Combining constraints from tsunami modeling and sedimentology to untangle the 1969 Ozernoi and 1971 Kamchatskii tsunamis

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[1] Large tsunamigenic earthquakes occurred in 1969 (Mw 7.7) and 1971 (Mw 7.8) along the Bering Sea and northernmost Pacific coast of Kamchatka. Both resultant tsunamis were recorded on tide gauges, but only the 1969 tsunami has cataloged observations of runup, and these observations are limited and questionable. We used a combination of field mapping of tsunami deposits and tsunami modeling to augment this historical record. We mapped tsunami deposits above A.D. 1956 and 1964 volcanic ash layers, along more than 200 km of shoreline. However, the 1969 and 1971 tsunami deposits are not distinguishable in the field. The distribution of tsunami-deposit elevation has two latitudinal peaks. From 58° to 57° sediment runup typically ranges from 2 to 4 m, decreasing to the south. From 57° to 56° sediment runup typically ranges from 3 to 6 m (maximum more than 10 m), increasing to the south. Models of local runup for the 1969 and 1971 tsunamis explain most of the sediment distribution, differentiate the two tsunamis in some localities, and elucidate the earthquakes' focal mechanisms and rupture areas. **Citation:** Martin, M. E., R. Weiss, J. Bourgeois, T. K. Pinegina, H. Houston, and V. V. Titov (2008), Combining constraints from tsunami modeling and sedimentology to untangle the 1969 Ozernoi and 1971 Kamchatskii tsunamis, *Geophys. Res. Lett.*, *35*, LXXXXX, doi:10.1029/2007GL032349.

1. Introduction and Background

[2] Even though the Mw 7.7 1969 Ozernoi and the Mw 7.8 1971 Kamchatskii tsunamigenic earthquakes (Figure 1) occurred in the era of seismic instrumentation, the earthquakes and especially the associated tsunamis are poorly characterized because the region is remote and sparsely populated. Despite shortcomings in historical and instrumental records, however, Kamchatka is an excellent field location for studying tsunami deposits, leading to greater understanding of the earthquakes and their tectonic setting. Foremost, well-studied tephra deposits from prolific volcanoes along the Kamchatka arc provide excellent chronological control. Also, low rates of human, plant and animal disturbance (bioturbation) offer high levels of deposit preservation in peats, beach-ridge swales, and marine terraces. Plate boundaries in the region produce high numbers of earthquakes, and many historical tsunamis have affected Kamchatka (Figure 1, Table S1 of the auxiliary material),[1] leaving geologic traces. In spite of all these favorable conditions, it is still not possible to separate the 1969 and 1971 tsunami deposits through field observations and stratigraphic analysis because dating techniques are not that accurate, and there is not a tephra layer between them (Table S1). Previous publications have ascribed all deposits to the 1969 tsunami [*Melekestsev and Kurbatov*, 1998; *Bourgeois et al.*, 2006]. In this paper we use sedimentological data coupled with computer modeling of tsunami propagation and inundation in order to examine these two earthquake-generated tsunamis and to answer the following questions. Can we explain all of the deposits with one or the other tsunami, or are both required? Can we explain deposit extent solely by earthquake-induced tsunamis, or must we invoke tsunamigenic landslides?

1.1. Tectonic Setting

[3] The northwesternmost Pacific Ocean and southwestern Bering Sea overlie a tectonically complex region; the Mw 7.8 1971 earthquake, though it occurred only a few hundred kilometers from the Mw 7.7 1969 earthquake, was located in a distinctly different tectonic setting (Figure 1). Moreover, the plate boundaries near these two earthquakes are not well established-geoscientists have subdivided the region into several different plate configurations (six are summarized by *McElfresh et al.* [2002]). In the simplest, 3-plate (Pacific, North America, Eurasia) model, Kamchatka belongs to the North American plate. However, this three-plate model cannot explain the 1969 earthquake [*Pedoja et al.*, 2006], and the 1971 earthquake lies within a complex plate-corner setting, in any model (Figure 1).

[4] In multiplate models, the placement of Kamchatka on the Okhotsk block [*Cook et al.*, 1986; *Apel et al.*, 2006] more easily explains the location and mechanisms of the 1969 and 1971 earthquakes. Compression between the Okhotsk block and the Komandorskii Island block occurs in the region of the Kamchatskii Peninsula (Figure 1), and the inner, southern boundary of the Komandorskii Island block is the locality of the 1971 earthquake. To the north, compression occurs between a rotating Bering block [*Mackey et al.*, 1997] and the Okhotsk block, and this boundary is the site of the 1969 Ozernoi earthquake. The April 2006 Koryak (or Olyutorskii) earthquake (Figure 1)

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[1]Auxiliary material data set is available at ftp://ftp.agu.org./apend/gl/2007gl032349.

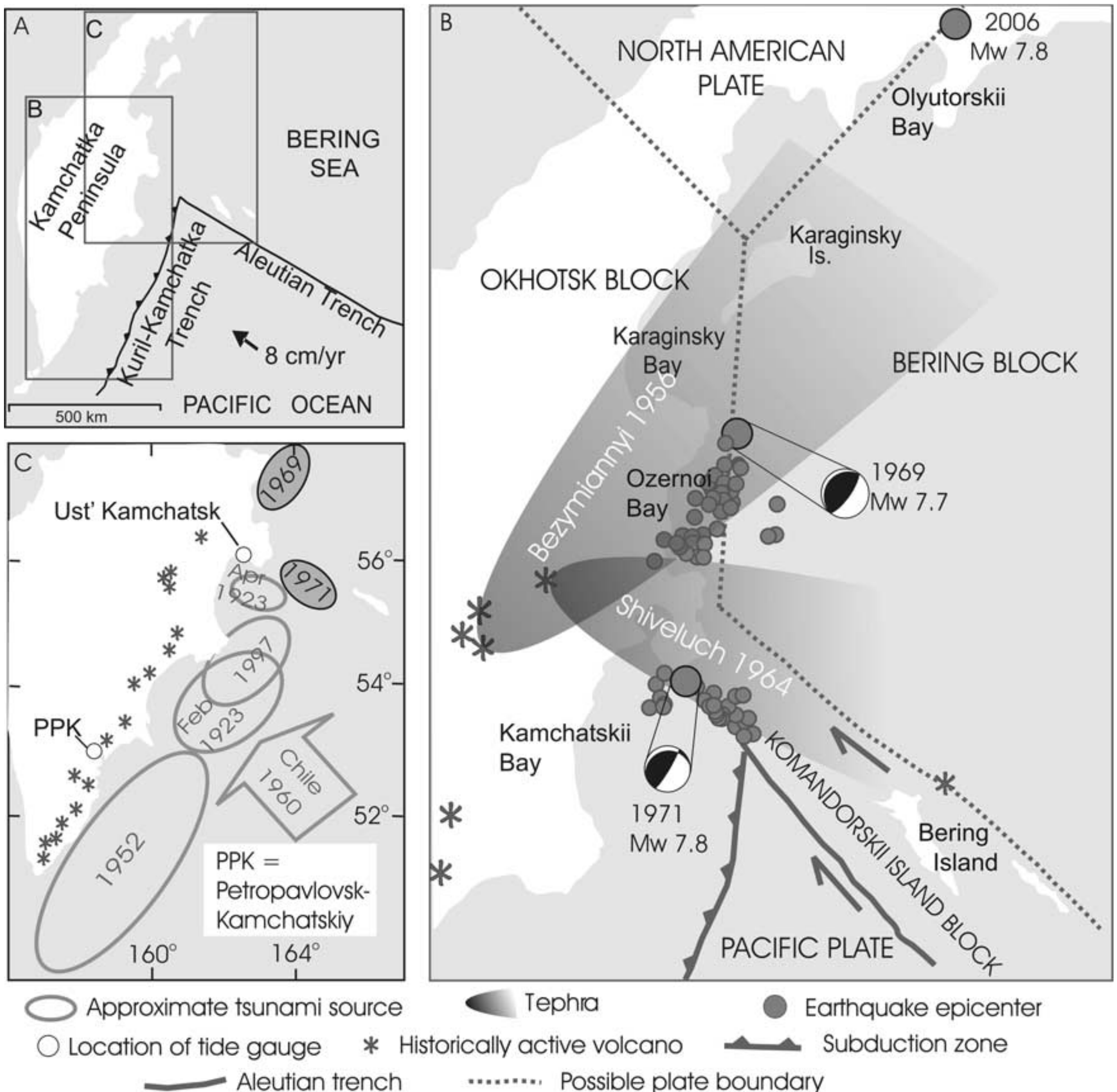

Figure 1. (a) Location of the field area and tectonic setting, with Pacific plate motion relative to North America. (b) Tephra and earthquake locations referred to in this study, including one-week aftershocks of the 1969 and 1971 earthquakes; additional proposed plate boundaries shown in dashed lines (see text for references). (c) Approximate source area of selected historical tsunamis.

also occurred on the (proposed) Bering/North America boundary [*Rogozhin et al.*, 2007].

1.2. Ozernoi Earthquake and Tsunami of 1969

[5] On 22 November 1969 at 23:09 local time, a Mw 7.7 [*Gusev and Shumilina*, 2004] thrust earthquake occurred off the Ozernoi Peninsula, Russia, in the western Bering Sea (Figure 1). Originally, *Fedotov and Gusev* [1973] concluded that the fault plane was nearly vertical and the earthquake was strike-slip. Later, *Cormier* [1975] and *Daughton* [1990] concluded the 1969 earthquake was a low-angle (5–10°) thrust. The associated tsunami, though it had little human impact due to sparse population, was described at a number of local sites, with a maximum reported runup of 10–15 m on the Ozernoi Peninsula (Table S1). Several workers have suggested that a landslide associated with the 1969 earthquake caused this reported high runup [*Zayakin*, 1981; *Melekestsev*, 1995; *Gusiakov*, 2003]. The tsunami was also recorded on local tide gauges in Ust' Kamchatsk and Petropavlovsk-Kamchatskii, as well as far-field sites including Hilo (Table S1).

[6] Deposits from the 1969 tsunami were reported by *Melekestsev and Kurbatov* [1998] from Karaginsky Island (Figure 1c), along with evidence that the tsunami had changed the course of a stream, an oxbow cutoff. *Bourgeois et al.* [2006] described tsunami deposits attributed to 1969 in southern Ozernoi Bay. Based on tsunami deposit distribution, Titov in a preliminary model of the tsunami used a low-angle thrust with 3.5 m horizontal shortening during the 1969 earthquake [*Bourgeois et al.*, 2004].

1.3. Kamchatskii Earthquake and Tsunami of 1971

[7] On 15 December 1971 at 20:30 local time a Mw 7.8 [*Gusev and Shumilina*, 2004] oblique-thrust earthquake occurred off the Kamchatskii Peninsula near the line of demarcation between the Bering Sea and Pacific Ocean

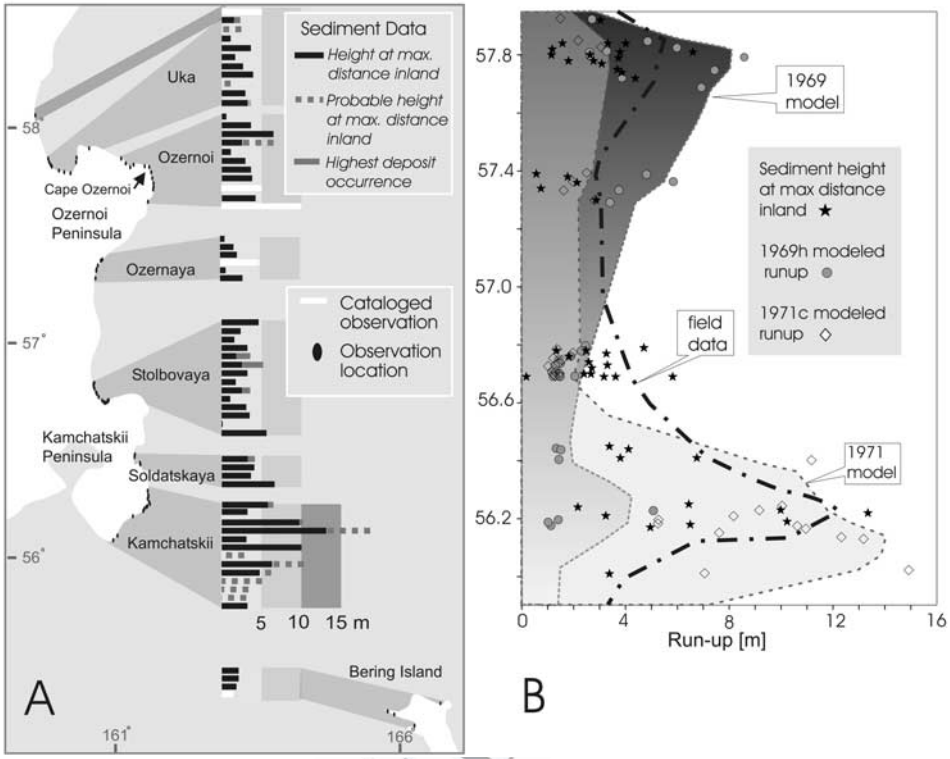

Figure 2. (a) Elevation distribution of tsunami deposits discussed in the text [*Zayakin and Luchinina*, 1987] (see also Figures S1, S2, and S3). "Height at maximum distance inland" is what is usually termed runup, and modeling gives a comparable value, at the limit of inundation. Maximum height of the deposit, where that number is greater than runup, is also given. (b) Comparison of field sediment heights to runup modeled for the 1969 and 1971 tsunamis, plotted by latitude. Dot-dash line shows envelope of field sediment runup, excepting outliers. Shaded areas, shown for visual ease, are very simplified because runup models were run only where we had topographic profiles; see Figure 3 for the overall pattern of tsunami amplitude. Modeled runup should exceed sediment runup (field data) to satisfy conditions for a fit. The 1969 model exceeds field data in the north, the 1971 model exceeds field data in the south, and neither exceeds the data in the middle.

(Figure 1). *Gusev* [1975] documented observations of the 1971 earthquake and tsunami including building destruction in Ust' Kamchatsk and on the Kamchatskii Peninsula, tide-gauge records of the tsunami, and reports of ice cracking 1 km up the Kamchatka River from Ust' Kamchatsk, probably from the tsunami. *Cormier* [1975] and *Okal and Talandier* [1986] resolved thrust mechanisms for the earthquake.

[8] There are no recorded eyewitness accounts of the tsunami or prior publication about tsunami deposits from the 1971 tsunami. Tide-gauge records from Ust' Kamchatsk and Hilo (Table S1) indicate that in these locations 1971 tsunami amplitude was about twice that of the 1969 tsunami, as expected, given size of the earthquake and location of the tsunami source area.

2. Tsunami Deposits

2.1. Field Methods

[9] Field work was carried out in the summers of 1999, 2000, and 2002–2004 in seven locations along the Bering Sea coast of Kamchatka from north of the Uka River to the Kamchatskii Peninsula and Bering Island (Figure 2). The coastline in this region varies from long series of low beach ridges (e.g., Uka) to steeply sloping coasts and narrow beach plains (e.g., Kamchatskii Cape) (Figures S1, S2, and S3). Field methods were as in *Bourgeois et al.* [2006], including topographic profiling with a transit and rod, and multiple trench-like excavations along profiles (see S6). All profiles were measured beyond the extent of the deposit. To provide consistency among profiles, we normalized the height and distance inland of the deposits with respect to the high tide mark because we assume that this datum does not change considerably along the explored sections of coastline. The 1969 tsunami occurred near high tide, but the 1971 tsunami occurred near low tide; tide range in the region is ~1.5 ± 0.5 m.

2.2. Field Results

[10] In all seven field locations, in 59 of 77 profiles (Figures S1–S3), we found a tsunami deposit [or possible tsunami deposit] above either the 1956 or 1964 tephra (Figure 1c). In 57 cases, the last excavation clearly did not contain the deposit. This deposit, comprising sand and fine gravel transported from the beach, is typically a few centimeters thick, ranging up to 20 cm. We call the elevation of the deposit at its maximum horizontal extent inland "sediment runup." (Maximum extent inland is defined as *inundation*.) The distribution of tsunami-deposit elevation has two latitudinal peaks (Figure 2). From 58° to

Table 1. Parameters Used for Initial Deformation for MOST Model Runs[a]

Run	Longitude, °E	Latitude, °N	Length, km	Width, km	Dip, °	Rake, °	Strike, °	Slip, m	Depth, km
1969d	163.1	57.4	100	50	14	90	210	3.5	5
1969e	163.1	57.6	100	50	14	90	210	3.5	5
1969f	163.1	57.4	71	71	14	90	210	3.5	5
1969g	163.1	57.4	100	50	14	90	210	4.5	5
1969h	**163.1**	**57.3**	**100**	**50**	**14**	**90**	**210**	**3.5**	**5**
1971c	**164**	**55.8**	**100**	**50**	**12**	**53**	**258**	**8**	**5**
1971d	164	55.8	71	71	12	53	258	8	5
1971e	163.9	55.8	100	50	12	53	258	8	5
1971f	164	55.9	100	50	12	53	258	8	5
1971g	163.26	56	100	50	11	55	330	8	5

[a]Original sources for model parameters: 1969d, *Daughton* [1990], *Cormier* [1975]; 1971c, *Okal and Talandier* [1986]; 1971g, *Cormier* [1975]. Preferred runs in bold.

57° sediment runup typically ranges from 2 to 4 m, decreasing to the south. From 57° to 56° sediment runup typically ranges from 3 to 6 m (maximum more than 10 m), increasing to the south.

[11] On the Ozernoi Peninsula, we measured maximum sediment runup of about 4 m above high tide, significantly lower than reported catalog runup observations of 10–15 m south of Cape Ozernoi [*Zayakin*, 1981]. This and other discrepancies could be due in part to sediment extent being less than actual tsunami wave runup/inundation. However, we think maximum deposit elevations on the Ozernoi Peninsula, as well as modeling described below, cast doubt on the 10–15-m cataloged runup.

[12] In general, sediment extent is greatest on Ozernoi and Kamchatskii peninsulas, which are also the areas with some of the steepest profiles (Figures S1–S3). In areas such as Ozernaya and Uka (Figure 2), profile elevations rarely exceed 5 m above high tide (Data Set S1), so though the tsunami may have been higher than 5 m, there will be no sedimentological evidence left behind. On these low profiles, however, the deposit can extend farther inland.

3. Tsunami Modeling

3.1. Methods

[13] Tsunami modeling is done in two stages. The first stage is the computation of initial deformation of the ocean surface due to the earthquake, which is used as initial conditions for a tsunami propagation model. The second stage is computation of tsunami wave evolution including runup. For each earthquake, after preliminary runs, we tested five initial conditions based on the given parameter range from seismologic analysis (Table 1). We used the MOST (Method of Splitting Tsunami, *Titov and Synolakis* [1995, 1998]) model to generate runup. Our goal was to vary initial conditions to find the best match of modeled tsunami runup with the minimum runup indicated by tsunami deposits.

[14] To determine the source mechanisms that best explain our field sedimentological observations we started with published focal mechanisms [*Cormier*, 1975; *Okal and Talandier*, 1986; *Daughton*, 1990] (Figure 1; Table 1). We held the seismic moment constant for each earthquake and used the same shear modulus [30 GP] in all cases. Because the published focal mechanisms do not completely agree, and because each focal mechanism represents two possible fault planes, we started with four possible fault-plane solutions for each earthquake (each had two published focal mechanisms). We ran preliminary models were run for all four configurations, but favored the low-angle solution for both 1969 and 1971 based on published data, local structures, and tectonic setting. Then, using mapped aftershocks of each earthquake, we varied rupture location, slip, length and width. We then used equations derived by *Okada* [1985] to compute surface deformation-the initial tsunami condition.

[15] To model tsunami wave evolution including runup, we used the MOST code with three telescoping grids. In the first two grids (resolutions 90 and 27 arcsec) the shallow-water wave equations (SWE) are numerically solved with reflective boundaries for land, and radiating boundaries for water to account for propagation. The third grid has a resolution of 3 arcsec, and in this case the SWE are solved with radiating boundaries for water, and a moving boundary for land to account for inundation. Finally, in order to constrain model parameters, for each simulated tsunami we made comparisons of time series of the model output to tide-gauge records from Ust' Kamchatsk (Figure S4). Given uncertainties in bathymetry, tide-gauge location, and quality of tide-gauge records, these comparisons are difficult; but remain an important means to gain confidence in the tsunami sources we used.

3.2. Modeling Results

[16] Modeling of the two tsunamis indicates that most of the identified deposits can be explained by the 1969 and 1971 earthquakes (Figure 2). Inundation computations using MOST showed that both earthquakes generated significant tsunamis in the region of field investigations (Figures 2 and 3), and both tsunamis are needed to explain the field data. Model runup of the 1969 tsunami is highest on the Ozernoi Peninsula and also north of the Stolbovaya field area (Figures 2 and 3); the latter is a region where we have no field data because the coastline is dominated by cliffs. Model runup of the 1971 tsunami is highest on the Kamchatskii Peninsula (Figures 2 and 3).

[17] In general, deposits from field areas to the north—Uka, Ozernoi, and Ozernaya—are in good agreement with the preferred model of the 1969 tsunami, and deposits to the south—Soldatskaya and Kamchatskii—are in good agreement with the 1971 model (Figure 2). The source of the deposits in Stolbovaya is ambiguous (Figure 2). Catalog data of runup for 1969 (Table S1; Figure 2) are slightly

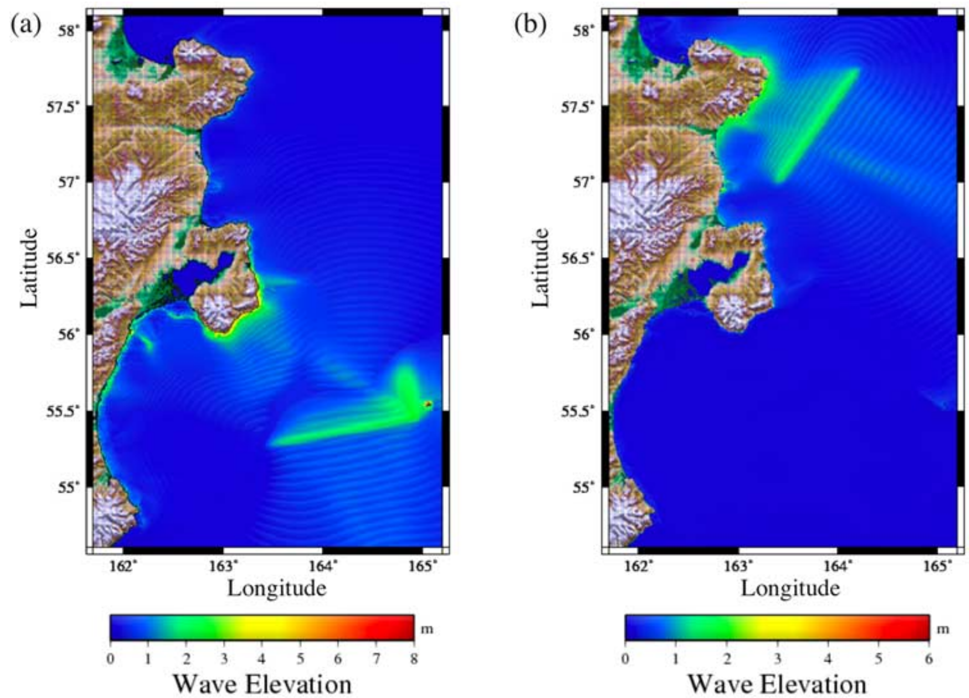

Figure 3. Maximum plot of wave elevation from preferred model runs. (a) 1969h and (b) 1971c (parameters given in Table 1).

higher than computed runup values in most localities, and much higher just south of Cape Ozernoi. The field data agree better with model results than with catalog data, so we are inclined to interpret the catalog data as exaggerated.

4. Discussion and Conclusions

[18] We conclude that modeled initial conditions can explain most of the tsunami-deposit distribution (Figures 2 and 3) without invoking submarine landslides. However, lack of available high-resolution topographic and bathymetric data did not allow us to compare model results with sedimentological data on a profile-by-profile scale. Also, because modeling with MOST is limited to water dynamics and does not involve sediment transport directly, model results must be achieved that show runup values higher than sediment data. In comparison, reported observations of tsunami runup from the catalog would be expected to be similar to modeled heights, though eyewitnesses commonly overestimate tsunami runup. If a landslide augmented tsunami runup, sediment and catalog heights would be expected to be higher than modeled heights, possibly only in one field area.

[19] Only one site—Stolbovaya (56.6–56.8° N)—shows significant discrepancies between the model and sediment data (Figure 2). These discrepancies may be explained by limitations in the model, particularly of bathymetric resolution, or by a local submarine landslide from the nearby submarine canyon, or both. Local submarine landslides, which commonly are earthquake-triggered, are possible throughout region due to steep bathymetric gradients and to river-supplied sediments. However, given uncertainties in determining initial conditions from seismologic analyses, and limitations in available bathymetric data, there is no clear need to invoke submarine landslides. Further, and in any case, a local submarine landslide off northern Kamchatka would generate highly dispersive waves) [e.g., *Lynett and Liu*, 2003] which would not produce a recognizable signature on far-field tide gages such as Hilo, 5000 km away (Table S1).

[20] Tsunami modeling indicates that, although there are no catalog data for 1971 tsunami runup, sand deposits on the Kamchatskii Peninsula were most likely deposited by the 1971 tsunami, rather than the 1969 tsunami. Thus this study extends our knowledge of the largely ignored 1971 tsunami, for which there are few cataloged or recorded observations. In a region of complex tectonics, the 1971 earthquake shows the potential for large oblique-thrust earthquakes in an area close to, but not on, a major active plate boundary and may be an indicator of more diffuse stresses in the Kamchatskii Peninsula region.

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