Pinegina et al. A nexus of plate interaction: Vertical deformation of Holocene wave-built terraces on the Kamchatsky Peninsula (Kamchatka)

Data Repository 2013301

Discussion of differences with Pflanz et al. (2012)

Of relevance to our work, in the same region (western Kamchatsky Peninsula), Pflanz et al. (2012) report eight dates of (quartz from) sand from excavations or outcrops, five of which in their results are Holocene (1.8 to 7.8 ka), and three of which they report as late Pleistocene (12.1 to 34.2 ka) (their Table 3, Blocks A and B). In addition, they reject some dates based on interpretation (not on method), as discussed below. The method they use for dating is optically stimulated luminescence (OSL), which dates the last time a grain was exposed to the sun, that is, the time of burial.

The major difference in the method and analysis of Pflanz et al. (2012; e.g., their Figure 7) compared to ours is that they use the maximum age of sand (dated by OSL) within any terrace excavation to assign a terrace age, whereas we use the oldest tephra preserved within any given terrace to assign *the age when the terrace was removed from the zone of reworking*, an elevation we can relate directly to surveyed modern profiles. Pflanz et al. state, "Some studies (e.g., Pinegina et al., 2010) date marine terraces on the Kamchatka Cape Peninsula [=Kamchatsky Peninsula] by analysis of volcanic ashes. The age of the ashes is reflecting a minimum age of the terrace but it does not date the construction of the terrace itself." That is, in fact, all that Pflanz et al. say about Pinegina et al. (also citing it incorrectly). Moreover, the three late Pleistocene dates they report are inconsistent with data from our excavations at the same localities (based on maps and reported elevations). Pflanz et al. (2012) also report analysis of older Pleistocene terraces but do not compare their analyses to Pedoja et al. (2006) (which they do not cite), where our group also reported terrace ages and rates of uplift, in particular of Pleistocene terraces.

While we agree there may be older sand deep in sub-MIS 5e terrace excavations on the outer Kamchatsky Peninsula, an OSL date on that sand cannot be used to quantify uplift because sand *without vegetation and soil development* can be deposited at a range of elevations above and below sea level. It is for this very reason that we use the oldest preserved tephra in an excavation, which we correlate with first vegetation, in order to quantify uplift, as discussed in our methods. We do acknowledge that because there are time gaps between ash falls, that our method has some age error, as we discuss and roughly quantify.

It is difficult to compare in more specificity our analyses of Holocene terraces and uplift rates with those of Pflanz et al. (2012) because their profiling and sampling methods are unclear. For example, they state that samples were taken on "well-preserved profiles on the shoreline angle," but the Holocene profiles do not have shoreline angles in a classical sense, and the location of their excavations as shown on Figure 7, for example (Figure DR1), are at the front edge of individual platforms. Moreover, the indication on their Figure 7 is that they took samples close to the crests of beach/dune ridges. We typically avoid excavating on beach ridges because they are more strongly influenced by storm and eolian activity, and the sections are typically over-thickened.

As best we can tell, the Cape Africa Holocene profile illustrated in Pflanz et al. (2012) Figure 7 (unnumbered their case) is near the same location as our Profile 9 (Figure DR1). The photo in their Figure 7 is looking north from Cape Africa, toward our profiles 9 and 8 (Fig. DR2) (northward from the Cape), with our most proximal profile south of 9. On the south side of Cape Africa, is our profile 14. An attempted detailed comparison of our profile 9 with their profile in Figure 7 (Fig. DR1) indicates that their profile is schematic and does not accurately show the step-wise and morphologically similar nature of most of those steps. That is, the reversals in topographic dip as shown in their drawing are almost non-existent.

On this Cape Africa Holocene profile (their Figure 7), Pflanz et al. (2012) reject OSL dates from two of the three sampled terrace steps (a and c, Figure DR1) as too young and interpret the sand as eolian; however, these dates are consistent with our analysis based on tephra. Moreoever, there is no geomorphic evidence of eolian bedforms on these steps, and the stratigraphy in excavations is not indicative of eolian transport – eolian sands being very well sorted fine sand, typically in more wedge-like sand bodies. Moreover, their rejection of these dates requires a post-hoc interpretation to explain an age reversal between b and c.

On the middle terrace (b), they accept the OSL dates and assign an age of 5.5 ± 1.1 ka to this terrace step, an age inconsistent with our analysis based on tephra. Moreover, in the same excavation, they report an age of 2.6 ± 0.5 ka, just 68 cm higher in the section than the date of 5.5 ± 1.1 ka. However, unless all these materials are reworked, there should be at least several marker tephra between these two levels (old to young, SH_{dv}, SH_{3800}, SH_{sp}, tephra that are present in excavations farther landward on profile 9 and elsewhere on the peninsula (Bourgeois et al., 2006). If indeed the sand at the base of the excavation is about 5500 years old (in contrast with younger ages rejected for their higher terrace c), the date could possibly represent the foundational age of the mid-Holocene sea-level highstand. It is also possible that the sand was excavated from an older layer and redeposited quickly (as a tsunami might do), without resetting the clock. In any case, the OSL date cannot provide an accurate uplift rate on a century to millennial time scale, and "choosing" the older date, as Pflanz et al. (2012, their Figure 7) do, yields an unreasonably slow rate of uplift compared to a very consistent set of rates in our data from the Holocene of Cape Africa. It is difficult, also, to explain two dates in the same excavation separated by 3000 years but only 68 cm of clean sand. The OSL results also do not explain why this 68 cm of sand contains no marker tephra (their Table 3) and we would suggest, instead, that if these dates hold, they represent erosion and rapid burial of older sand.

A similar problem of date divergence is present in Pflanz et al.'s samples from their "Block A," a locality that appears to be (their Figures 4 and 11) just north of our profile 3/4. These two samples (K08-LU11 and K08-LU12) are separated by less than a meter of sand but yield widely separated dates of 12.1 and 26.7 ka, in turn yielding uplift rates of 3.4 and/or 7.5 mm/yr (their Table 3). The higher rate is out of range of rates we have calculated for Holocene and particularly for Pleistocene terraces (our Figure 6). Yet we see no method for deciding which rate to choose in such cases.

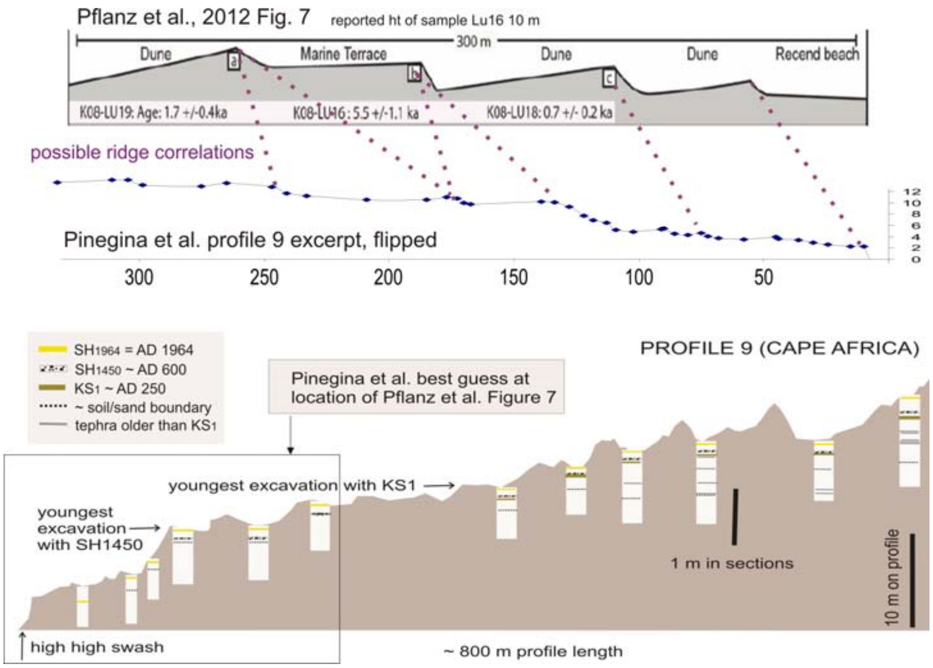

Figure DR1. Comparison of Pflanz et al. Cape Africa profile with our study's Profile 9. See more details of Profile 9 in Figure DR2.

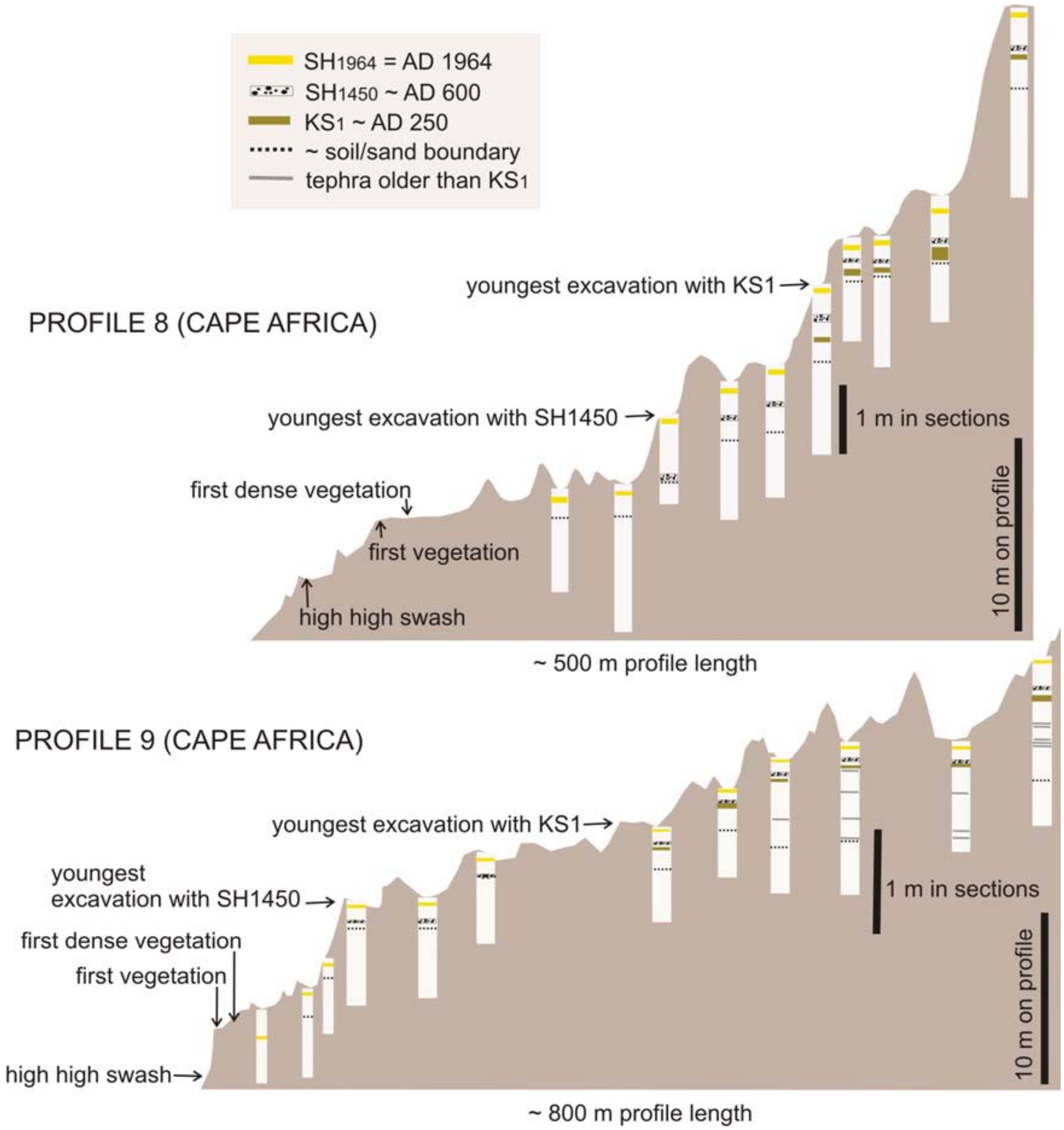

Figure DR2. Schematic illustration of profiles 8 and 9 from northern Cape Africa (see Fig. 2 and 6 in main text), showing rates of high uplift and in the case of profile 9, preservation of older, undated Holocene terraces (unspecified tephra younger than 5 ka). The upper terrace on Profile 9 is buried in colluvium, so there may be older tephra deeper in the excavation. Note that the sections are shown at finer scale than the profile; otherwise, details would not be visible. The profiles themselves are plotted at slightly different scales because 9 is almost twice as wide as 8. Profile 8 was measured near low tide, Profile 9 near high tide; our datum for calculating uplift is “first dense vegetation”.

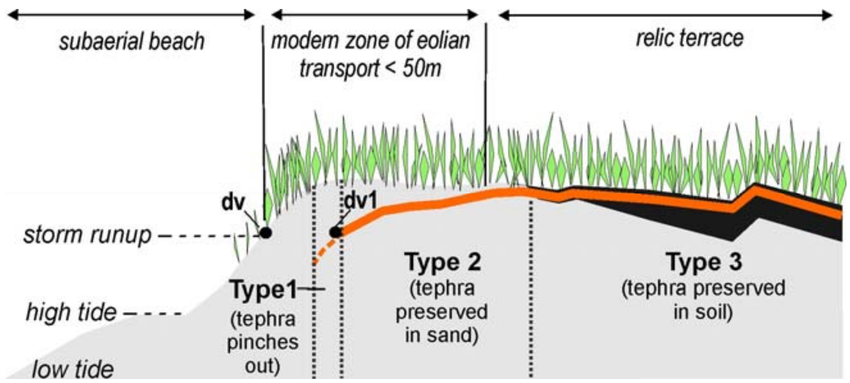

Fig. DR3. Schematic geological section across a marine aggradational terrace (in the first months to several years after a tephra fall); ***dv*** – modern point of the dense vegetation; ***dv1*** – dense vegetation point by the time of tephra fall.

Methods supplement – error analysis of terrace age and thus uplift rate – to accompany Table DR2 (see below)

In analyzing the error in calculating terrace uplift rates (Table DR2)**,** we have subdivided the analysis into three types of error, depending on the seaward-most position of a tephra (Fig. DR2): 1) *dv* point (tephra pinchout) located, 2) tephra preserved in sand, 3) tephra preserved in soil. In all cases, R = uplift (or subsidence) rate, and A = difference in elevation between final (seaward) tephra occurrence and the modern *dv* point.

Type 1. In the one profile where we found the actual paleo *dv* points (tephra pinchouts) (Table DR2, profile New(a)), we calculated the average rate of vertical movement by dividing the difference in elevation of the two *dv* points (=A) by the time interval between the two tephra (or by the age of tephra, if the upper time boundary was the present (we use AD 2000). Since tephra were dated using 14C, the age and therefore estimated average rates have a 14C-dating error. This error was estimated based on error analysis of multiple dates for SH_{1450} (1400 ±50 yr) and KS_1 (1750 ±90 yr).

R(mm/yr)=A(mm)/ (1750 ±90 yr) for interval between 2000 AD and KS_1

R(mm/yr)=A(mm)/ (1400 ±50 yr) for interval between 2000 AD and SH_{1450}

R(mm/yr)=A(mm)/((1750 ±90 yr)-(1400 ±50 yr)) for interval between KS_1 and SH_{1450}

Type 2. In most cases the exact *dv* point was not exposed by our excavations, but the last seaward occurrence of a tephra was in sand (Fig. DR2, Type 2). For these cases we interpreted the position of this excavation to have been in the ***zone of eolian transport*** when the tephra was deposited. The age of a terrace in this zone would be somewhat older than the age of tephra. According to our estimation the ***zone of eolian transport*** on Kamchatsky Peninsula coasts typically has been forming for less than about 50 years, that is, in the case of prograding coasts, it takes about 50 years for the zone to develop into a “relic terrace.” This estimate is based on species composition of plant communities in the modern ***zone of eolian transport***, field descriptions of paleo ***zones of eolian transport*** (in excavations) and the distance between modern *dv* points and 1964 *dv* points known from SH_{1964}). Therefore, a tephra preserved in a paleo ***zone of eolian transport*** can be up to 50 years older than the age of the *dv* point associated with that surface. Thus the terrace within the limits of paleo ***zone of eolian transport*** is not younger than the tephra, but not older than the tephra age plus ~50 years. In these, the most common cases, our resulting error consists of two parts: error of the surface age estimation and 14C-dating error:

R(mm/yr)=A(mm)/ (1775 ± 115 yr) for interval between 2000 AD and KS_1
R(mm/yr)=A(mm)/ (1425 ±75 yr) for interval between 2000 AD and SH_{1450}
R(mm/yr)=A(mm)/ ((1775 ± 115 yr)- (1425 ± 75 yr)) for interval between KS_1 and SH_{1450}

Type 3. On profile 23, our excavations did not expose the paleo ***zone of eolian transport*** because after the KS_1 and SH_{1450} tephra falls the terrace was significantly eroded. In this case we used the seaward-most excavation with tephra in soil (Fig. DR2, Type 3). To estimate the age of surface, we used the average soil accumulation rate on relic terraces, calculated using depths of tephra KS_1 and SH_{1450} in many excavations on the Kamchatsky Peninsula. This rate is 0.012 ±0.006 cm/yr. In the type 3 case our resulting error consists of two parts: error of soil accumulation rate estimation and ^{14}C-dating error.
R(mm/yr)=A(mm)/ (((1750 ±90 yr) + 50 yr) + (extra age ± extra age error)).

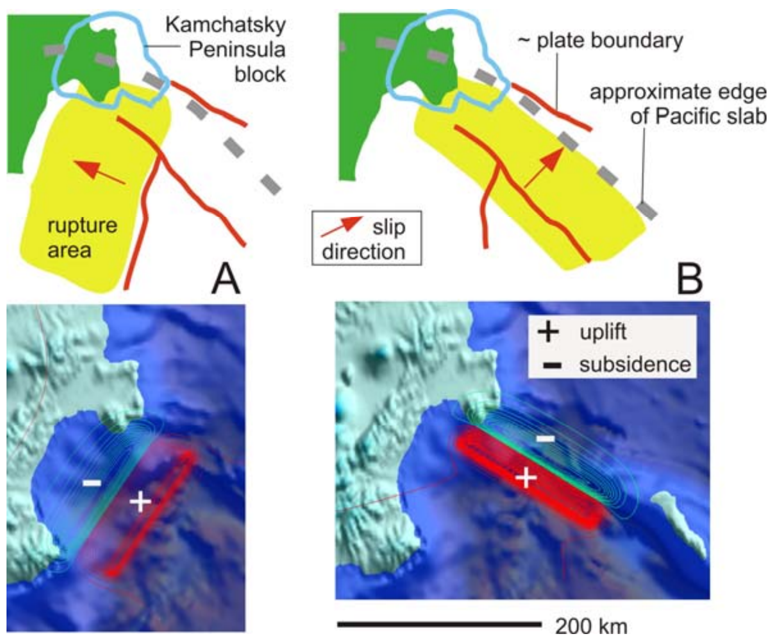

Figure DR4. Simple and generalized cartoon to show two possible (but not necessarily probable) scenarios that would generate co-seismic subsidence in the SW Kamchatsky Peninsular block. A – subduction-type scenario, B – Sumatra-type scenario; below A & B the modeled coseismic displacement from the hypothetical ruptures are shown. The vertical deformations were calculated from Okada's surface deformation formulas (Okada, 1985). The hypothetical parameters for A: length 100 km, width 50 km, depth 5 km, dip 12^{o}, slip 8 m, strike 233^{o}; The hypothetical parameters for B: length 160 km, width 30 km, depth 5 km, dip 20^{o}, slip 15 m, strike 303^{o}.

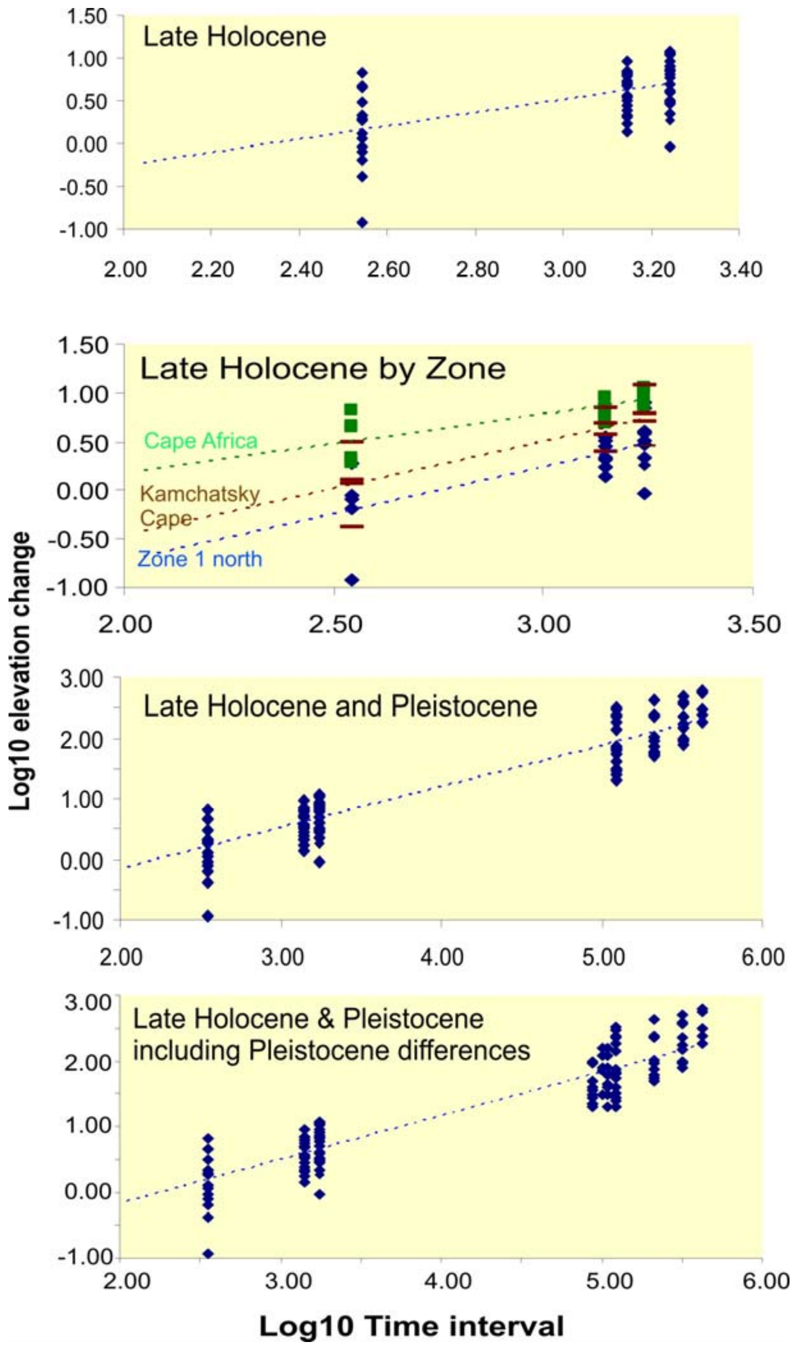

Figure DR5. Log-log plots of elevation change (in meters) between sea level and terraces or between two terraces plotted against time interval (in years) of the change (as in Gardner et al., 1987). **Late Holocene**—all data as in Table 2 in main text. **Late Holocene by zone**—data plotted by zones shown in Figure 7 in main text. The zone between Cape Africa and Kamchatsky Cape has only one point so is not plotted. **Late Holocene and Pleistocene**—all data from Table 2 for Holocene plus data from Pedoja et al. (in press) for the Pleistocene, for the latter only showing elevation difference with modern sea level. **Late Holocene & Pleistocene including Pleistocene differences**: same as above, plus differences in elevation and time between individual pairs of terraces (such as MIS 5e and MIS 7).

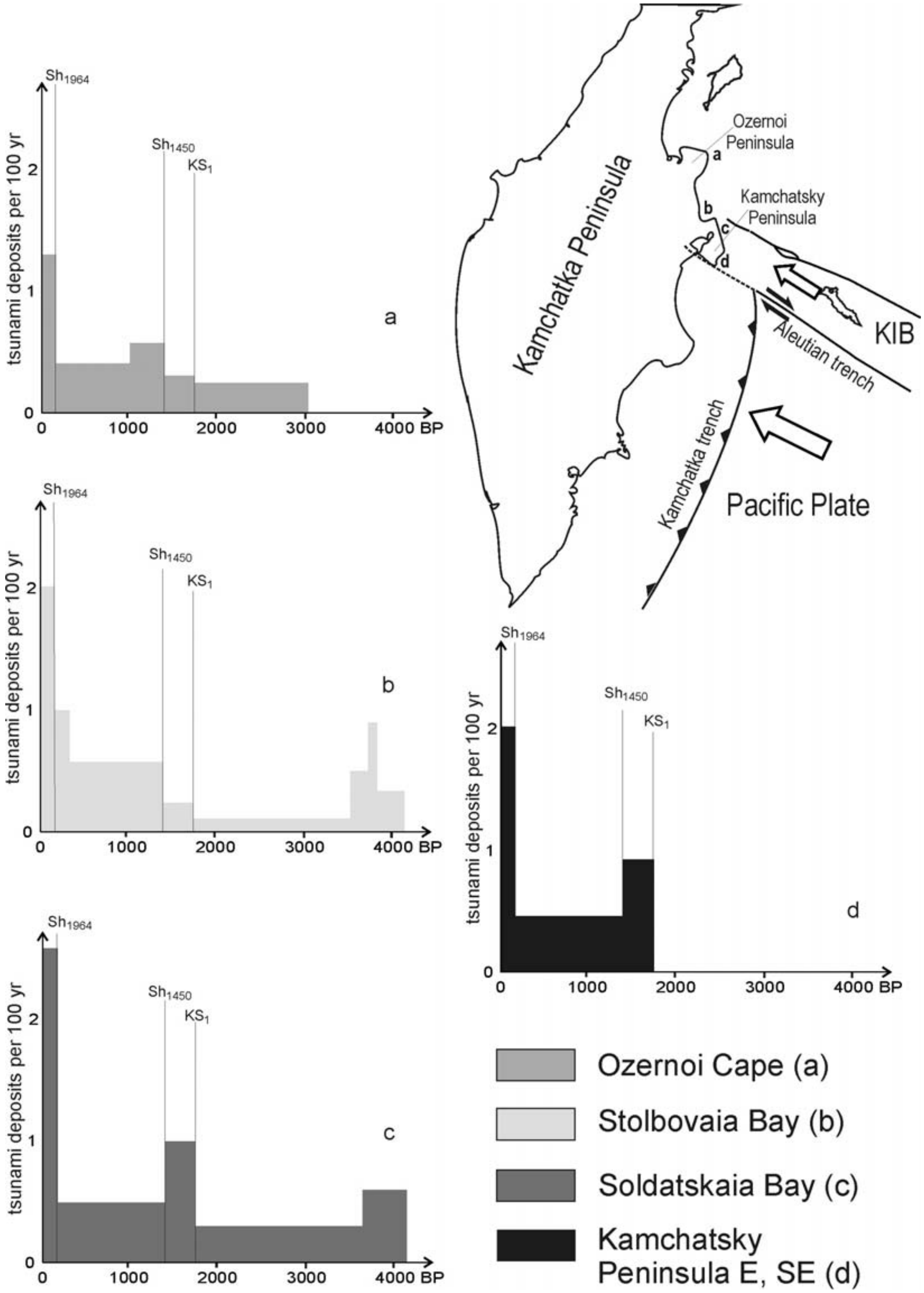

Fig. DR 6. Frequency of tsunami deposits between selected marker tephra, for four localities north of the Aleutian trench. Whereas the two northern sites (a,b) show fewer tsunamis between KS1 and SH1450, the Kamchatsky Cape localities (c.d) show higher tsunami frequency during that time. The two sites with records that extend back to about 4000 years show a relative lull in tsunami frequency between KS1 and about 3500 BP, with increased frequency in the time period before that.

TABLE DR1. NEW RADIOCARBON AGE BELOW KS_1 FROM SOLDATSKAYA BAY, KAMCHATSKY PENINSULA

Lab # (Beta Analytic)	190893
Field designation	KSU SOLD-03
Measured ^{14}C age	1890 ±40
Conventional ^{14}C age	1850 ±40
$^{13}C/^{12}C$ ratio (ppm)	-27.2
Calibrated calendar age, 1 σ	[cal AD 125: cal AD 226] 0.984981
Calibrated calendar age, 2 σ	[cal AD 71: cal AD 249] 1.0
Sample description	woody stems from dwarf shrub in growth position, buried by KS_1 ash

Notes: Calibration data set: intcal09.14c (CALIB 611; ref. Reimer et al. 2009)

TABLE DR2. UPLIFT (AND SUBSIDENCE) RATES CALCULATED FROM HOLOCENE COASTAL TERRACES, WITH TYPES OF ERROR CALCULATIONS (see text)

Profile (N to S)	Profile Latitude*	Profile Longitude*	1750 BP - 0 BP vertical offset rate	net error	**error calc.**	1400 BP - 0 BP vertical offset rate	net error	**error calc.**	1400 BP - 1750 BP vertical offset rate	net error	**error calc.**
	degrees N	degrees E	mm/a	± mm/a	**type**	mm/a	± mm/a	**type**	mm/a	± mm/a	**type**
New (a)	56.45338	163.24941	1.04	0.05	**1**	1.22	0.04	**1**	0.34	0.13	**1**
Northern (b)	56.45177	163.24921	2.21	0.14	**2**	2.30	0.12	**2**	1.86	1.01	**2**
Southern (c)	56.44438	163.24833	1.70	0.11	**2**	1.48	0.08	**2**	2.6	1.41	**2**
Camp (d)	56.43522	163.25758	1.25	0.08	**2**	0.99	0.05	**2**	2.29	1.24	**2**
Black Rock N (e)	56.41825	163.28912	0.53	0.03	**2**	-	-		-	-	
Black Rock S (f)	56.41127	163.29349	2.32	0.15	**2**	1.52	0.08	**2**	5.54	3.01	**2**
Cape Reef (h)	56.32710	163.35305	-	-		2.02	0.11		-	-	
3/4	56.25153	163.33766	~4.6†	-		-	-		-	-	
2	56.24913	163.33786	~4.0†	-		-	-		-	-	
1	56.24860	163.33796	-	-		2.5†	0.3	**2**	-	-	
5	56.23052	163.34330	1.83	0.12	**2**	-	-		-	-	
6	56.22231	163.34555	6.38	0.41	**2**	6.45	0.34	**2**	6.09	3.30	**2**
7	56.21445	163.34630	6.15	0.40	**2**	4.52	0.24	**2**	12.78	6.94	**2**
181	56.20509	163.34962	5.12	0.33	**2**	4.89	0.26	**2**	6.06	3.29	**2**
8	56.19693	163.35201	6.49	0.42	**2**	3.41	0.18	**2**	19.03	10.33	**2**
9	56.18995	163.35911	6.55	0.42	**2**	4.91	0.26	**2**	13.23	7.18	**2**
14	56.18071	163.34413	-	-		4.44	0.23	**2**	-	-	
13	56.17326	163.32295	-	-		3.62	0.19	**2**	-	-	
11	56.16215	163.29628	4.20	0.27	**2**	3.91	0.21	**2**	5.37	2.92	**2**
10	56.15418	163.28801	4.53	0.29	**2**	-	-		-	-	
16	56.13075	163.17356	-1.04	0.07	**2**	-	-		-	-	
18	56.09948	163.12281	~1.8†	-		-	-		-	-	
19	56.09386	163.11398	~3.7†	-		-	-		-	-	
20	56.03191	163.05925	1.64	0.11	**2**	1.75	0.09	**2**	1.17	0.64	**2**
21	56.02541	163.05508	2.84	0.18	**2**	2.62	0.14	**2**	3.72	2.02	**2**
22	56.01826	163.04913	3.43	0.22	**2**	3.47	0.18	**2**	3.29	1.78	**2**
23	56.01828	162.96598	6.79	1.61	**3**	4.89	0.26	**2**	8.77	4.71	**3**

*in most cases, longitude and latitude at the shoreline, in others, excavation closest to shoreline

\- record is eroded, cannot calculate rate and error

† calculated from river level near mouth

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