Summary of changes made both in response to reviewers our own changes
Journal: NHESS
Title: 1997 Kronotsky earthquake and tsunami and their predecessors, Kamchatka, Russia
Author(s): Joanne Bourgeois and Tatiana K. Pinegina
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Included below in our response are:
1) Summary of changes made both in response to reviewers and adding new historical information
2) Authors' response to reviewer #1 (Barbano) – previsously provided
3) Authors' response to reviewer #2 (Witter) – previsously provided
4) Marked up manuscript noting changes in text and figure captions. (Changes to tables and figures were minor corrections according to reviewers and to our own review)

1) Summary of changes made both in response to reviewers and adding new historical information

As our responses to reviewers note (see below), we took into account most editorial suggestions, and we made some clarifications based on reviewers' recommendations. These include:
a) reorganizing the abstract, while its content and conclusions remain the same
b) adding a paragraph to the introduction that states our questions/goals, as well as reorganizing the following paragraph
c) adding to and clarifying our methods, briefly, and including a brief reference to possible tsunami runup via nearby rivers
d) clarifying our reasoning for favoring 1960 Chile over 1952 Kamchatka, and also our reasoning for NOT favoring either Feb or April 1923.
e) clarifying our reasoning and argument for a more northerly Kronotsky 1997 rupture, and against other models for the earthquake rupture (Sections 5.1 and 7.2)
f) clarifying our reasoning for not correlating pre-historic deposits (it is difficult enough for historic cases)
g) clarifying our reasoning for using only specific cases for our statistics (e.g., above 5 m)
h) making minor corrections and changes in figures (not included here), and clarifying figure captions (included in marked-up text)

Our own changes irrespective of reviews (and/but which do not affect our conclusions) include:
j) changing "south" Kamchatsky Bay to "south to central" because our data extend about to the middle of the bay; this is important in interpreting the data
k) adding some information from two historical sources, particularly to the database for April 1923 tsunami – these notes extend knowledge of that tsunami to most of Kamchatsky Bay; see Section 2.3, also Tables 1 and S4
[note that we standardized spacing to 1 space rather than 2 after periods and semi-colons; this and some other formatting are shown by track changes, we decided not to try to 'mess with' these notes, sorry]

2) Authors' responses to reviewer #1 (previously provided)

Response to Professoressa Serafina Barbano:

We thank Dr. Barbano for her very careful, constructive and timely review of our manuscript. Her suggestions and corrections are easily incorporated into a revision. She did a very thorough edit, for which we are grateful. We will rewrite/clarify our abstract accordingly and make changes in the text, figures, tables and supplement. Dr. Barbano raises at least two significant issues: distinguishing the historic deposits, and locating the 1997 earthquake rupture. Here are notes on those issues:

Notes about distinguishing the historic tsunami deposits:
1) Numerical dating: We reason that neither OSL nor radiocarbon would distinguish the two 1923 events, or 1960 from 1952. Our use of chemically and/or mineralogically finger-printed tephra in such cases is more reliable. The sand at the surface must be 1997, and that reasoning agrees with the Hawaiian tide-gage data.
2) We reason that the intermediate sand layer is 1960 based on the observations that 1952 is dying off to the north, but yes, that interpretation is also supported by the presence in a few localities of the 1955 Bezymianniy tephra.
3) As to the two 1923 events, Dr. Barbano's comments, corrections and questions will help us clarify our reasoning. We cannot make a strong case to distinguish the two, to say with confidence that the deposit is from one, not the other (or both). The primary reasoning for reinterpreting the magnitude of the April event comes from the far-field tide=gage record.

A note about actual location of the 1997 rupture: We will clarify our own interpretation, although we are hesitant to draw boundaries on the rupture area. We think that with the recent interpretations of others, we can be more clear about which ones are consistent with our data. We will clarify that when we say "lower in the south" we mean the Kronotsky Peninsula sites, as well as Olga Bay to the south, not Chazhma vs. Storozh.

3) Authors' responses to reviewer #2

Response to review of Dr. Rob Witter

Response to general comments

… the introduction does not clearly articulate the relevant scientific questions. One way to improve the introduction would be to specifically lay out the central questions addressed by the research, and how the study addresses them.

Response: we will write a short introductory paragraph BEFORE the other paragraphs laying out the basic questions: How do tsunamis inform earthquake interpretations? The 1997 tsunami requires a different earthquake source region than geophysically interpreted: we address the (previously unrecognized) significance of the 1997 tsunami to that interpretation. Do the historic earthquakes in the northern part of the KSZ characterize it as rupturing in shorter segments than southern part? How does the prehistoric record inform the question? What are the strengths and limitations of reconstructing prehistoric tsunamis, even with strong age control from well-dated and well-mapped tephra?

For the paper to meet international standards of practice in tsunami science, the authors should place greater emphasis on the methods used in the study. In fact, the authors are leaders in this field and pioneered many of the methods used today. However, the brief presentation of these methods obscures important details and raises questions about some of the conclusions of the study. For example, the authors describe tsunami deposits generally as sand sheets that become thinner and finer-grained in a landward direction (line 245). But was this used in the study? [**Response**—yes, in the cases of historic events and the general trends in prehistoric deposits]

In detail, the deposits mapped in profile 110 are thickest in exposure 45, the farthest site from the sea; [**Response**—reviewer is wrong about this—for example, the historic deposits do not even occur in excavation 45; the deposits he is talking about are older and cannot be correlated from excavation to excavation; the fact that the deposits are more numerous in excavation 45 is a matter of preservation and identification, NOT thickness or grain size]

and no particle size data are included in the results. [**Response**—only relevant for historical deposits except for general trends—would the reviewer like to have copies of all our field notes? These are general trends—on one hand he wants us to write more, but we feel he is looking for contradictions where there are none.]

What differentiates a sand layer on the coast of Kamchatsky Bay from a flood deposit of the Chazhma River, [**Response**—we can add a sentence that flood deposits here are muddy, and most of our sites are above flood level] *or a sandy fan deposit produced by storm wave wash over? In 2013 Typhoon Haiyan's storm surge produced sheet-like overwash deposits up to 8 cm thick that extended over 1000 m inland (Pilarczyk et al., 2016).* [**Response**—(there is a 2017 paper on Haiyan deposit as well) we can repeat as in prior studies that tropical storms & their surges do not occur at these latitudes, and our elevations are high enough to preclude regional storms; we don't see a reason to repeat what is in prior papers, unless more than one reviewer requests it. But if the editor asks, we will comply, in the Supplement, not in the main text.]

In some of the figures, the predominant sediment is sand **--***how do tsunami deposits stand out in this sedimentary environment? Do aeolian processes deposit sheet-like sand layers along Russian coasts?* **[Response**—if the editor requests this, we can copy and paste our discussions from prior published papers, in the supplement.]

The authors should provide additional explanation on the methods used to determine paleo-elevation and shoreline positions used to estimate past inundation and runup. **Response**—see Figure S5 as well as the paper that actually uses this information in detail (Pinegina et al., 2013). What more does the reviewer want? Why repeat what is published?

One example that needs clarification is application of the method to deduce long-term uplift and subsidence. For example, the authors present contrasting topographic profiles in southern Kamtchatsky Bay that they interpret as evidence for opposite senses of tectonic deformation over distances of what looks like less than about 50 km. [**Response:** The reviewer's question does not have to do with method but with cause (tectonic segmentation, not the point of this paper). Reviewer appears to have read Pinegina et al., 2013, which discussed tectonics more than this paper, for which it is not the point; further discussion below]

Profile 001 in Figure 7 shows the low-lying Bistraya River valley that flanks higher coastal deposits, yet the authors do not present clear evidence for tectonic subsidence.[**Response**: In general, we rule out uplift here; see next response] *Does the evidence preclude coastal erosion that removed tephra deposits seaward of the Bistraya River that drape the lower valley topography?* **Response**—yes, some tephra are eroded because the profile became lower (subsided)—**there are older tephra that are essentially at sea level**, whereas tephra are not preserved on the coast below the general storm limit (see our discussion and also Figure S5).

In Figure 8, the authors interpret Chazhma profile 110 as evidence for uplift based on reconstructions using seaward termination of tephra deposits [no—based on elevation of oldest preserved tephra]. *If there is a marked change in tectonic deformation between the Bistraya and Chazhma Rivers, what mechanism accommodates the opposite senses of motion?* [**Response:** The reviewer does not dispute our observations but wants a tectonic explanation—see our response above **--**reviewer appears to have read Pinegina et al., 2013, which discussed tectonics more than this paper, for which it is not the point. We do note in this paper that Kronotsky is where the Emperor Seamount chain impinges on Kamchatka]

A more complete explanation of methods, and presentation of the evidence will help substantiate the authors' interpretations here.]**Response**—we can expand our methods section in the supplement if requested by the editor. However, reviewer does not dispute our data or our interpretations, as far as we can tell.]

The figures are well designed, readable, and present important observations. However, an additional figure might be added to demonstrate how tephra stratigraphy is applied to deduce tectonic subsidence at Bistraya. [**Response**—see Figure S5—Storozh and Bistraya are along the same coastal plain, as noted in our introduction to the area.]

Additional improvements to Figure 1, suggested in comments in the reviewed manuscript copy, could help the reader place the study sites into the overall tectonic and geographic setting. **Response—**will do.

Finally, I want to see representative photographs of the tsunami deposits to help show how they are distinguished from sandy soils, fluvial deposits and sand deposited by storm waves and aeolian activity. **Response—**this can be shown in text, but reviewer should know well that photographs will not show it, and that is true even when we make meter-long excavations, not cores, as most other workers do most of the time, for example, in Japan, at lower elevations that in Kamchatka.

The paper would be incomplete without the supplementary material. More detailed explanation of the methods, and tables showing the reconstructions of paleotsunami deposit elevations based on tephra stratigraphy help substantiate the authors' interpre-
tations. To help readers understand the paper without relying on the supplement, some of these details should be included in the main paper.
Response—which? We differentiate our data and interpretations based on those data – in the main body of the text **--** from additional information on methods and other peoples' observations, e.g., of tide-gage records. If we expand our discussion of methods with regard to identifying tsunami deposits, it would be in the supplement because it is already published, as is our method for reconstructing shorelines. Note that in this field location we have several historical deposits to use as interpretive guides. Should we say that more specifically?

Additional responses to Reviewer 2, Dr. Witter:

General comment about distinguishing tsunami deposits. We can add a few lines/sentences but do not feel the need to repeat material in prior publications. We would put it in the supplement. Note that tropical cyclones like Haiyan do not occur at these latitudes.

General comment about sea level history. We will add a sentence about late Holocene sea level stability in this region; our analysis goes back only about 2000 years and thus does not require a repeat of material discussed in detail in a prior publication (Pinegina et al., 2013) that covers more time and where the amounts of relative sea level change are more relevant.

General comment about tectonics: They are not the focus of this paper. We do note that the profiles indicating uplift are close to Kronotsky Peninsula, which is going up. It is not the purpose of this paper to discuss tectonics, as we did in a prior paper. We do not have a long enough record here to do the same kind of analysis. Nor has this region been examined for active faults, as had the Pinegina et al. 2013 paper (and companion Pedoja et al.).

General comment about limitations to methods. We believe we are very clear that our methods have limitations. Reviewer tends to point these out, also, but we cannot find examples where we haven't pointed the same out ourselves, with a few minor examples noted below. For example, p. 2 line 4-5 of supplement, our sentences actually describe specific cases where inundation will be underestimated or overestimated, in two sentences. We feel as if the reviewer did not read the sentences with their qualifications. There is no general rule, and we are also clear throughout that our estimates are minima, within the constraints of the methods. Same on that page with lines 15-16. However, we will do some rewriting of that sentence to make it clearer.

Dr. Witter makes some other important but completely addressable points in the pdf review of the manuscript, which we address below:

Line 7 (abstract) – We will change this word to “portion” and used “segment” when speaking specifically of segmentation, which is the more technical term.

Lines 35ff. We think this is an appropriate sentence for an introduction, which is setting up our study.

Figure 1. We will add scale. The addition of boxes will obscure information. Olga Bay and Kozlov Cape are in tables. Cape Africa was in the table but has been removed, thus we can remove that, but there is no real reason to remove information, this is a locator map.

Line 74-75. Reviewer’s questions are already addressed in the existing manuscript. This is an introduction.

Line 79. Reviewer’s questions are already addressed in the existing manuscript. This is an introduction. We wish the reviewer should have gone back and re-read his comments/questions after reading the paper.

Figure 2. Will address small corrections. Points above hypocenters can be mapped.

Figure 3. We will expand the caption. However, clearly the reviewer did not read the caption carefully because it states that the photos were all taken on the same day. Figure S3, previously published and hence not in the main body of the text, shows a sketch. We can label sand and sea foam.

Line 201. We do not use the word predecessors because it implies the other events were similar to 1997, and they were not.

Line 206-207. Why crossed out?

Table 1. Questions will be addressed, table will be easily clarified.

Line 213. Will clarify – it’s the bolded column on the table.

Lines 211-222. Will correct labels and shorten text.

Lines 224-225. We disagree with deletion. It is important to note that catalogues existence does not mean that all events are recorded.

Figure 4 left. Will remove asl and note that the lower right corner of each profile is 0.

Lines 251-255. Reviewer is wrong; this has nothing to do with 3-D tsunami behavior. We are here defining NOT tsunami elevations, but rather deposit elevations and distances. Even IF the tsunami did not overtop some point but came from the side, its sediment (minimum, as we note) runup and inundation on THAT PROFILE would what it is. If the tsunami got there and left a deposit, that distance and elevation had to have been reached.

Figure 5 caption. We will add a note about this being a simple 2-D profile. HOWEVER, if the tsunami came from the side rather than over the beach ridge, it had to carry the sand even farther, so its elevation would almost certainly be greater than as shown, and its inundation at least as much. The sketch is based on data from this profile, but also on our knowledge of the regional topography – beach ridges do not just appear on 2-D profiles. See Figure 4.

Line 266. We wish the reviewer would read on and then correct his question. There are three most consistently present and one that is not as extensive, as stated in the next sentence.

Table 2. We are sorry there is more than one designation for these tephra, such information needs to remain in the table. We will use AD dates in the text.

Line 279 – insert "and" between "past" and "must"

Line 282 – we can elaborate a bit, but here we are dealing only with the last 2000 years or so, we don't need to review the last glaciation. Insert "relative to sea level" after changes in elevation. [reviewer later notes, as we have, that some profiles have gone up and others down, not expected if from eustasy]

Line 287. The name Chazhma is just our shorthand. Details of the rivers is not necessary. The table lists latitudes and longitudes. We cannot provide topographic maps as they are proprietary. Google Earth is available to reader.

Line 309. If the tide was low at the time of the survey, we would get a maximum, whereas we want a minimum, so we correct to high tide. We could add this note to methods.

Line 316-317. Reword: We also report the maximum height the tsunami had to exceed IF it traveled ACROSS the profile. Reviewers concern is also addressed in the next sentence.

Line 319: Add: note that for most profiles, the ridge crossed continues laterally (e.g., see Figure 4 profiles)

Line 330 – this concern is already addressed in our methods text on sediment inundation and runup.

Table 3. Will write out m.a.s.l. The depth to these 20th century deposits is insignificant. For prehistoric deposits, it is recalculated.

Line 370. Add "and other historical deposits".

Line 388 resolves to most slip

Line 410. Disagree with deletion.

Figure 7. Reviewers question is answered in the figure text.
Figure 7 caption – older tephra are preserved below sea level, thus subsidence –clarify in caption.

Figure 8. We will add to the caption – "sand" undifferentiated means that the section was too sandy to identify individual deposits.

Line 456. First, we do not use cores, we use excavations. Still, correlating individual beds is fraught with potential errors. We would argue with anyone who says otherwise, based on historical examples (closely paired events, e.g.) and extensive field work.

Figure 9. Profile 140. Yes, this section has older material, which we report here but do not use in our analysis. The older tephra identifications are tentative, but done in consultation with Vera Ponomareva who has mapped them regionally. Both profiles – when deposits of tephra or sand are more patchy, they are shown as not extending across the section; we will add that information here and note in the Key in Figure 4.

Line 464 (figure caption) will add that there is not a river nearby.

Line 470. Soil between sand layers was not distinct enough. Will add to text.

Line 475-476. Yes, in this case runup could be different, but not for the other excavations on this profile. We are being honest about cases where water might have come a different way, though we think it unlikely. Such uncertainty does not affect the overall analysis.

Line 480. Deposits cannot be correlated. We never count more than the maximum number of deposits. However, the deposit with the greatest sediment inundation may be on a low profile, whereas the deposit with the highest sediment runup may be on a steeper, shorter profile. We are likely undercounting.

Line 489-490. Reviewers comment is exactly why the lack of higher paleo-runups is an artefact of the sites used. Yes, the higher profiles were lower in the past, so we cannot "get" a record of high runups.

Lines 505-507. Add to caption. One would expect smaller events to be more frequent, which in general is the case (clustering in the lower front), whereas larger events are more scattered. However, the 1923 deposit is about as large as any, and it's within a short time interval. If we removed that axis, information would be lost. But we want to point out there is some time bias.

Line 523 and Figure 11. The red line is runup and does not go below 5 m. We are considering only the largest tsunamis, and by staying about 5 m, as clearly stated.

Lines 552-553. We are pointing out that even modern survey data have limitations. In our case of studying deposits where there are no survey data, we still for the historical record pair runup and inundation. However, for the prehistoric record it is simply not possible. Reviewer does not seem to contest that. We are thus recording typical recurrences of sediment runups and inundations over the last 2000 years, while being careful not to overinterpret.

Line 556. Please keep reading the paragraph, it explains why in this case, with our data.

Line 561-562. Add: While we cannot determine the tide level for "1923" because it is one of two events, the 1997 earthquake occurred just after local high tide, so tide cannot explain the higher record from 1923.

Line 568. change wording from "asperity" to "locked or continuously slipping zone" because it could be locked (an asperity) or continuously slipping (as interpreted by some of the gravity people)

Line 584-585. The issue is illustrated by Hayes' more westerly location, which cannot explain the tsunami, even though his rupture focus is more northerly than others' interpretations. We are not sure what the reviewers point/question is.

Line 588. Seismic gap is a well-defined and oft-used term. It completely describes the 1997 location in our interpretation (and earlier Russian publications)

Line 590. An asperity is defined by IRIS and others as a locked zone with POTENTIALLY high slip. We are not sure where "elsewhere" the reviewer means.

Line 605-606. (as shown in our this paper, our papers, and papers on Japan—need we repeated here?) A large part of the paper relies on tephra for reconstructions. As have been used in Japan, as well. Is reviewer disputing this statement?

4) Marked-up text including tables and figure captions

1997 Kronotsky earthquake and tsunami and their predecessors, Kamchatka, Russia

Joanne Bourgeois[1], Tatiana K. Pinegina[2]

[1]Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195-1310, USA
[2]Institute of Volcanology and Seismology, FEB RAS, 9 Piip Boulevard, Petropavlovsk-Kamchatsky, 683006, Russia

Correspondence to: Joanne Bourgeois (jbourgeo@uw.edu)

Abstract. The northern part of the Kamchatka subduction zone (KSZ) experienced three tsunamigenic earthquakes in the 20th century -- Feb 1923, April 1923, Dec 1997 -- events that help us better understand the behavior of this segment. A particular focus of this study is the nature and location of the 5 December 1997 Kronotsky rupture (Mw ~7.8) as elucidated by tsunami runup north of Kronotsky Peninsula in southern to central Kamchatsky Bay. Some studies have characterized the subduction zone off Kronotsky Peninsula as either more locked or more smoothly slipping than surrouding areas and have placed the 1997 rupture south of this promontory. However, 1997 tsunami runup north of the peninsula, as evidenced by our mapping of tsunami deposits, requires the rupture to extend farther north. Previously reported runup (1997 tsunami) on Kronotsky Peninsula was no more than 2-3 m, but our studies indicate tsunami heights for at least 50 km north of Kronotsky Peninsula in Kamchatsky Bay, ranging from 3.4 to 9.5 m (average 6.1 m), exceeding beach ridge heights of 5.3 to 8.3 m (average 7.1 m). For the two 1923 tsunamis, we cannot distinguish their deposits in southern to central Kamchatsky Bay, but the deposits are more extensive than the 1997 deposit. A reevaluation of the April 1923 historical tsunami suggests that its moment magnitude could be revised upward, and that the 1997 earthquake filled a gap between the two 1923 earthquake ruptures. Characterizing these historical earthquakes and tsunamis in turn contributes to interpreting the prehistoric record, which is necessary to evaluate recurrence intervals for such events. Deeper in time, the prehistoric record back to ~300 A.D. in southern to central Kamchatsky Bay indicates that during this interval, there were no local events significantly larger than those of the 20th century. Together, the historic and prehistoric tsunami record suggests a more northerly location of the 1997 rupture compared to most other analyses, a revision of the size of the April 1923 earthquake, and agreement with previous work suggesting the northern KSZ ruptures in smaller sections than the southern KSZ. The latter conclusion requires caution, however, as we continue to learn that our historic and even prehistoric records of earthquakes and tsunamis are limited, in particular as applied to hazard analysis. This study is a contribution to our continued efforts to understand tectonic behavior around the northern Pacific and in subduction zones, in general.

Key words: Kamchatka, subduction zone, 1997 Kronotsky earthquake, 1997 Kronotsky tsunami, Kamchatsky Bay, paleotsunami, paleoseismology

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1 Introduction

In this paper we intend to illustrate how tsunamis may inform interpretations of their earthquake sources. For example, by presenting previously unpublished tsunami-deposit data we show that the December 1997 Kamchatka tsunami requires a different earthquake source region than geophysically interpreted, a source that lies between prior historical events (in a seismic gap). This conclusion leads us to the question, do earthquakes in the northern part of the Kamchatka Subduction Zone (KSZ) characterize it as rupturing in shorter segments than the southern part? We address this question, particularly for northern portion, by studying the history and the prehistory of tsunamis in this region. In conducting this analysis, we illustrate some of the strengths and limitations of reconstructing prehistoric tsunamis, even with strong age control from well-dated and well-mapped tephra.

Without post-tsunami or tsunami-deposit surveys, remote spots in the world may experience large events without a written record, as illustrated, e.g., by references to the "modest" or "small" tsunami of the 15 December 2006 central Kurils earthquake (Ammon et al., 2008; Liu, 2009). In fact this tsunami generated an average of 9.6 m runup over an along-rupture length of 390 km (MacInnes et al., 2009). The case we present herein of the 5 December 1997 tsunami following the Mw 7.7-7.9 Kronotsky earthquake (Fig. 1, Fig. 2), however, is even more complex historically, because there *was* a post-tsunami survey quickly following (Zayakin and Pinegina, 1998), though of limited extent. The local tide-gage record for this 1997 tsunami is also incomplete, and deep-water pressure recorders deployed at the time were not positioned to get distinctive recordings from a tsunami originating near Kronotsky Cape (Bourgeois and Titov, 2001). The earthquake and tsunami occurred in the dark of a December night in an area with no permanent settlements.

In the summer of 2000, we conducted a field survey for historical and paleo- tsunami deposits in south Kamchatsky Bay (Fig. 1), north of Kronotsky Peninsula. We expected to find evidence for historical Kamchatka tsunamis such as 1923 (Table 1; Table S1), but not for 1997 Kronotsky because on the Kronotsky Peninsula, the post-tsunami survey found evidence of quite limited runup. Thus we were surprised to find a sand layer just at the surface, covered only by plant debris such as grass and leaves, distributed much as we have come to expect of tsunami deposits, and at elevations of 5 m or more above sea level. Although we were skeptical at first, we could find no alternative to explain the layer and its distribution other than a tsunami from the 1997 earthquake.

The implications of this case, where an earthquake was analyzed without full knowledge of its tsunami, are several. First, the fact that there was runup greater than that reported by a post-tsunami survey changes our view of the tsunami as well as of the earthquake. Further, the size of the tsunami, based on its deposits and a corroborating eyewitness account (acquired in 2001), helps constrain rupture characteristics of this earthquake. This constraint in turn leads to an interpretation of segmentation of the northern KSZ, and our interpretation that the tsunamigenic portion of this earthquake rupture occurred in a gap between two 1923 tsunamigenic earthquakes.

This recent historical tsunami also helps us interpret earlier historical and well as prehistoric earthquakes and tsunamis along the northernmost part of the Kuril-Kamchatka subduction zone. Tsunamis originating from this region commonly have an impact not only locally but also on Hawaii, as did the February 1923 tsunami, and in some cases even on the western coast of the Americas, as did the 2006 central Kurils tsunami.

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2 Background

2.1 The 1997 Kronotsky earthquake

On 5 December 1997 at 23:26:51 local time (11:26:51 UTC), a large earthquake (Mw 7.7-7.9; we use 7.8) shook the region of the Kronotsky Peninsula, Kamchatka, Russia (Fig. 1, Fig. 2; Gordeev et al., 1998). The earthquake was characterized by a typical foreshock-mainshock-aftershock sequence (Gusev et al., 1998; Fedotov et al., 1998; Balakina, 2000; Zobin and Levina, 2001; Kuzin et al. 2007; Slavina et al., 2007). Most studies of the earthquake calculate a moment magnitude of 7.8 for the energy released in the first 60-80 seconds of the main rupture (e.g., Zobin and Levina, 2001). Gusev and Shumilina (2004), in reassessing many Kamchatka earthquakes, assign Mw 7.9 to Kronotsky 1997. In addition to the mainshock, and using GPS measurements, Gordeev et al. (2001) calculate Mw 7.7 for deformation in the *pre-seismic* half month, and approximately Mw 7.9 for *post-seismic* deformation; Bürgmann et al. (2001) calculate Mw 7.7 of (*post-seismic*) aseismic energy release in the 2 months following the mainshock, also based on GPS data.

The locations of the mainshock and of any slip concentration for this earthquake have not been well resolved, and with one early exception (Sohn, 1998), locators have not used tsunami data. Based on seismic data, the locations of foreshocks and the mainshock/epicenter (Fig. 2) are in the northern part of the interpreted rupture area. A number of analytical locations of the mainshock lie under the NE Kronotsky Peninsula (Fig. 2; Table S2). Some analyses interpret the rupture to have propagated NE to SW (Petukhin et al., 1998), deepening toward the SW. Gusev (2004) maps the entire aftershock zone as part of the 1997 event (Fig. 1). On the other hand, the linear zone of aftershocks in the SW (Fig. 2) has been interpreted to be a separate stress zone (Kuzin et al., 2007) potentially along a separate transverse fault (Slavina et al., 2007). In an analysis focused on GPS data, Bürgmann et al. (2001) place the majority of the primary rupture energy in the southern half of the aftershock zone.

2.2 The recorded 1997 Kronotsky tsunami

The most complete contemporary record of the 1997 Kronotsky tsunami is from far-field tide gages. Both proximal tide gages, in Ust'-Kamchatsk and in Nikolskoe (Bering Island) (Fig. 1), were not functioning when the tsunami arrived. The Petropavlovsk-Kamchatsky gage is very protected and shows a wave train with an amplitude of about 0.01 m (Zayakin and Pinegina, 1998). The tide gage at Nikolskoye resumed recording after the first 10 hours of the tsunami, with a few cm of amplitude remaining (Zayakin and Pinegina, 1998). The far-field tsunami had tide-gage amplitudes in Alaska/Aleutians and Hawaii in line with other tsunamis traveling to Hawaii from the Russian Far East (Table S3; Fig. S4). The tsunami was recorded on at least 12 tide gages, with the highest amplitude (half of wave height) of 0.3 m at Kahului, Maui, Hawaii (NCEI online database). Deep-water pressure sensors deployed at that time in the north Pacific were all in tsunami shadows for this tsunami source, and in all cases, the modeled and measured tsunami was within the noise level of the buoys (Bourgeois and Titov, 2001; no event page at http://nctr.pmel.noaa.gov/database_devel.html).

A truncated post-earthquake and tsunami survey by helicopter took place on 9 December 1997 (Leonov, 1998; Zayakin and Pinegina, 1998). The survey reached as far north as Kronotsky Cape on the Kronotsky Peninsula (Fig. 1) and found that the tsunami had not exceeded the unvegetated sandy beach. At this time, the beach was

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covered with a thin layer of ice and snow, which in places had been coated by the tsunami with a thin sand layer and elsewhere had been broken up by the tsunami (Fig. 3). The team did not have surveying equipment and estimated runup to be no more than 3 m (T. Pinegina notes), and the published report gave a maximum of 1-1.5 m. The turnaround point in the survey was dictated by fuel and available daylight.

On 5 December 1997, two rangers were in a cabin near Big Chazhma River (Fig. 1); one of them was interviewed (in Petropavlovsk-Kamchatsky) by T. Pinegina 19 April 2001. They felt the earthquake that night, and the next day, as was their custom, they went via snowmobile to survey the northern coastal part of Kronotsky reserve, to the Little Chazhma River area. At the mouth of the Big Chazhma, they saw jumbled ice and seaweed on the snow; a cabin on the south bank of the Little Chazhma River was partly wetted, and there was seaweed on the snow. Normally the rangers crossed the river near this cabin, but the river was a jumble of ice and they had to go some distance upstream in order to cross (on ice). On the other side, they could not continue north because there was water in the low spot between beach and hill (see Fig. 4, our profile 100).

Based on results of the post-tsunami survey (reported to Sohn by V. Gusiakov), Sohn (1998) analyzed the tsunami with regard to its earthquake source and concluded that the main rupture must have lain largely under land, in order to explain the low runup accompanying a moment magnitude she calculated as Mw 7.7.

2.3 Historical record of earthquakes and tsunamis affecting the field area

The Kamchatka Peninsula has a short but rich historic record of large earthquakes and attendant tsunamis, of which we discuss herein only 20th century tsunamis originating in or having been recorded in the field region of Kamchatsky Bay (Table 1). In addition to locally originated tsunamis, Kamchatka is vulnerable to tsunamis from Chile, less so from Peru, and not so much from Japan, Alaska, Aleutians and Central America, due to directivity (e.g., see Table S1). Based on scant records (Table 1), the 1960 Chile tsunami likely reached elevations of 3-5 m above sea level along Kamchatsky Bay (Fig. 1), on the order of twice as high as the 1952 southern Kamchatka tsunami in this bay (Table 1).

The largest documented local tsunamis from earthquakes near Kronotsky Peninsula (Fig. 1; Table 1) are two from 1923, both having local as well as farfield records (Table S4); both may have affected south-central Kamchatsky Bay. There was also a 24 Feb 1923 Mw 7.6 earthquake in this area (Fig. 1; Gusev, 2004); however, it has no historical tsunami record in the near or far field. The Mw 8.0 1917 earthquake along the Steller fracture zone (Fig. S1) also did not produce a recorded tsunami. The 3 Feb 1923 Kronotsky Bay earthquake (Mw 8.5) was located south of Kronotsky Cape (Fig. 1), and its tsunami was large (6-8 m) in Kronotsky Bay (Table 1), decreasing northward; a sled team in the area during and after the earthquake reported a coastal ice rampart being pushed about 3 km upstream on the (Big?) Chazhma River, north of Kronotsky Cape. The 13 April 1923 north Kamchatsky Bay earthquake (Mw 7.3 in NCEI catalogue; 14 April local time) generated a very high tsunami in north to north-central Kamchatsky Bay (Table 1; Table S1), with large(st) ("naibolshii") effects south to Cape Shubert in south-central Kamchatsky Bay (Fig. 1) (Troshin and Diaghilev, 1926). [Based on tsunami amplitudes, Gusev and Shumilina (2004) suggested this April 1923 earthquake had a moment magnitude of 8.2 (Table S1, Fig. S2)] In sum, the

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February and April tsunami runup was large south and north (respecitively) of our field area, decreasing toward that field area.

The record of earthquakes and tsunamis on Kamchatka prior to the 20th century is spotty but improving (Zayakin and Luchinina, 1987; Godzikovskaya, 2010). Earthquakes on 17 May 1841 and 17 October 1737 originated in the region of the 1952 south Kamchatka great earthquake, so likely did not have significant effects in (southern) Kamchatsky Bay (see Table 1, 1952 runup). Other tsunamis that may have affected southern Kamchatsky Bay are an autumn 1849 tsunamigenic earthquake in the vicinity of the Komandorsky Islands (Godzikovskaya, 2010) and a 1791 event which has an intriguing account of having affected the mouth of the Kamchatka River (Ust'-Kamchatsk), reported to reach 7 km upstream (Zayakina and Luchinina, 1987).

3 Methods

We measured 15 topographic profiles (Fig. 4) perpendicular to the shoreline along the coast of southern to central Kamchatsky Bay (Fig. 1; Fig. S2), and made 117 hand-dug excavations along these profiles in order to document historical and paleotsunami deposits. We used a surveying rod with a transit level (hand level and tape for profile 001 and upper part of profile 120) (methods as in Bourgeois et al., 2006). We usually excavated to 0.5-1 m deeper than the lowest preserved tephra overlying clean sand (not exhibiting soil weathering).

It is well-established that tsunamis create sedimentary deposits as they flood a coastal plain with turbulent, turbid water, and there are means to distinguish tsunami deposits from those of floods, storms and wind. The general characterization of a tsunami deposit in sandy coastal systems is a sand sheet which typically thins and fines landward, following topography and commonly thickening in swales (Bourgeois, 2009). Many factors, from sediment availability to coastal topography and surface roughness to the velocity profile of incoming and outgoing waves, play a role in sedimentation. Kamchatka field sites are primarily sandy, vegetated coastal plains and associated peat marshes, where shoreline availability of sand and onshore vegetative cover maximize the likelihood of generating and preserving tsunami deposits. (Many historical Kamchatka tsunamis have occurred during winter snow cover; deposits would have been "let down" onto a vegetative mat as the snow melted.) In these settings, river flood deposits are muddy (not clean sand), and eolian deposits are rare, not sheetlike, and consistently fine-grained; storm waves and storm surge at these latitudes rarely exceed elevations and particularly distances of our surveyed profiles (see Bourgeois et al., 2006).

We use three measurements to characterize tsunamis via their deposits (Fig. 5): sediment inundation (L), sediment runup (h), and maximum height seaward of a deposit on a given profile (H). The maximum distance inland of a tsunami deposit (*sediment inundation*, Fig. 5) and the deposit's elevation at sediment inundation (*sediment runup*, Fig. 5) represent minimum estimates of tsunami extent for several reasons; Tsunami deposits can only be more limited (not more extensive) than water runup and inundation, the final limit of a deposit is not always located in the field on any given profile, and thin deposits may not be identified or preserved.

Primary age control in excavations is provided by dated regional and local marker tephra layers (Table 2), which in general have been well studied on Kamchatka (e.g., Braitseva et al., 1997), although tephra in the southern Kamchatsky Bay area had not previously been examined. Based on our own and previous work, as well as on more

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recently published isopach maps (Kyle et al., 2011; Ponomareva et al., 2017), the three most consistently present layers in the sections are KSht$_3$ (A.D. 1907 — we use KS$_{1907}$)—most useful for studying the historical record, SH$_{1450}$ (A.D. ~600) and KS$_1$ (A.D. ~300), the latter used as the lower boundary for our tsunami statistics. A fourth marker, SH$_2$ (A.D. ~1130), is commonly present in more northerly profiles. Recent work around Shiveluch volcano and Kamchatsky Peninsula (Fig. 1) has led to redesignation of Shiveluch tephras and to more definitive model ages of these tephra (Ponomareva et al., 2017). In addition to the silicic marker tephra (Table 2), there are local basaltic-andesitic tephra layers, which can be from Kliuchevskoi, Bezymianny, Tolbachik or Gamchen volcanoes; we used these tephra only as local field guides. In the northernmost of our profiles, a historic ash from Bezymianniy 1955 (year before the 1956 paroxysmal eruption) is locally present and used as a factor in distinguishing Chile 1960 tsunami deposits from Kamchatka 1952.

For the prehistoric record of tsunami runup and inundation, topographic profiles would not necessarily be the same as in the recent past and thus must be reconstructed to account for succeeding topographic changes in elevation and distance along the profile. While we cannot typically reconstruct profiles that have been changed by erosion, we can reconstruct profile progradation (building seaward), which affects profile width. Our method uses preserved tephra as discussed, e.g., in Pinegina et al. (2013) and MacInnes et al. (2016), as summarized in Fig. S5. Changes in elevation relative to sea level are quantified by determining the age and elevation of the lowest former soil horizon above marine sand in any excavation (Fig. S5) (as in Pinegina et al., 2013). For the case herein, reconstructing less than 2000 years of coastal history, our calculated changes in relative sea level are due to active tectonics, not eustatic or regional sea-level fluctuation.

3.1 Field localities

The southern field site (Fig. 1) which we call “Chazhma” (Fig. 4) is a narrow strip (~400 m wide or less) of Holocene accumulative coastline along a rugged coast just north of the Kronotsky Peninsula. The two profiles near river mouths (Chazhma 210 and Chazhma 130; Fig. 4) maintain lower elevations (< 4 m) over much of their distance, though both reach elevations of more than 6 m above sea level. The other five profiles rise, typically in sharp steps indicative of Holocene uplift events (as in Pinegina et al., 2013), reaching typical maximum levels of 8-10 m (Fig. 4). Net uplift on these profiles is consistent with longer-term uplift of Pleistocene terraces on the Kronotsky Peninsula (Melekestsev et al., 1974).

The northern field site which we call “Storozh,” extending north to the Bistraya River (Fig. 1; Fig. 4), is a broader strip (typically 600 m wide) of Holocene accumulative coastal plain associated with active and drowned river mouths. Two of these profiles (140, 001; Fig. 4) drop in elevation behind one or more beach ridges. The other seven profiles are typified by a series of beach ridges, of which the seaward ridges are higher, reaching typically 6-7 m, with an average elevation of the profile in the range of 4-6 m (Fig. 4). Such profiles indicate minor subsidence or no vertical change in the late Holocene.

4 Results -- 20th century tsunami deposits

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In field season A.D. 2000, the sand we interpret to have been deposited by the 1997 Kronotsky tsunami formed a sheet-like layer at the surface, buried only by grass, leaves and other dead vegetation, in general decreasing landward in thickness and grain size. The deposit we interpret to be "1923" (from one or both of two tsunamis in 1923) lies above the marker tephra KS_{1907} with less soil thickness between KS_{1907} and "1923" than between the top of "1923" and the base of the modern turf. Our interpretation of "1923" as well as a rare sand layer between "1923" and 1997, which we assign to the 1960 Chile tsunami, is discussed below.

Using identified and mapped tsunami deposits, we calculate minimum sediment runup and inundation on each of the 15 profiles (Table 3, Figure 6), correcting to high tide from tide at the time of survey. The 1997 tsunami occurred just after high tide; in all cases, using a high tide datum gives us minimum runup values. We determine minimum sediment runup (h) by the presence or absence of distinct 1997 and "1923" deposits on each profile. We distinguish between profiles where the farthest landward excavation still contains the 1997 or "1923" deposit and ones that do not. If no deposit is present in one or more excavations landward of ones with a deposit, the limit of sediment inundation (L) occurs within the measured profile (Fig. 5, example of 1997) and actual tsunami runup is estimated from sediment runup. For profiles where a particular tsunami deposit extends beyond all excavations (Fig. 5, example of 1923), the actual size of the tsunami could be, in some cases, significantly greater than our sediment-runup and inundation minima. We also report the maximum height the tsunami had to exceed (H) as it traveled along a profile (across the accumulative marine terrace). In a few cases, the farthest inland excavation was at a low elevation that could have been reached via the river rather than over the profile (Table 3, Fig. 6), although the deposits observed were not muddy. Note that maximum elevations and inundation distances are affected by elevations and distances along actual profiles (Fig. 4), e.g., a profile cannot record sediment runup higher than its maximum elevation, and a short, steep profile will record shorter sediment inundation distances.

4.1 1997 tsunami

Sediment runup data (Table 3, Fig. 6) indicate that in southern to central Kamchatsky Bay, the 1997 Kronotsky tsunami ran up to as much as 9.5 m, averaging 6.1 m, with moderate inundation distances of 100-300 m. The general pattern over about 100 km of coastline, including post-tsunami survey observations on Kronotsky Peninsula itself, is relatively smooth, and we also expect based on the pattern that there was runup north of our northernmost profile (Fig. 6), but north-central Kamchatsky Bay comprises sea cliffs, not coastal plain. The maximum elevation reached by the tsunami deposit is higher on southern (Chazhma) profiles. However, lower runup numbers on northern profiles may be an artefact of their lower elevations (Figure 4); inundation distances are greater on these profiles (Table 3). On some profiles the 1997 deposit is absent.

4.2 1923 tsunamis

Sediment runup and inundation data for "1923" indicate that this tsunami was larger than 1997 in the region of our profiles. The deposit we interpret as from 1923 is usually thicker and more extensive, and never less extensive, than the deposit from 1997 (e.g., Figs. 5,7,8,9). The "1923" deposit is present on all measured profiles whereas the 1997 deposit is missing on six (Table 3, Fig. 6). Only on profiles where the sediment limit was not found (e.g. 100), or

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where profiles dropped to low elevations at their landward extent (001, 180, 160, 140, 100, 130, 210) were "1923" deposits at similar or lower elevations than 1997, and in many of these cases (001, 180, 160, 130), inundation distances for "1923" were longer. Even in the few cases where our field locations did not distinguish 1997 from "1923" by sediment runup or inundation (e.g., Storozh 140, Fig. 9), the "1923" deposit was coarser and/or thicker than 1997.

4.3 Chile 1960 deposit

Between "1923" and 1997 deposits on a few profiles (Table 3), there is a thin, patchy and less extensive deposit which we attribute to the 1960 Chile tsunami (e.g., Fig. 4, right). We favor 1960 Chile over 1952 Kamchatka for two reasons. First, the 1960 tsunami was larger than 1952 *in the Kamchatsky Bay region* (Table 1); the more locally generated 1952 tsunami dies off in amplitude along strike of the rupture (MacInnes et al., 2010), whereas the Chilean tsunami on Kamchatka is little affected by latitude (Zayakin and Luchinina, 1987). Second, supporting the 1960 interpretation, in one excavation on profile 001, this intermediate tsunami deposit lies above the Bezymianny 1955 tephra layer (Fig. 7).

4.4 Historical tsunami deposit close below KS_{1907}

In many excavations (e.g., profile 100 in Fig. 4, Profile 110 in Fig. 8), there is a tsunami deposit within a few cm of the base of KS_{1907} and which is comparable to 1997 and 1923 in thickness and extent. Although pre-1907 sedimentation rates are difficult to determine this tsunami deposit must fall within the historical period, which extends back to 1737. However, the more complete historical records are from southern Kamchatka, and records from the second half of the 19^{th} century are particularly spotty (Gusev and Shumulina, 2004). Thus there is no known historical event we can assign to this deposit; OSL dating might help in interpreting this deposit.

5 Discussion – 1997 and "1923" Deposits

5.1 1997 tsunami

Our observations are consistent with 1997 being a seismogenic tsunami source *with significant rupture energy expended in the northern portion of the zone of aftershocks*. The extensive and relatively smooth distribution of runup (Table 3; Fig. 6) and the ratio of maximum runup to distance over which the tsunami had significant runup (on the order of 10^{-5}) indicate that this tsunami was typical of a seismogenic source rather than a landslide source (cf. Okal and Synolakis, 2004). The far-field tide-gage records (e.g., Hilo, Table 1) are also indicative of a broad rather than a point source. Given that the post-tsunami survey reported runup that did not exceed the beach on the Kronotsky Peninsula and that the deposits we mapped north of the peninsula are from the 1997 tsunami, *any source model must explain the low ("water") runup on Kronotsky Peninsula and relatively high ("sediment") runup north of this peninsula* (Fig 6). Source-region models by Bürgmann et al. (2001) and Llenos and McGuire (2007), e.g., do not include the northern aftershock area, and such models have been used to interpret Kamchatka subduction-zone behavior (e.g., Song and Simons, 2003; Bürgmann et al., 2005; Llenos and McGuire, 2007; Bassett and Watts, 2015). On the other hand, source regions by Gusev et al. (1998; also Gusev, 2004) and Levina et al. (2013) tend to include

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the entire aftershock zone, overlapping Feb 1923 in the south but also filling the gap between Feb 1923 and April 1923 (Fig. S1), which might not be consistent with the tsunami data. Slavina et al. (2007) interpret the southwestern aftershock activity (Fig. 2) to be on a separate, transverse fault, and Kuzin et al. (2007) interpret the SW portion of the (extended) aftershock region to be a separate stress zone, interpretations more consistent with tsunami data.. Zobin and Levina (2001) favor most mainshock energy being generated in the middle zone defined by fewer aftershocks (see Fig. 2), but this region is in shallower water, less conducive to tsunami genesis. A recently published finite-fault model resolves to most slip being under the Kronotsky Peninsula, with most energy release focused in the north (Hayes, 2017; https://earthquake.usgs.gov/earthquakes/eventpage/usp0008btk#finite-fault). As with Sohn's 1998 analysis, Hayes' (2017) model cannot explain the 1997 tsunami runup because the rupture is mostly under the Kronotsky Peninsula. Shifting this pattern of deformation eastward could resolve the discrepancy.

5.2 1923 tsunamis

There are reasons to favor either or both the 3 February 1923 and the 13 April 1923 Kamchatka tsunamis as the generator(s) of the deposit above KS_{1907} that we identify as "1923" (e.g., Figs. 7,8,9). Given what is known (Table 1), south-central Kamchatsky Bay is the place most likely to have *comparable* runups from each. Both tsunamis have a record in Hilo, but one is runup and the other tide-gage amplitude. There is no case on Kamchatka of a pair of similarly measured records from the same locality with which to compare the two tsunamis, with the exception of observations that the April tsunami generated more damage at the Tsutsumi fish plant southeast of Ust-Kamchatsk (Table S4). The 3 February tsunami was larger in most catalogued locations (Table S4) but apparently smaller than April 1923 in *north* Kamchatsky Bay. The two 1923 tsunamis both occurred while the ground would have been snow covered so that following snowmelt, it would be nearly impossible to distinguish two different deposits. The source regions of the two 1923 Kamchatka tsunamis have been mapped (Fig. 1) but are not easy to constrain in detail other than that the February earthquake was south of Kronotsky Peninsula and the April earthquake north of it (Fig. 1). The February earthquake has been catalogued as Mw 8.3 - 8.5 (ISC event 911271; NCEI) and the April earthquake as Mw 7.1 - 7.3 (ISC event 911331; NCEI), but the local and far-field tsunami runup for April 1923 suggests it may have been significantly larger (Gusev and Shumilina, 2004); based on its tsunami, Gusev suggests Mw 8.2 for the April earthquake. A moment magnitude around 7.8 – 8.0 for the April earthquake would be more consistent with its tide-gage amplitude in Hilo (Fig. S2).

6 Tsunami deposits pre-20th century back to KS_1 (~A.D. 300)

Goals in reconstructing paleotsunami history include both scientific and practical objectives. Scientifically, southern Kamchatsky Bay paleotsunamis can help us see patterns of subduction-zone behavior. Are the historical tsunamis (and their generating earthquakes) comparable to events in the past? What is the "typical" event and what are the rupture patterns of the northern Kamchatka subduction zone? Practically, these questions apply also to probabilistic hazard analysis – at what frequencies do tsunamis occur and what is their size-frequency relationship?

6.1 Occurrence and Size

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For the record and analysis of tsunami deposits below KS_{1907}, for each excavation we count the number of deposits between marker tephra and determine the approximate elevation above sea level and distance from shore of the excavation locale in that time (tephra) interval (Fig. S5) (see Figures 7,8,9 and their captions for more detail on our interpretations). For some layers, an excavation may be their limit and for others not (e.g., Fig. 9). We do not attempt to correlate sand layers from excavation to excavation (or profile to profile), though there are cases where it is possible; the problem with distinguishing Feb 1923 from April 1923 deposits illustrates potential for miscorrelation. The reasons that not all deposits are present in all excavations range from preservation to separation – for example, excavations near the coast will commonly contain amalgamated sand layers (e.g., Bourgeois et al., 2006). For each profile, we count the maximum number of tsunami deposits between tephra, which is our indication of how many tsunami events have occurred.

In order to summarize paleotsunami sizes, we determine sediment runup--or the highest point seaward, whichever is higher--and sediment inundation for tsunami deposits on each profile. For each tephra interval along each profile, there will be deposits at maximum distances and maximum elevations; the two measures are treated separately because tsunami deposits are not correlated (in fact, high runup is associated with shorter, steeper profiles and long inundation with low-relief profiles). For example, for the historical deposits, two points are plotted (Fig. 10) – their point of maximum inundation and their point of maximum runup, which are usually on separate profiles.

A few of the paleo-events are comparable to Chile 1960 (Fig. 10), but most are likely from locally generated tsunamis because Chile 1960 was an outsized event, and its deposit is not well represented on the profiles. The 1997 tsunami has dimensions similar to the majority of paleotsunamis as represented by sediment runup of on the order of 5-7 m (Fig. 10). The “1923” deposit, for which we do not know if related to February or April or both, is a “typical largest” event (Fig. 10). Recall that in these field sites there are few excavations at elevations of 10 m or more (Fig. S6), and that these higher elevations are on uplifted profiles, so in this situation we cannot have a record of older paleotsunamis reaching such elevations, simply as an artefact of the profile history (Fig. S5). This issue is present also for paleo- inundation on prograding profiles, but is not such a strong artefact in our dataset. Overall, the number of deposits tends to decrease away from the coast and at higher elevations (density of points on Fig. 10), although there is a lot of scatter in the data, likely due to preservation and identification differences (e.g., Fig. 9).

6.2 Recurrence

To determine tsunami recurrence according to size, we consider all tsunami deposits above KS_1 (A.D. ~300) at elevations greater than 5 m (Fig. 11). We only use excavations now at or reconstructed to be more than 5 m above sea level or landward of a beach ridge (reconstructed to be) higher than 5 m to be more confident we are analyzing tsunami deposits, not those of storms or floods, and to eliminate most non-local tsunamis. We did not use intermediate Shiveluch tephra layers between KS_{1907} and KS_1 (Table 2) because their presence is not consistent enough to break down recurrence statistics, and the time intervals are short relative to the number of events, so statistical analysis cannot be supported. The grand total of the maximum number of events (per each interval) is 18 deposits, including the historical cases. For each event, we determine a maximum sediment runup, that is, if there are four deposits between two marker tephra on a given profile, we determine the four highest points those deposits

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reach; e.g., two may reach 8.3 m and the other two only 7.2 m (all four reaching 7.2 m). We use reconstructed distances and elevations for each time interval below KS_{1907}. The maximum elevation is either sediment runup, h, or maximum elevation before sediment runup, H (as in Fig. 5), whichever is higher. Independent of the determined maximum elevation, we determine a maximum sediment inundation for each deposit in each tephra interval.

All 18 deposits represent large tsunamis, reaching minimum elevations of 5 m (smaller not considered) and inland distances of 100 m, each factor with a recurrence interval of about 100 years (Fig. 11). Note again that runup and inundation are not paired; high runup commonly occurs on shorter, steeper profiles and long inundation on lower profiles. Tsunamis reaching an elevation of at least 7 m have a recurrence of ~200 years (Fig. 11). The largest reconstructed tsunamis as recorded by tsunami deposits have runup of 10 m or more and occur on average every 425 yr. Tsunamis with inundation of 600 m or more occur on average every ~570 yr.

7 Discussion and conclusions

7.1 Historical tsunamis

This work adds to the tsunami catalogue for 1997 Kronotsky and 1960 Chile, but not February or April 1923 Kamchatka events because we cannot differentiate the (two) 1923 deposits. The nearfield nature of the 1997 Kronotsky tsunami is significantly revised by our report herein of coastal profiles north of the Kronotsky Peninsula, adding substantial data to its catalogue. The 1997 tsunami reached runup heights of more than 9 m, averaging 6 m over about 60 km of coastline. As would be expected, tsunami heights (as indicated by deposits) and inundation distances are influenced by coastal topography, with higher runups on steep profiles and longer inundation on lower-relief profiles. Data catalogues do not commonly provide topographic profiles, yet this information can be critical to understanding a tsunami and potentially its generating source.

Based on deposits from 15 profiles and more than one hundred excavations, we conclude that in southern to central Kamchatsky Bay the 1923 tsunami (February or April indeterminate) was larger than the December 1997 Kronotsky tsunami, but the summary and tabulated data (Fig. 6, Table 3) are tricky to interpret, with sediment inundation (L) being more indicative of tsunami size than runup (h) or highest point seaward of runup (H) (e.g., see Fig. 5 illustration). On the basis of the total number of profiles exhibiting a deposit, "1923" is more extensive, but its average sediment runup (h) value is lower because the farthest point it reached on a number of profiles is actually lower than the closer-to-shore points for 1997. Moreover, even though "1923" exceeded more of the high beach ridges seaward of the (sediment) runup point (H), the average of those is almost the same as for 1997 (Table 3). Thus the most telling measurements *distinguishing* 1997 from "1923" are sediment inundation distances, with the average for "1923" almost twice that for 1997.

The 1952 tsunami deposit in southern Kamchatka (and the northern Kuril Islands) (MacInnes et al., 2010) reaches greater heights and inundation distances along its earthquake rupture zone than any of the historical tsunami deposits along the northern part of the Kamchatka subduction zone (this study; also Pinegina, 2014). While this observation is not surprising given that 1952 was Mw 9.0 and the historical events to the north no larger than about Mw 8.5, the question to address is, Can (does) the northern part of the subduction zone produce Mw 9 events, or

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does Kronotsky Cape represent a locked or continuously slipping zone that keeps ruptures shorter, as in 1923? For that, we must turn to the prehistoric record.

7.2 Implications for the 1997 Kronotsky earthquake rupture and the 1923 events

The sediment runup and inundation data reported here require a reevaluation of rupture source models for the 1997 Kronotsky earthquake; we favor slip focused within the northern half of the aftershock zone shown in Figure 2 (also see Fig. S9). *Models which place most rupture energy to the south of or under the Kronotsky Peninsula (Fig. S9; e.g., Bürgmann et al., 2001; Bürgmann et al., 2005; Llenos and McGuire, 2007; Bassett and Watts, 2015; Hayes, 2017) are not consistent with the tsunami data*. The tsunami, rather than being unusually small for its generating earthquake's moment magnitude (Sohn, 1998), generated runup averaging 6 m over about 60 km of coastline, and 30 cm amplitude on the Hilo tide gage, requiring a "normal" offshore, subduction-zone rupture. Moreover, some significant portion of that rupture must be under substantial water depth to produce the indicated tsunami in the bay north of Kronotsky Cape, while not generating as much runup on the Cape, or to its south. While part of the rupture could well have been under the Kronotsky Peninsula and the relatively shallow region directly offshore, *deformation in deeper water east and north of the peninsula is needed*.

We conclude that a rupture consistent with the mainshock and aftershock locations from Kamchatka's network are more reasonable than more westerly locations, e.g., in the ISC catalogue (Fig. 2, Table S2). This issue is illustrated by the Hayes (2017) inversion, which takes the NEIC hypocentral location (Table S2) to start and, while his inversion results in most slip to the north (Fig. S9), locates that slip under the peninsula, where it cannot generate a tsunami. If this inversion were located based on the Kamchatka network's mapped mainshock, it might explain the 1997 tsunami.

The northern part of the Kamchatka subduction zone ruptured in two large tsunamigenic events in February 1923 and April 1923 (Fig. 1), and our study indicates that a substantial portion of the energy released by the 1997 Kronotsky earthquake was generated in a seismic gap between those earthquakes (and a large 24 Feb 1923 aftershock; Fig. 1), as originally recognized by Fedotov et al. (1998) and predicted by his group's earlier work. The Kronotsky Peninsula lies landward of the (subducting) Emperor Seamount chain, which has been postulated to generate a locked or slowly slipping zone on the KSZ, a zone characterized by a relatively strong positive gravity anomaly (e.g., Bürgmann et al., 2005, Llenos and McGuire, 2007; Bassett and Watts, 2015) (Fig. S9). The behavior of the subducton zone off/under Kronotsky Peninsula may well keep the northern Kamchatka subduction zone from generating 1952-scale (Mw 9) Kamchatka earthquakes, but the 1997 tsunami is evidence that this segment does rupture.

7.3 Paleotsunami results – implications for tectonic studies and hazard analyses

Southern to central Kamchatsky Bay has a relatively short but well-preserved record of paleotsunami deposits which can be calibrated with the historical record. Combined with the record in northern Kamchatsky Bay (Pinegina et al., 2012) (the north-central bay is characterized by cliffs), the pattern of runup and inundation in the prehistoric record for the last 1700 years does not diverge from the 20th century record. Compared with southern

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Kamchatka, the region where Mw 9-scale events occurred in 1952 and 1737, the northern subduction zone has generated smaller and less extensive tsunamis, in agreement with analyses of Bürgmann et al. (2005) for the modern and Pinegina (2014) for the prehistoric record.

A robust, 1700-year-long record may be sufficient to generate a probabilistic hazard analysis that can be used for both local and far-field hazard studies, and not only for tsunami recurrence statistics, but also for recurrence statistics that include tsunami size. Reconstructing paleo- runup and paleo- inundation requires, and is thus limited by, accurate reconstructions of past shoreline locations and past (relative) sea levels. Coastlines with well-established marker tephra can enable such reconstructions, as shown by this study.

As are seismologists, paleoseismologists are cautioned to qualify our generalizations by the lessons of the 11 March 2011 Tohoku earthquake and tsunami. Characterizing subduction-zone behavior and quantifying its hazards are goals which we will only ever accomplish imperfectly.

Supplement link (will be included by Copernicus) – see supplemental material

Author contribution – we contributed equally and together

Competing interests -- none

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Table 1. 20th century tsunamis affecting the Kamchatsky Bay region of Kamchatka*

Earthquake Parameters			Records of Tsunami Runup (meters) (*tide gage records in italics*) (blank where							
			Locations South to North (see Figure 1)							
Date (local)	Source region	Mw	Kron Bay	Kron. Cape	**Chazhma - Adr-Bistr R.**	3rd River ~45 km s.of U-K	1st River ~30 km s.of U-K	Tsutsumi ~20 km s.of U-K	*U-K tide gage*	Dembi Spit, U-K
5 Dec 1997	**Kronotsky Peninsula**	**7.8/7.9^**	**0.5-1**	**1.5**	**this paper**				***gage broken***	
15 Dec 1971	Commander Is.	7.8^							*0.47*	
23 Nov 1969	Bering Sea	7.7							*0.2*	
24 May 1960	**Chile**	**9.5**	**4**				**3**		***0.8***	**3-4**
5 Nov 1952	**s. Kamchatka**	**9**	**10-13**			**0.5-1**			***0.1***	
13 Apr 1923	**Kamchatsky Bay**	**7.3/8.2^**					**20#**	**>5**		**11#**
3 Feb 1923	**Kronotsky Bay**	**8.5^**	**6-8**		**~3 km up Chazhma**			**~3**		

***Bold: tsunamis most likely to leave a sedimentary record in south Kamchatsky Bay**; see Table S1 for a more complete list of tsunamis and Table S4 for specific
Primary sources: Zayakin and Luchinina, 1987; NCEI historical tsunami database

^Kamchatka Mw's from Gusev and Shumilina, 2004; G&S 8.2 for 13Apr23 is based on tsunami; see text discussion

#The 20-m and 11-m numbers are from higher-relief shorelines than the other measurements

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Date (local)	Source region
5-Dec-97	**Kronotsky Penins**
15-Dec-71	Commander Is.
23-Nov-69	Bering Sea
24.май.60	**Chile**
05.ноя.52	**s. Kamchatka**
13.апр.23	**Kamchatsky Bay**
03.фев.23	**Kronotsky Bay**

***Bold: tsunamis most likely to leave a s**
Primary sources: Zayakin and Luchinina
^Kamchatka Mw's from Gusev and Shur
#The 20-m and 11-m numbers are from hi

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Table 2. Marker tephra layers <2000 years old in shoreline profile sections, southern Kamchatsky Bay*

Code Field/Classic^	Code New*	Source volcano	Modeled age* (years B.P.)	Assigned age* (calendar years)	Field description	Field thickness
$KSht_3$^	$KSht_3$	Ksudach	Historical	A.D. 1907	Light to medium gray, fine to very fine sand	0.5-2 cm
SH_2	SH#6	Shiveluch	817 +59/-57	A.D. 1134	White (faint gray, yellow white), fs-vfs, has pumice	0.5-1 cm; distinct toward north
SH_{1450}	SH#12	Shiveluch	1356 +52/-45	A.D. 596	Pale yellow, yellow gray, lt gray, vfs-ms, salt & pepper —grainy	1-2.5 cm; typically 1-2 cm
KS_1	KS_1	Ksudach	1651 +54/-61	A.D. 298	Lt brown, beige, "coffee cream"; thin gray cap; si-vfs	1-3 cm; usually not >2 cm

*Ponomareva et al., 2017

^Braitseva et al., 1997; in our text, we supplant $KSht_3$ with KS_{1907}

Comment: I change Shubertovo village to 3ed River - that would not confuse the reader

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Table 3. Sediment runup and sediment inundation for historical tsunamis above KS_{1907}, southern - central K

Region	Profile #	Latitude	Longitude	1997			1960			
				h	L	H	h	L	H	h
Bistraya River	001	55.6226	161.7799	3.4	200	5.3	3.3	**126**	5.3	2.0
	001 via river									0
Bistraya River	002	55.59735	161.7680							4.4
	002 via river									2.2
Bistraya River	003	55.5781	161.7600							4.8
Adrianovka R.	180	55.5275	161.7484	4.8	118	5.6				3.5
Storozh River	150	55.4851	161.7414							2
Storozh River	160	55.4582	161.7394	6.6	159	7.5	**6.2**	107	7.5	6.1
Storozh River	140	55.4387	161.7393	5.8	**330**	5.8				5.8
Storozh River	170	55.3860	161.7340							3.6
Little Chazhma R.	100	55.1407	161.8281	7.4	125	7.4	4.5	107	6.2	7.4
Little Chazhma R.	130	55.1235	161.8379	4.4	109	6.3	4.4	78	5.1	1.8
Chazhma	110	55.1181	161.8408	6.6	200	8.3				8.1
Chazhma	120	55.1019	161.8514	**9.5**	200	9.5				**12**
Big Chazhma R.	220	55.0794	161.8679							7.7
Big Chazhma R.	210	55.0710	161.8760	6.0	305	8.0				6
Big Chazhma R.	200	55.0629	161.8879							6.6
	200 via river									5
			AVERAGES	*6.1*	*194*	*7.1*	*4.6*	*105*	*6.0*	*4.9*

h - elevation of excavation meters above sea level high tide (m a.s.l.); equals "sediment runup" (maxima in bold)

L - distance from the shoreline, m; equals "sediment inundation" (maxima in bold)

H - highest elevation (m a.s.l.), between shoreline and excavation; likely exceeded where there is a sand deposit (

If the tsunami reached a low inland point via the river (indeterminate), H from the profile is not relevant.

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[Bourgeois & Pinegina FIGURE CAPTIONS]

Figure 1. General tectonic setting and study locations. **Upper left**: Major topography of and bathymetric features around Kamchatka. **Lower left**: locations of sites mentioned in text and tables. **Right**: Interpreted rupture locations of 20th century tsunamigenic (except *1923.II.24*) earthquakes along the Kamchatka portion of the Kuril-Kamchatka subduction zone (modified from Gusev , 2004, Fig. S1; Martin et al., 2008). The rupture area of the 1997 earthquake shown here is from Gusev (2004) and outlines the entire aftershock zone (Fig. 2). Tide-gage locations PK = Petropavlovsk-Kamchatsky; UK = Ust-Kamchatsk; BI = Bering Island.

Figure 2. Foreshocks (3-5 Dec 1997), mainshock and aftershocks of the 5 December 1997 Kronotsky earthquake (Gusev et al., 1998), including location of nearest seismic station, MKZ. Plotted foreshocks and MKZ aftershocks include only cases where P and S arrivals could be read from MKZ records. Locations of epicenters are from various analyses, both local and farfield as reported from the International Seismological Center (Table S2). Slavina et al. (2007) interpret the southwestern aftershock activity to be on a separate, transverse fault; Kuzin et al. (2007) also interpret the SW portion of the (extended) aftershock region to be a separate stress zone.

Figure 3. Photos taken by T. Pinegina on 9 Dec 1997 near Kronotsky Cape (location on Fig. 1). For additional photo and sketch for context, see Fig. S3. **Above** (helicopter for scale): the tsunami deposited sand on the snow up to about the line of grassy vegetation at the back of the beach (see detail, lower right photo); white zone in foreground is sea foam. **Lower left:** Ice and snow broken up by the tsunami (excerpted from photo in Fig. S3). **Lower right** (compass for scale): detail of tsunami-deposited sand above snow that covered the beach, scraped by hand away from a crack in the snow/ice which is interpreted to have been made during an aftershock.

Figure 4. Left. Topographic profiles measured in southern Kamchatskiy Bay (locations on Fig. 1, arranged from south (bottom) to north (top), except 001 and 002 reversed to reveal topography. Distances and elevations are measured from 0 at the water line (lower right corner of each profile), corrected to high tide. **Right**: Chazhma Profile 100 used as a key to collected profile data and interpretations *(interpretation in italics)*; background deposits are soil or sandy soil, unless noted.

Figure 5. Terminology for sediment runup and sediment inundation, and interpretation of deposits from 1997 and 1923, using example of an actual profile (Storozh 160; vertical exaggeration ~10). Near the shoreline on this profile, both tsunamis had to exceed a point (H) higher than "sediment runup" (h) and that, although the minimum sediment runup for 1923 is not much greater than for 1997, 1923 was likely higher to generate greater inundation, which is also be related to tsunami wave length. Note that a 2-D interpretation of (orthogonal) tsunami flow over this and most study profiles is justified by the lateral continuity of ridges. In a few cases (discussed in text), the tsunami may have reached a runup/inundation point via a lower, more circuitous route. Distances and elevations are from surveying.

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Figure 6. Water runup (Zayakin and Pinegina, 1998) and sediment runup (this paper, Table 3) for the 1997 Kronotsky tsunami on and north of the Kronotsky Peninsula, southern Kamchatsky Bay (locations on Figure 1; also see Fig. S2). Water runup was not measured with instruments but was estimated; tsunami did not exceed the unvegetated beach (e.g., Fig. 3); it could have been somewhat higher than reported, shown on this figure by dashed blue line. Sediment runup is also illustrated for the tsunami deposit closely above KS_{1907}, which we interpret as from 1923 February or April (see text discussion). Sediment inundation is given in Table 3, as well as latitudes and longitudes for the 15 profiles. Figures 4 and 5 illustrate methods and terminology.

Figure 7. Northernmost profile, southern Kamchatsky Bay (Fig. 1 location; more extensive key in Fig. 4; tephra and tsunami deposits that are shown as narrower bands, e.g., 1997 in excavation 268, indicate thin, patchy deposits). This profile shows evidence of subsidence through time -- the landward part of the profile is lower. This lower profile has been subjected to river erosion -- the "mixed zone" is mostly fluvial sediment containing clasts of older material. Excavations having this mixed zone (273 to 270) all contain a tephra older than KS_1, indicating that older strata are preserved below the reworked material. In this profile 001, there is an ash layer from the 1955 eruption of Bezymianny, a year before its major eruption. With this tephra present, we can assign the tsunami deposit above (in excavation 267) to Chile 1960 rather than to Kamchatka 1952.

Figure 8. Profile 110, Chazhma area (Fig. 1 location; more extensive key in Fig. 4). This profile has been uplifted through time – the landward part of the profile is higher. Exc. 45 contains many tsunami sand layers currently at high elevation, which when reconstructed were lower (Fig. S5). In excavations 37 and 31, some of the section was too sandy (not enough soil development) to distinguish individual sand layers. The profile shows the distribution of 20th century deposits, as well as a tsunami deposit very close below KS_{1907}. The 1923 tsunami(s) reached the highest point shown on this profile, whereas 1997 and "below KS_{1907}" were smaller. The deposit we tentatively assigned to Chile 1960 on this profile is not included in Table 3 because the deposit was not well preserved; it is higher than any other excavation containing a deposit we attribute to Chile 1960.

Figure 9. Example of two profiles that illustrate paleotsunami deposits used in analyses. Also see Figs. 4, 7, 8; ; tephra and tsunami deposits that are shown as narrower bands, e.g., 1997 in excavation 268, indicate thin, patchy deposits. **Storozh Profile 140 (top).** Here we use this profile to illustrate an analysis of tsunami deposits between KS_{1907} and SH_2; note that the deposits thin landward, in general. In most excavations there are six tsunami deposits between KS_{1907} and SH_2; excavation "x" has only three. Thus all six tsunamis reached "a" but only three reached "x"; or, three of the six tsunamis only reached "a". All six tsunamis had to exceed the height of the shoreward beach ridge at the time of deposition. **Chazhma Profile 200 (bottom).** As in Profile 110 (Fig. 8) this profile has undergone uplift through time. For sub-SH_2 deposits, the profile was reconstructed to 4 m lower and 150 m narrower. Sites 229-233 are young; the profile from 228 landward is older than KS_1 (A.D. ~300). Site 223 is not far from the modern Chazhma River and in the past some tsunamis may have flooded this site via the river, when the profile was

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lower. Sites 226 and 225 both have six deposits between SH_2 and SH_{1450}; no other excavation on this profile provides a good count in this interval, but these six deposits probably are in the record at 223, and 224 was simply too sandy (lacking soil separation between layers) to count all layers in this interval. SH_2 is not preserved (was not detected) in the peat excavation (223), but the 23 tsunami deposits in this excavation can be used in the overall count above KS_1. Excavations 223, 225 and 226 all preserve tsunami deposits between SH_{1450} and KS_1. In this interval the peat excavation (223) contains six deposits to the two in 225 and 226, for two possible reasons; first, peat is a better preserver/displayer of thin layers, and second, 223 is lower than 225 and 226 and at this time all were closer to shore. For the latter reason, 223 may have received tsunamis and their deposits directly from the river rather than over the beach ridge(s).

Figure 10. Three-dimensional diagram summarizing sediment runup and inundation for tsunami deposits, south Kamchatsky Bay, above KS_1 tephra (A.D. ~300, up through A.D. 2000) (from data plotted in Figs. S7 and S8). The three historical tsunami deposits are highlighted with their two points of maximum runup (and corresponding inundation at that point) and maximum inundation (and corresponding runup at that point), which do not coincide. For prehistoric events, we calculated (sediment) runup and inundation per tephra interval, with adjustments for changes through time in shoreline location and excavation elevation (see text and Fig. S5).

Figure 11. Tsunami (>5 m) recurrence for exceeded elevations (sediment runup) and exceeded distances from shoreline (sediment inundation) based on tsunami deposits since KS_1 (A.D. ~300) in south Kamchatsky Bay. (For runup, integers of m are shown; for inundation, multiples of 100 m.) For example, tsunamis with runup of 8-9 m or more occur on average every 283 years. Tsunamis exceeding inundation of 500 m occur on average every 340 years. Recall that runup and inundation are not paired (see text).

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, remind us that without post-tsunami or tsunami-deposit surveys, remote spots in the world may experience large events without a written record

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and its aftermath could explain the layer and its distribution.

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, at least one of which was locally larger than 1997

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Date (local)	Source region	Mw		Kron Bay	Kron. Cape	**Chazhma - Adr-Bistr R.**	3ed River ~45 km s.of U-K	1st River ~30 km s.of U-K	Tsutsumi ~20 km s.of U-K	*U-K tide gage*	Den Spit, U
5-Dec-97	**Kronotsky Peninsula**	**7.8/7.9^**		**0.5-1**	**1,5**	**this paper**				***gage broken***	
15-Dec-71	Commander Is.	7.8^								*0,47*	
23-Nov-69	Bering Sea	7,7								*0,2*	
24.май.60	**Chile**	**9,5**		**4**				**3**		***0,8***	**3-**
05.ноя.52	**s. Kamchatka**	**9**		**10-13**			**0.5-1**			***0,1***	
13.апр.23	**Kamchatsky Bay**	**7.3/8.2^**						**20#**	**>5**		**11**
03.фев.23	**Kronotsky Bay**	**8.5^**		**6-8**		**~3 km up Chazhma**			**~3**		

*Bold: **tsunamis most likely to leave a sedimentary record in south Kamchatsky Bay**; see Table S1 for a more complete list of tsunamis and Table S4 for
Primary sources: Zayakin and Luchinina, 1987; NCEI historical tsunami database

^Kamchatka Mw's from Gusev and Shumilina, 2004; G&S 8.2 for 13Apr23 is based on tsunami; see text discussion

#The 20-m and 11-m numbers are from higher-relief shorelines than the other measurements