–4 km from the coast).

Tsunami layers are best preserved where deposited on a

Table 2
Radiocarbon dates from Zhupanova River field site

Field sample number[a] (locality no. - sample no.) [cm below surface]	Laboratory sample number[b]	Age (^{14}C yr B.P.)	Material, notes
96602-A1 [85]	GIN8800	3020 ± 100	Charcoal in soil
96611-A1 [225]	GIN8790	3950 ± 90	Peat
96611-A2 [212]	GIN8802	3620 ± 90	Peat
96611-A3 [198]	GIN8798	3320 ± 40	Peat
96611-A4 [155]	GIN8795	2600 ± 100	Peat
96611-A5 [135]	GIN8792	2380 ± 40	Peat
96607-A1 [175]	GIN8796	1940 ± 40	Peat
96607-A2 [170]	GIN8794	2120 ± 40	Peat
96607-A3 [135]	GIN8793	2050 ± 100	Peat
53-A2 [47]	GIN8508	420 ± 60	Peat above AV 400
53-A3 [49]	GIN8509	320 ± 100	Peat above AV 400
53-A4 [60]	GIN8510	700 ± 150	Peat, ~10 cm below AV 400
53-A5 [85]	GIN8511	1120 ± 40	Peat
53-A6 [115]	GIN8512	1510 ± 60	Peat
96608-A1 [28]	GIN8799	modern	Peat
96608-A2 [60]	GIN8797	modern	Peat
48-A3 [32]	GIN8505	410 ± 100	Peat below AV 400

[a] Dates are plotted on Fig. 3, except for 48-A3, used to assign age to AV 400. Localities are plotted on Fig. 2.
[b] ^{14}C ages are from the Laboratory of Geochronology, Moscow Geological Institute, Russian Academy of Sciences, L.D. Sulerzhitsky, Director.

vegetated surface that persisted or recovered quickly after a tsunami and where protected from erosion or other surface disruption. Individual tsunami deposits vary in thickness and preservation even in the walls of a single excavation. Moreover, where we could correlate a deposit from site to site, there is considerable variation in character and degree of preservation, even in neighboring sections. In general, this variation can be tied to small changes in topography, but other roughness elements, such as vegetation, can affect the deposit. Also, preservation factors—bioturbation and varying rates of soil formation and peat accumulation—can account for variations. In a few cases, there is evidence of erosion at the base of the deposit (e.g., section 96608, Fig. 3).

For these reasons, numerous excavations are necessary to generate a reliable count of tsunami layers. Even so, we probably have missed some events. Our experience suggests that coring, rather than excavation, would make such a study much more difficult and perhaps impossible. On the basis of the above-stated criteria, in 20 key sections, the oldest of which contain AV 7150 or KO or KRM (Table 1), we identified as many as 50 horizons of black and dark-gray sand and pebbly sand that we interpret to be tsunami deposits (Fig. 3). Details of the deposits, with interpretations, are summarized in Pinegina et al. (2000).

Records and deposits from historical tsunamis

Before examining the millennial-scale record, it is instructive to examine the historical record of earthquakes and tsunamis for this region (Zayakin, 1996; Gusiakov et al., 1999). Because our sites are all ≥3 m above sea level, and most are higher than 5 m, we see only the record of large tsunamis. Which historical tsunamis should have left a deposit at the Zhupanova River mouth, and can we identify those deposits? How many deposits at this site may be not from locally generated tsunamis, but rather from far-traveled tsunamis (teletsunamis), for example, from Chile?

The most complete historical earthquake and tsunami record for Kamchatka is from the settlement of Petropavlovsk-Kamchatskiy, founded in 1740, which is within Avachinskiy Gulf (also called Avacha Bay in tsunami databases) and well protected from tsunamis (Fig. 1). Sites expected to respond to tsunamis most similarly to our field site are Khalaktirka, Zhupanovo village, and Semlyachik; other sites show greater (and lesser) amplification (Fig. 1).

The most complete record on Kamchatka of a large tsunami is for the 1952 Kamchatka tsunami. Two other strong tsunamis were recorded near our field site during the 20th century: 4 February 1923 Kamchatka and 1960 Chile (Fig. 1). Based on the Petropavlovsk record, several other local tsunamis may have had a large runup at Zhupanova: 1792, 1827, 1841, 1848, and 1904. Of these, the strongest was probably 1841. The notorious 1737 Kamchatka tsunami (see below) is the oldest and most likely the largest historic event known for this region.

The 1960 Chile tsunami is the only teletsunami with historically recorded large runup on Kamchatka (Fig. 1). Because of directivity, tsunamis from Alaska (e.g., 1964) and from all but the outermost Aleutians do not produce significant runup on Kamchatka. Runups from 1960 Chile in southern Kamchatka were, in general, about half those of the local 1952 tsunami (Fig. 1). Near the Zhupanova site, fjord-like Morzhovaya Gulf is the exception.

If we use the historical record from northern Japan as a proxy for earlier historical trans-Pacific tsunamis, 1960 Chile was the only severe (>3 m runup) teletsunami to strike the Sanriku coast of northern Japan in the last 300 years (Minoura et al., 1994). Also in northern Japan, the 1700 Cascadia event (Satake et al., 1996; Tsuji et al., 1998) produced no more than moderate runups (1–3 m); we expect no greater runup from 1700 Cascadia in areas like Zhupanova.

Deposits from the historical period

There are two historical tephra layers at the Zhupanova field site—1963 Karymsky (KM 1963) and 1907 Ksudach (KS 1907). The prior tephra, "AV 400," we assign an approximate age of A.D. 1500, based on three local radiocarbon dates of peat [410 ± 100 ^{14}C yr B.P. (below), 420 ± 60 ^{14}C yr B.P. (above), and 320 ± 100 ^{14}C yr B.P. (above)].

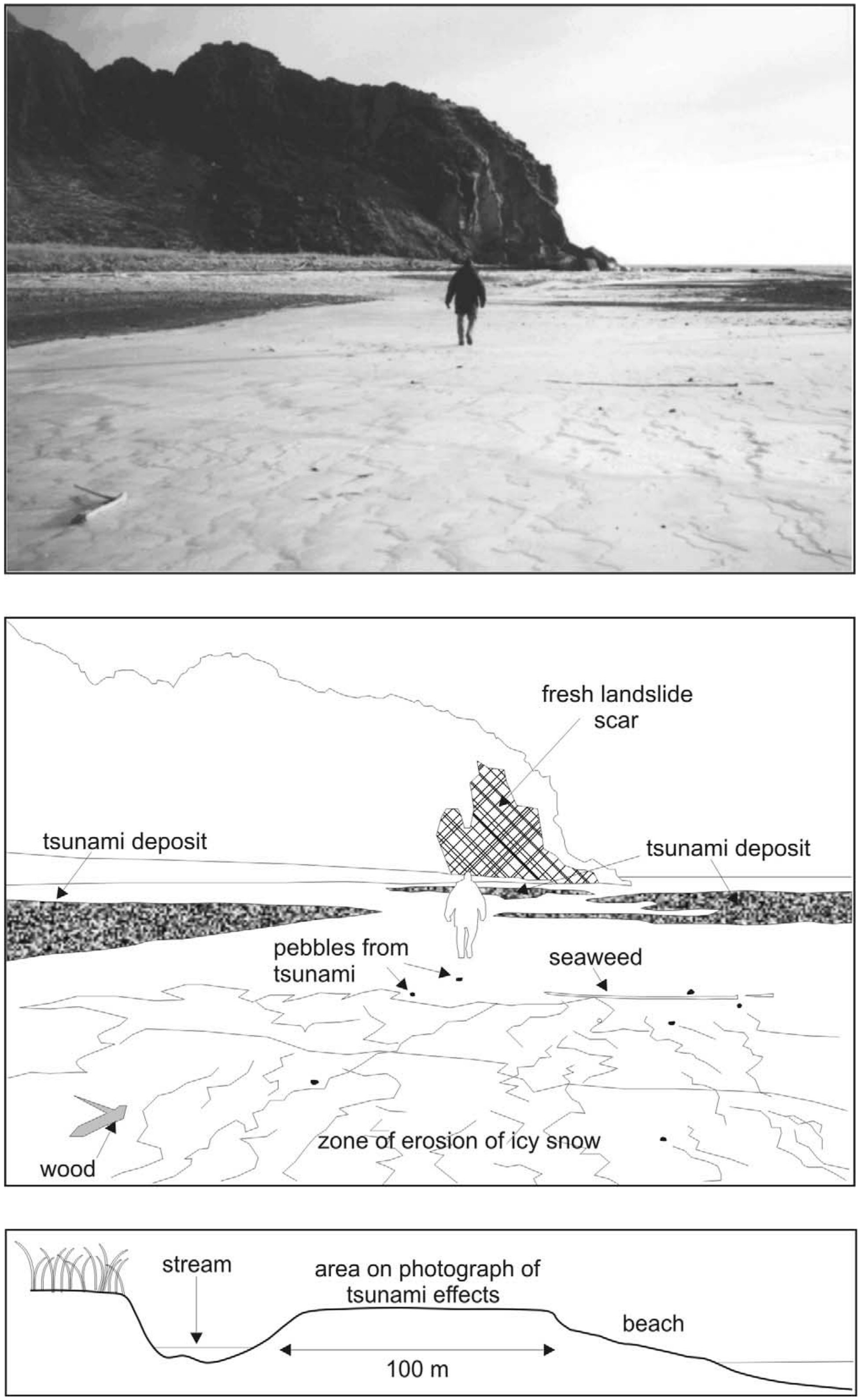

Fig. 4. (Top) Photo of snow-covered, modern beach terrace (diagram) on the southeastern side of the Kronotskiy Peninsula, following the Kronotskiy earthquake and tsunami of 5 December 1997. (Middle) Drawn-over version of photo outlines 1997 tsunami deposit (primarily medium to coarse sand, with some pebbles) and other effects of the earthquake and tsunami. The tsunami deposit is patchy; in the foreground is an area of snow that experienced erosion. If our excavations were to encounter such a tsunami deposit, we must have a grid of excavations, because the deposit is present over less than 50% of the surface. Photo taken 10 December 1997 by Pinegina.

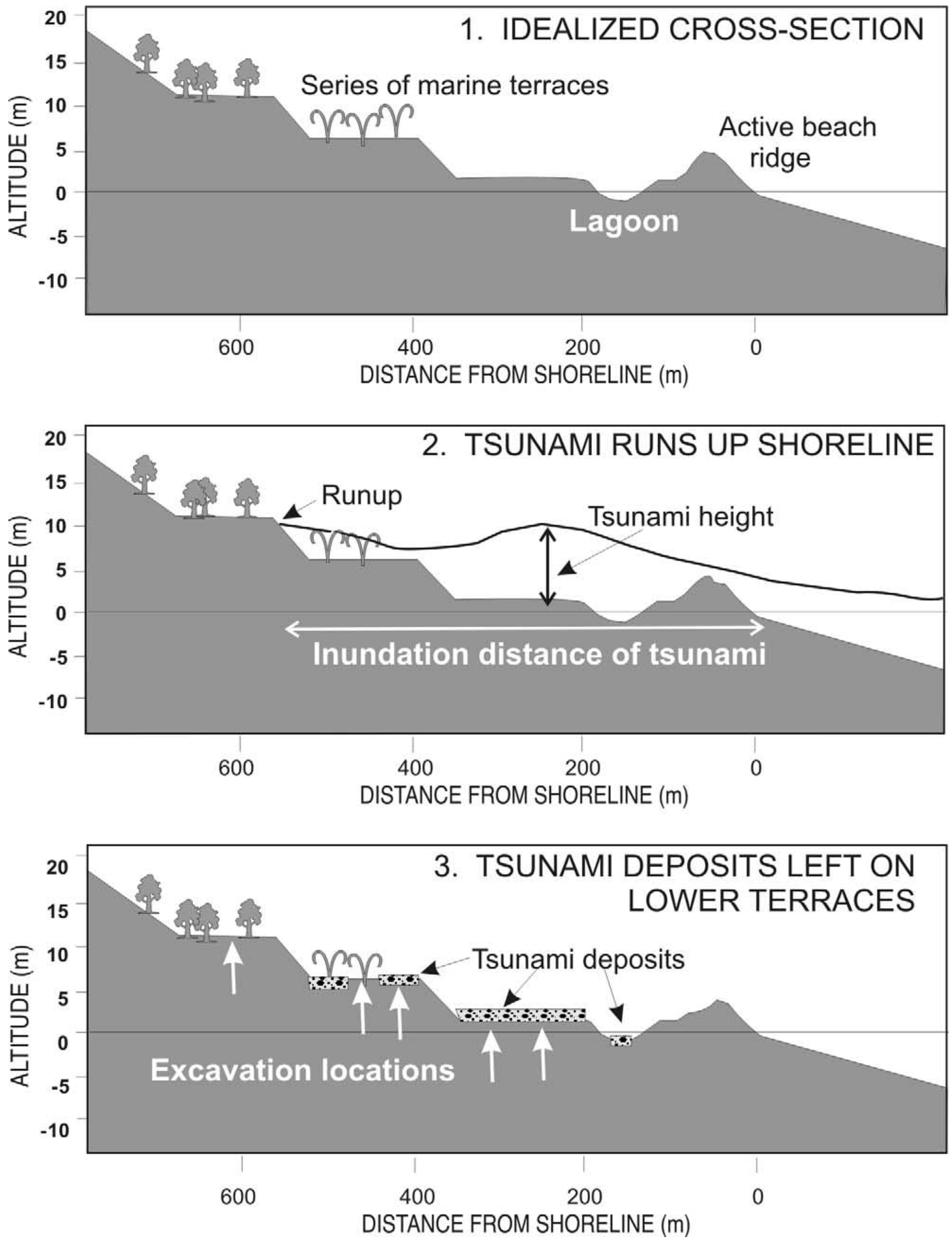

Fig. 5. Schematic illustration of how tsunamis leave deposits on typical Kamchatka coastal sites. (1) Generalized geomorphology; age of coastal terraces is determined by age of oldest tephra layer in excavation on that terrace. (2) Inundation by a tsunami with runup of about 10 m and penetration of about 550 m. (3) Tsunami from box 2 left a deposit on surfaces below 10 m elevation, but not on the highest terrace, which will be revealed in excavations.

The section between AV 400 and KS 1907 should represent about 400 years, with the 1737 Kamchatka tsunami occurring near the middle of this period.

With exceptions discussed below, only one tsunami deposit lies between KM 1963 and KS 1907 tephras (Fig. 3), and we attribute this layer to the 1952 Kamchatka tsunami. Runup from this tsunami was typically 5–10 m along this part of the Kamchatka coast (Fig. 1). We reject the alternative sources—(4 February) 1923 Kamchatka and 1960 Chile—because in the former case, the deposit is high in the section (closer to 1963), and in the latter case, the tsunami was only about half as large as that of 1952. Moreover, the soil between the tsunami layer and KM 1963 is more developed than we would expect if the tsunami deposit were from 1960 Chile.

In shallow excavations on beach ridges, less than 200 m from the shoreline, more than one sand layer is sometimes found above KS 1907. These excavations are not used for reference or for statistics because they are too sandy, and some of these sand layers may be from storms. Nevertheless, possibly these sand layers represent 1923 or 1960 tsunami deposits (in addition to 1952). Moreover, one peat section (locality 51, not illustrated) contains two sand layers between KS 1907 and KM 1963. We attribute one of these layers to 1952, but we are not sure if the second sand layer is from 1923 or from 1960. In any case, the general absence of a deposit from the 1923 tsunami at the Zhupanova River site leads us to conclude that local runup from this event was less than local runup in 1952, contrary to some reports (Zayakin and Luchinina, 1987; Gusiakov et al., 1999).

The deposit we assign to the 1952 tsunami is a dark gray, unstratified sand 2 to 6 cm thick, and is similar to beach sand in appearance. The grain size ranges from coarse or very coarse sand to fine or very fine sand. This deposit is found up to 4–5 m altitude, and up to 1 km from the coast, on the north side of the river mouth. About 200–300 m from the coast, the deposit is a bed of coarse to medium sand 6 cm thick; about 700 m from the coast it thins to a parting of predominantly fine to very fine sand.

Up to five tsunami deposits lie below Ksudach 1907 and above AV 400. Judged from calculated rates of peat accumulation, three (possibly four) of these tsunami deposits may be attributed to historical tsunamis. Based on historical narratives (e.g., Krasheninnikov, 1755), the 1737 tsunami was the largest in the last 300 years. Therefore, we attribute the topographically highest tsunami deposit between these tephras to the 1737 Kamchatka tsunami.

In sum, based on the stratigraphic record, in the last 500 years the Zhupanova River locality experienced at least six large tsunamis (seven if we count the one case where there are two deposits between 1963 and 1907 tephras), with runup of 4–5 m or more. Probably all these events were locally generated; 1960 Chile may have generated a deposit proximal to the shore. Only one of these tsunamis, 1952 Kamchatka, has a nearby historic record (Zhupanovo village), with some other tsunamis observed at nearby sites.

Tsunami deposits on a millennial time scale

With some confidence from the historical record, we can extend our analysis back several millennia. Key to our analysis is the presence of marker tephra layers for correlation, as well as for age control. More important than the precise age of these tephras is the fact that they represent time lines. Many of the sections at Zhupanova cover at least the last 2000 years, and a number of sections go back about 4000 years. The oldest excavation contains tephra as old as 7700 ^{14}C yr B.P. (KRM, Fig. 3, section 96602). After we compiled stratigraphic sections and identified tephra layers, we correlated the sections (as in Fig. 3). Using 20 representative sections, we then calculated the total number of tsunamis from the maximum number of deposits recorded within each time interval in any one section, as delimited by tephras.

The record of early Holocene tsunami deposits at Zhupanova is spotty because peat older than about 3000 years is uncommon. Site 96611 (Fig. 3) is the oldest peat section excavated. Older sections are in terrace soils on coastal headlands south of the river (e.g., section 96602, Fig. 3). Preservation is not as good in these sections, but they have a record of some of the largest and oldest tsunamis at the Zhupanova site. The oldest tsunami deposit we found lies beneath Avachinsky tephra dated to about 7150 ^{14}C yr B.P. (about 6000 B.C.), on the coastal headland at 32 m altitude (site 96603).

Determination of tsunami age

In selected peat sections, we calculated ages for tsunami deposits confined between two dated ash beds by assuming a constant rate of sedimentation. This assumption is permissible because the marker tephra layers divide the sections into rather short time intervals. However, variance in stratigraphic thicknesses between dated tephras indicates that peat accumulation rates can vary even within the same section, as well as from section to section. These rates, and subsequent compaction, are controlled by a number of factors, some of which are common to all sections, such as climate and age. Others are particular to each section, such as local relief, or distance from the center of a lagoon (that is filling with peat).

Analyses were also attempted on some terrace soil sections (vs. peat), but the accuracy of ages is much lower because the accumulation rates are an order of magnitude slower, and the potential for erosion is greater. Also, because of the slow sedimentation rates, individual tephra layers and tsunami deposits are more difficult to distinguish. Hence, the analysis presented here is based on peat sections only.

Our analysis uses only known and well-dated tephras (Table 1), even though we sampled peat locally for radiocarbon dating (Fig. 3; Table 2). We attempted to assign numerical ages to each tsunami by a graphical technique (Fig. 6). For example, the most complete sections in peat were graphed where the *Y* axis is age in years and the *X* axis is depth below the surface of excavation (Fig. 6). The ages of marker tephras were plotted, with the slope of each line segment between tephra units indicating peat accumulation rate (after compaction); a gentle slope indicates rapid accumulation, and a steep slope slow accumulation. Ages of individual tsunami deposits were assigned by interpolation along straight lines. We tried other line fits, such as logarithmic and parabolic, but, except for the uppermost peat, a straight line best fits the tephra ages.

We assume that peat accumulation rates vary slowly and continuously and can be approximated by ages of bounding tephras. However, the intervening tsunami and tephra layers are deposited instantaneously, and if they are thick or otherwise noxious, they can for some time inhibit peat growth. This inhibition has been observed on Kamchatka, e.g., in the case of the 1907 Ksudach tephra where it is about 0.5 m thick and still at the surface above peat and soil (upriver from Mutnaya Bay, located on Fig. 1; T. K. Pinegina, field notes, 1996). Also, the 1952 tsunami deposit, where it is about 20 cm thick in Mutnaya Bay, was still at the surface

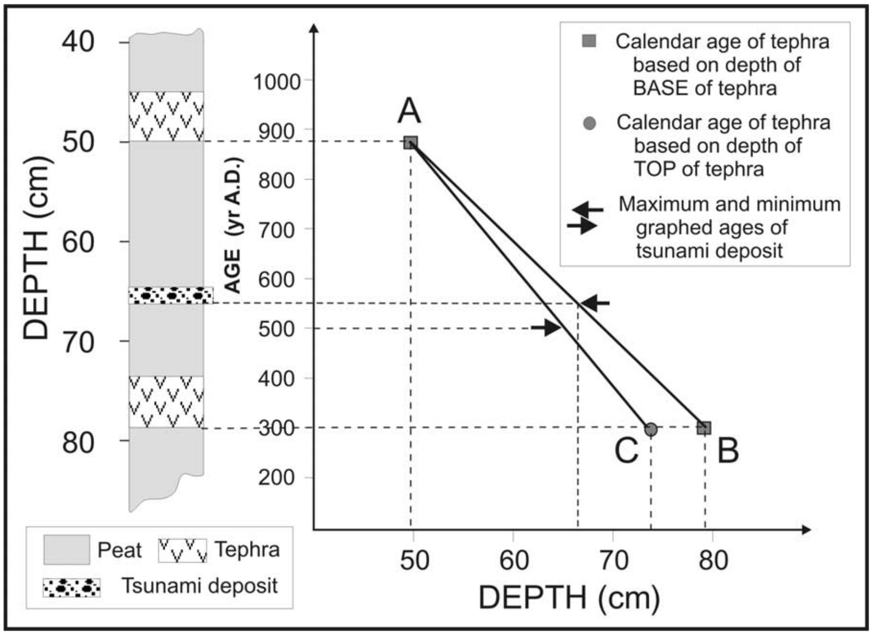

Fig. 6. Graphic tsunami age determination of a representative stratigraphic section. (Line AB) Accumulation rate including ash layer, giving minimum age of tsunami deposits (A.D. 550). (Line AC) Accumulation rate excluding ash layer, giving a maximum age of tsunami deposit (A.D. 500).

in 1996. Thinner deposits, however, may not inhibit peat growth. In an attempt to account for these variations, we graphed a maximum and a minimum age for each tsunami deposit (Fig. 6). The maximum uses all sediment thickness (peat, tephras, tsunami sands), and the minimum removes tephras and tsunami sands. In this treatment, the tephra or tsunami deposit thickness is taken as a proxy for the amount of time during which peat accumulation was inhibited. We performed this analysis on five sections (96600, 96607, 96608, 96611, and 53; Fig. 7).

Using this technique, we have identified a candidate for the 1737 tsunami in four of five sections (Fig. 7). Some sections have deposits between this postulated 1737 layer and the 1952 tsunami layer; but their correlation with known historical events (1792, 1827, 1841) is more difficult to confirm than for 1737, believed to be the largest event in the last 300 years.

On this basis we can construct a summary chronology of tsunamis having a runup of >5 m at the Zhupanova River mouth. Data in the chronology are most complete for the last 2000 years (Fig. 7), during which there was at least one tsunami in almost every century. Prior to ca. 4000 years ago, only the largest events, as recorded in uplifted terraces, are preserved.

Discussion and conclusions

The data obtained suggest some relationships between tsunami frequency and tsunami intensity, as well as between tsunami height and inundation distance. In the region of the Zhupanova River mouth, tsunamis more than 5 m high occurred an average of 12 times per 1000 years during the last 3000 years, with inundation distances on the order of 1 km. Tsunamis about 30 m high (on coastal headlands) occurred only once about every 1000 years, the maximum distance of penetration being 10 km upriver.

Based on the historical record, we believe that most (at least 8 or 9 out of 10) of the tsunami deposits we studied at the Zhupanova site are from subduction-zone earthquakes along Kamchatka because our field localities are almost all more than 5 m above sea level and several hundred meters from the shoreline. Between 1737 and 2000, the Zhupanova area experienced only one large teletsunami (Chile, 1960), which was locally about half as large as Kamchatka 1952, and probably had a runup at Zhupanova of 2–4 m (Fig. 1). In only one case among the 20 sections used for statistics is there a candidate deposit from 1960 Chile, whereas 10 of these sections have deposits from Kamchatka 1952.

Over the last 3000 or more years, tsunamis in the Kronotskiy Bay region apparently were most frequent within the first millennium A.D. (Figs. 3 and 8), coinciding with a time of marked volcanic activity. If the data are further broken down using marker tephras (Fig. 7), the period from ca. 200 to 500 A.D. was the most active tsunami interval. This time period is bracketed by ages of tephra layers from the two largest Kamchatka eruptions in the last 6000 or more years (Braitseva et al., 1995, 1997; also Gusev et al., in press), forming caldera V at Ksudach and the Baraniy Amfiteatr crater at Opala volcano (Table 1). Moreover, about this same time, Shiveluch had several powerful explosive eruptions (between ca. 200 and 700 A.D.; Ponomareva et al., 1998). Also during this interval (about 300 to 800 A.D.), several stratovolcanoes appeared (mid-north cone at

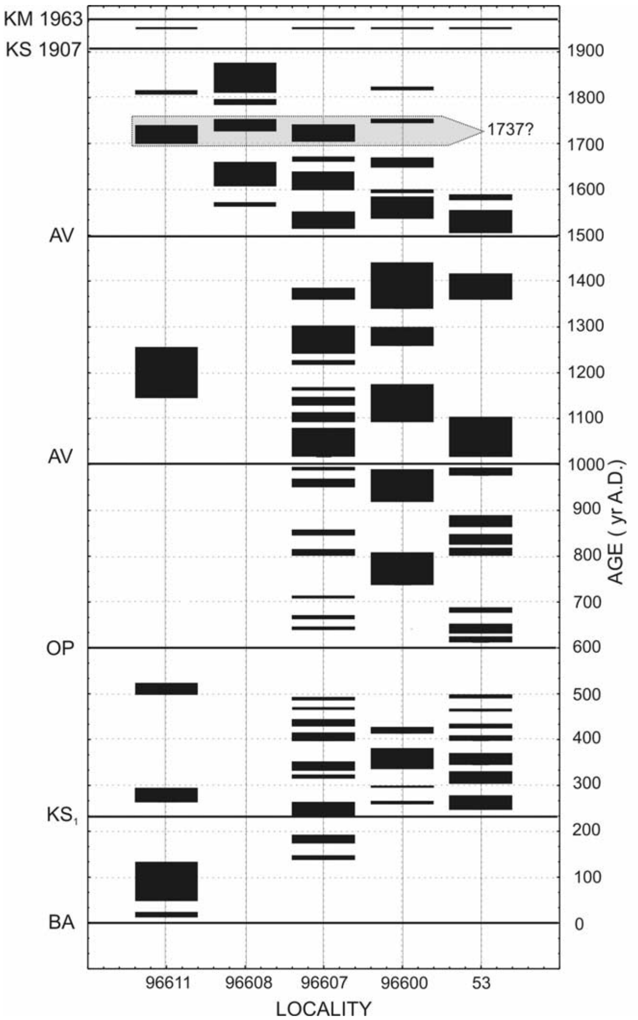

Fig. 7. Plot of calculated ages for five sections (Fig. 3) at Zhupanova River site, for the last 2000 years (above Black Ash, BA). Marker ashes (KM 1963, etc.), plotted as horizontal lines, are listed in Table 1. Because total number of tsunamis and correlation are more important than dating of these deposits, a single age range (without error bars) is assigned to each tephra. Calculated age of each tsunami deposit (maximum to minimum; Fig. 6) is shown in solid black. Candidate for 1737 tsunami deposit is outlined (see text).

Krasheninnikov, Savich cone at Kikhprinych, and Shtyubel cone at Ksudach), and a large extrusive dome of Mt. Nepriyatnaya was emplaced at the Dikiy Greben volcano (Braitseva et al., 1995).

The apparent increase in tsunami frequency in these sections may be a matter of increased preservation toward the present. We tried to correct for this factor by normalizing the data per number of observations (Fig. 8). Moreover, the apparent decrease in frequency in the last millennium leads us to believe that the higher frequencies from 0 to 1000 A.D. are real.

At the Zhupanova River site on the Pacific coast of Kamchatka, for the first time anywhere, more than 40 tsunami deposits have been recognized from a single area, at least 28 in the last 2000 years, and 41 in the last 4000 years. Based on 20 excavations containing distinctive and well-dated tephra layers, we used the maximum number of tsunami deposits between pairs of marker tephras to generate these numbers.

This geo-catalog is for large tsunamis only, with runup of ca. 5 m or more. Therefore (and based on the historical record for Kamchatka and northern Japan), most of these tsunamis likely were generated locally, along the southern Kamchatka portion of the Kamchatka–Kuril subduction zone. Deposits from teletsunamis such as 1960 Chile, and possibly from Cascadia, make up no more than 10–20% of the Zhupanova record.

In the first millennium A.D., in southern Kronotskiy Bay, there is an approximate doubling to tripling in frequency of large tsunamis, which we interpret as a proxy for Kamchatka subduction-zone seismicity. This same period is

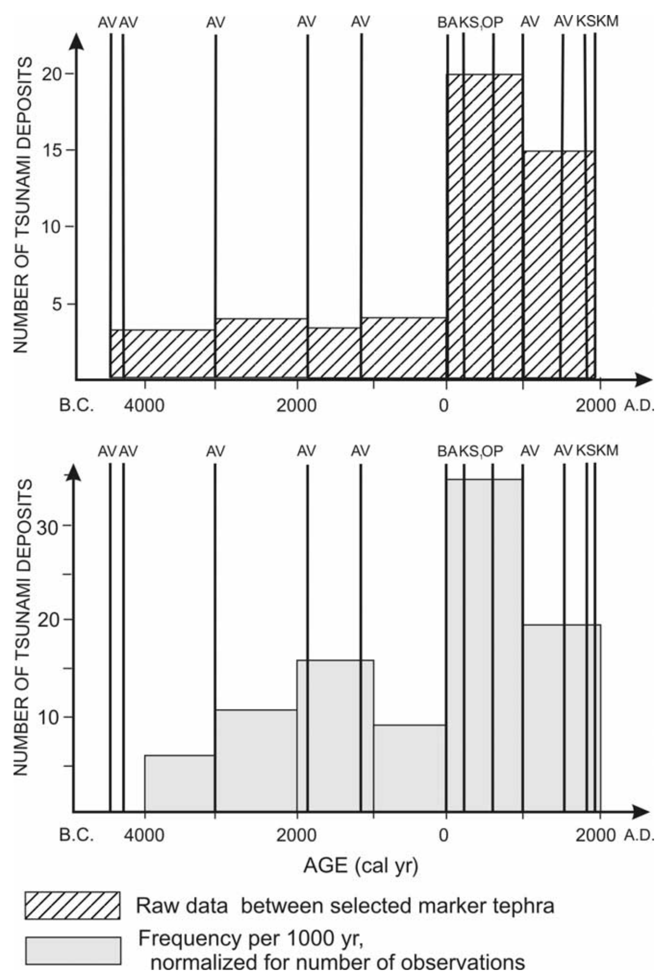

Fig. 8. Histograms of large tsunami (runup >5 m) occurrence at Zhupanova site, based on 20 excavations. Raw data are maximum number of tsunamis found in any one or more excavations between two tephras (AV, etc.; Table 1). These data were then recalculated per millennium; where tephra age is not close to a millennial boundary, we examined sections to assign deposits to one or the other millennium. We then normalized the recalculation for number of observations (per tephra interval, converted to millennia), because fewer sections contain older parts of the sequence.

characterized by marked volcanic activity on Kamchatka. The intensities of these processes may be linked.

This study is a benchmark for continuing work on Kamchatka. Paleotsunami studies are facilitated here by well-studied and abundant marker tephras, frequent large tsunamis, and widespread coastal peatlands and uplifted coastal terraces.

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