Recurrence of postseismic coastal uplift, Kuril subduction zone, Japan

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[1] Coastal stratigraphy of eastern Hokkaido indicates that decimeters of coastal uplift occurred repeatedly in the late Holocene. Employing radiocarbon dating and tephrochronology, we identify along a 100 km length of the Kuril subduction zone six uplift events since ~2,800 years B.P. Uplift events occur at the same frequency as unusually high tsunamis. Each coastal uplift event, which occurs on average every 500 years, is the product of decade-long post seismic deep slip on the down dip extension of the seismogenic plate boundary following an offshore multi-segment earthquake that generates unusually high tsunamis.
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1. Introduction

[2] The eastern Hokkaido coast of Japan sits above the Kuril subduction zone, the boundary between the Pacific and continental plates (Figure 1). Along the subduction zone, a series of earthquakes on single segments of the plate boundary, ranging in magnitude from 7.4 to 8.2, occurred in the last century (Figure 1). The most recent earthquake in 2003 (Mw 8.0) occurred within that segment of the plate boundary that ruptured in an earthquake in 1952 [*Yamanaka and Kikuchi*, 2003; *Satake et al.*, 2006]. The rupture patches of these single-segment earthquakes are located offshore and caused only minor amounts (7–30 cm) of coseismic subsidence along the eastern Hokkaido coast [*Shimazaki*, 1974; *Kato*, 1983; *Ozawa et al.*, 2004].

[3] Evidence for earthquakes that rupture multiple adjacent segments at once (multi-segment earthquakes), which are less frequent (at ca. 500 year interval) than single-segment earthquakes, comes from unusually high tsunamis that inundated coastal lowlands along 200 km of the Hokkaido coast [*Nanayama et al.*, 2003]. The unusually high tsunamis, which struck Hokkaido's coast approximately once every 500 years, deposited landward thinning sand sheets that extend 800 to 4000 m inland across a coastal plain at Kiritappu [*Nanayama et al.*, 2003] (Figure 1). Additional evidence for multi-segment earthquakes comes from recurrent uplift at two Hokkaido estuaries [*Sawai and Mishio*, 1998; *Sawai*, 2001; *Sawai et al.*, 2002], with the most recent uplift event, in the 17th century A.D., extending along at least 50 km of coast [*Atwater et al.*, 2004]. These earthquake-related uplifts are enigmatic because the depth of the subduction-zone plate boundary below the affected coast is ca. 60–80 km [*Kosuga et al.*, 1996; *Katsumata et al.*, 2003], which is too deep to cause coseismic brittle fracture manifest at the land surface as abrupt uplift. *Sawai et al.* [2004] therefore interpreted that the 17th century uplift was caused by postseismic creep on a down-dip extension of the seismogenic zone following the multi-segment earthquake. *Sawai et al.* [2004] demonstrated, using diatoms for paleo environmental reconstruction, that the uplift started immediately following an unusually high tsunami and persisted for years to decades.

[4] Coastal movements of eastern Hokkaido are in opposite directions for geodetic (~10^2 years) and geologic (~10^5 years) time scales. Tide gage records at Hanasaki and Kushiro (Figure 1) document ongoing (1958–1996) submergence of 8–9 mm/year [*Kato*, 1983; *Ozawa et al.*, 1997]. Given uncertainties in the rate of global sea-level rise [*Douglas*, 1991], tectonic subsidence of eastern Hokkaido may range from 6–10 mm/yr. In contrast, late Quaternary tectonic uplift as measured from ~200 ka and ~125 ka marine terraces along the Kushiro to Nemuro coast (Figure 1) [*Okumura*, 1996] is 0.2–0.5 mm/yr.

[5] Using 17th century postseismic coastal uplift, 20th century subsidence caused by strain accumulation on the locked plate boundary, and marine terrace uplift rates, *Atwater et al.* [2004] and *Sawai et al.* [2004] inferred that uplift events similar to that recorded in the 17th century must recur at recurrence intervals less than 1,000 years apart. Our objective was to determine whether recurrent uplift events do recur, and if so, what is their average recurrence time, and is there any other coastal geologic evidence for recurrent abrupt uplift. We correlate, using 26 cores and 15 radiocarbon dates from six sites on the eastern Hokkaido coast (Figure 1), a sequence of six uplift events along a 100-km coastal section with an average recurrence interval of 500 years.

2. Field Investigations

[6] We cored coastal wetlands along protected tidal bays and inlets where plant communities are sensitive to changes in ocean level. Our reconnaissance included 3–7 cores at each of six sites spanning 100 km of the coast parallel to the plate boundary (Figure 1). Our wide-ranging reconnaissance precluded lines of closely spaced cores and detailed paleoecologic study of microfossils in interbedded peat and mud.

[7] Core lithologies included peat, peaty mud or muddy peat, mud, sand and tephra units. Correlation of cores

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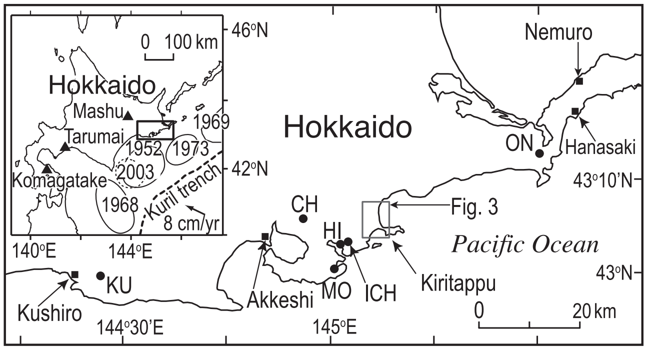

Figure 1. Coastline of eastern Hokkaido. Black circles, core sites used to infer late Holocene relative sea level changes. KU, Kushiro; CH, Chiraikaribetsu; MO, Mochirippu, HI, Hichirippu; ICH, Ichibanzawa; ON, Onnetoh. Inset: location map of the North American/Pacific plate boundary in the vicinity of eastern Hokkaido, showing location of Kuril trench. Ovals delineate approximate rupture area of plate-boundary earthquakes of the twentieth century [*Earthquake Research Committee*, 2004]. Solid triangles, volcanoes that are tephra sources.

among sites separated by tens of kilometers used both lithostratigraphy and tephra chronology and was tested using accelerator mass spectrometry radiocarbon dating of seeds (in 13 cases), leaf fragments (in 1 case) and peat (in 1 case) from the base of peat units (Table 1).

3. Tephrochronology

[8] Tephra, identified from geochemical analyses and sequence in cores, provided a means of correlation and age control. We identified from geochemical analysis all tephra from site ON and two tephra (Ta-a and Ko-c2) from site CH. Two tephra occur in the uppermost 20–45 cm: Ta-a, which erupted from Tarumai volcano (Figure 1) in 1739 A.D. and Ko-c2, which erupted from Komagatake volcano (Figure 1) in 1694 A.D. [*Furukawa et al.*, 1997]. A third less frequently encountered tephra (Ta-b, 1667 A.D. Tarumai volcano) [*Furukawa et al.*, 1997] is immediately below Ko-c2. Another useful tephra is B-Tm tephra (B-Tm, Baegdusan volcano on the Korea-China border) or a combination of B-Tm and Ma-B tephras (Ma-B, Mashu volcano, Figure 1). These tephra are ca. 1 ka in age [*Shoji and Masui*, 1974; *Horn and Schmincke*, 2000].

[9] The deepest tephra in Hokkaido coastal stratigraphy is Ta-c2, a product of a ca. 2 to 3 ka eruption from Tarumai volcano in southern Hokkaido [*Sato*, 1971]. Ta-c2 is bracketed by uplift events L and M (Figure 2) and its age is 2150–2750 years BP, the range from the two calibrated ages that bracket the tephra in core CH-2 (Table 1 and Figure 2).

4. Late Holocene Uplift Events on Eastern Hokkaido Coast

[10] We found two to six wetland peats underlying mud or peaty mud in cores at six coastal sites (Figures 1 and 2). The peats were deposited in abrupt contact above mud or peaty mud. Of the 47 peat/mud or peat/peaty mud contacts in Figure 2 (that is, changes from mud upward to peat), all except four occurred over less than 5 mm. At three of the six coastal sites (MO, CH, ON, Figure 1), previous diatom paleoecology investigations demonstrate that the upward transition from mud to peat records rapid emergence of the wetland from tidal to freshwater marsh settings [*Sawai*,

Table 1. Radiocarbon Age Data, Eastern Hokkaido

Sample Name:[a] Site Code-Core Site-Depth, cm	Laboratory ID Number	Lab-Reported ^{14}C Age, 2 Sigma Error	Calibrated Age Range, Year BP[b]
HP-1A-40[c]	BETA 151223	320 ± 40	300–470
	Peat D		
ICH-7-71	BETA 151229	720 ± 40	560–730
CH-1-102	BETA 151232	780 ± 40	660–760
CH-2-100	GrA 7415	500 ± 110	310–670
	Peat F		
HP-1A-97	BETA 151222	1490 ± 40	1300–1510
	Peat K		
KU-7-130	BETA 151230	1950 ± 40	1820–1990
CH-1-276	BETA 151233	2010 ± 40	1870–2100
HI-1-195	BETA 121220	1940 ± 50	1740–1990
ON-7-77	Wk 8055	1900 ± 60	1710–1990
	Peat L		
CH-2-232	BETA 151234	2320 ± 50	2150–2490
HI-1-214	BETA 151221	2320 ± 40	2160–2450
HI-3-200	BETA 151224	2240 ± 40	2150–2340
	Peat M		
ICH-N35 200	BETA 124221	2820 ± 40	2790–3070
KU-7-201	BETA 151231	2670 ± 40	2750–2850
CH-2-281	BETA 151219	2510 ± 50	2360–2750

[a]See site name abbreviations in caption to Figure 1.
[b]Calibrated years before 1950 A.D., using calibration program of *Stuiver et al.* [1998]. Calibration incorporates two standard deviations.
[c]The peaty mud in HP1A at 40 cm depth may have been deposited by the mid 17th century tsunami that immediately preceded deposition of Peat B.

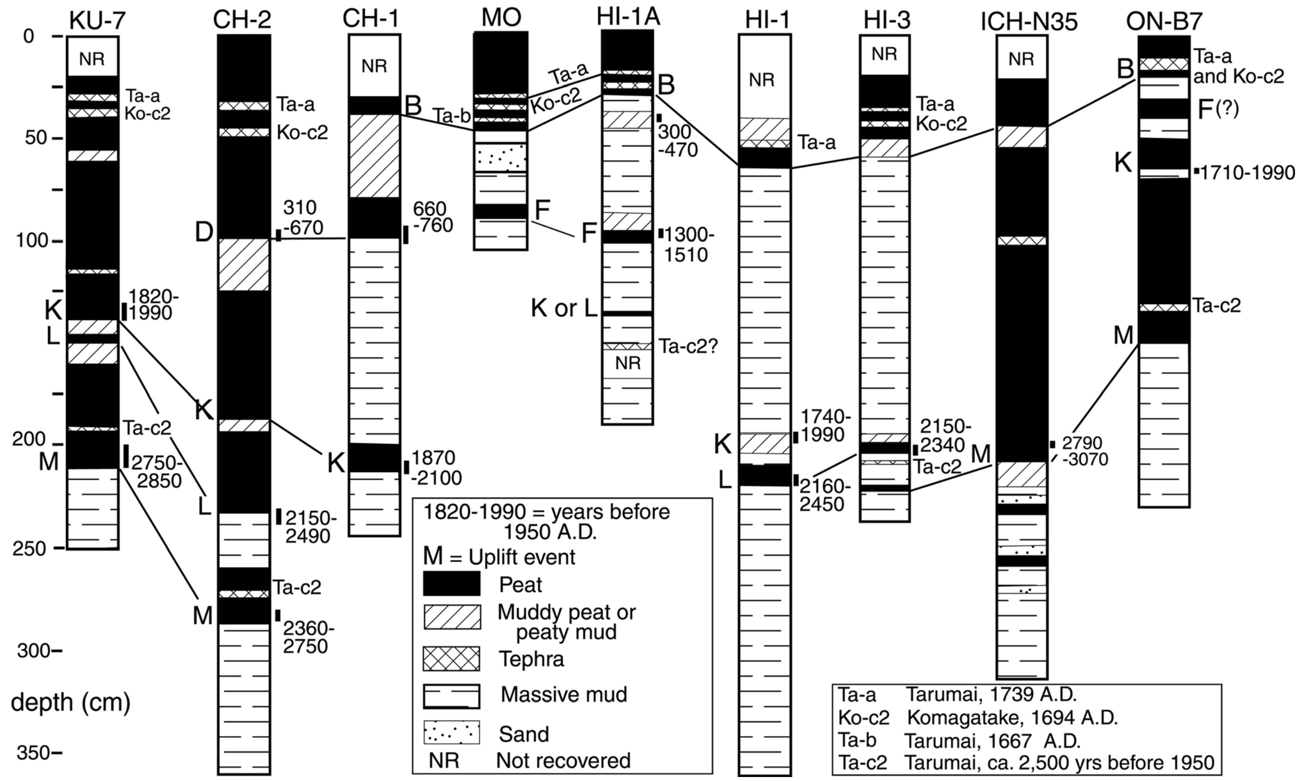

Figure 2. Cores from coastal wetland sites (locations in Figure 1). We infer that abrupt relative sea level fall caused by tectonic uplift is the cause of peat deposition on top of mud. Five such uplift events (B, D, F, K, L and M) can be correlated among cores that span ca. 70 km of the Kuril plate boundary; events K and M span ca. 100 km of the plate boundary (Figure 1). Event B is the mid 17th century abrupt uplift event documented by *Atwater et al.* [2004] and *Sawai et al.* [2004].

2001; *Sawai et al.*, 2002, 2004]. From the abrupt contacts and diatom paleoecologic data, we therefore infer that tidal mud flats were rapidly uplifted resulting in a rapid change in environment from tidal to freshwater and a corresponding sharp contact between underlying tidal mud and overlying freshwater peat.

[11] Because peat deposits can be physically and temporally correlated among sites (Figure 2 and Table 1), we infer that an uplift event is associated with each group of correlated peats and assign a letter to each event-associated peat (B, D, F, K, L and M) (Figure 2 and Tables 1 and 2). The approximate time that each peat started to form is tabulated (Table 2) based on the peat radiocarbon ages (Table 1).

[12] Peat M started to form prior to the eruption of Ta-c2 tephra, and with the exception of southern Kiritappu (ICH, Figure 2), peat M is the oldest peat abruptly in contact above massive mud and marks the first time in the late Holocene that the core site was uplifted above a subtidal elevation. Peats D, F, K, L and M are represented at three to five of the six wetland sites (Figure 2) and have assigned ages based on one to four radiocarbon ages (Table 2). Peat B occurs in five wetland sites and formed as a result of the mid 17th century rapid uplift event [*Atwater et al.*, 2004; *Sawai et al.*, 2004] (Tables 1 and 2).

[13] In summary, there were six instances of rapid uplift each represented by the deposition of a peat deposit abruptly on top of a mud or peaty mud, and five of these peats can be extensively correlated (Figure 2). Over the same time period, *Sawai* [2001] and *Sawai et al.* [2002] document only four uplift events from two wetland sites in coastal Hokkaido, illustrating that the stratigraphic record at any one site may be incomplete. Six instances of rapid uplift of the Hokkaido coast in the ~2,500 year period between 2,800 and 300 years B.P. yields an average interval of ~500 years between each abrupt uplift, the same as the average interval of large tsunami estimated by *Nanayama et al.* [2003]. We extrapolate, from *Sawai et al.*'s [2004] observations of the 17th century uplift (event B), that an unusually high tsunami immediately preceded each episode of abrupt coastal uplift.

5. Relation of Coastal Plain Beach Berms to Uplift Events

[14] Evidence for abrupt uplift events on the Hokkaido coast, in additional to buried peat deposits, is inactive beach

Table 2. Age and Site Distribution for Peat Deposits Correlated Among Study Sites

Peat Deposit, Identified by Letter Code[a]	Approximate Time Peat Started to be Deposited,[b] Year BP	Number of Sites (Out of Six Total) Where Peat Observed
B	300[c]	5
D	400–600	3
F	1400	3
K	1900	4
L	2300	3
M	2800	5

[a]See Table 1 and Figure 2.
[b]See Table 1.
[c]Age identified by tephra and by correlation with 17th century peat of *Atwater et al.* [2004] and *Sawai et al.* [2004].

storm berms preserved landward of the active berm. The ~30 km^2 Kiritappu coastal plain (Figure 3) is built by seaward accretion of beach storm berms, leaving a succession of former beach storm berms visible on aerial photographs (Figure 3). The plain consists of approximately ten relict storm berms and intervening troughs. The landward thinning sand sheets at Kiritappu, interpreted as tsunami deposits by *Nanayama et al.* [2003], blanket the uplifted berms (Figure 3). Since ca. 2,500 yrs B.P. (deposition age of tephra Ta-c2), five to six sand sheets have been deposited on the coastal plain (core GS1 [*Nanayama et al.*, 2000]) (Figure 3). In the same time period there have been five abrupt uplift events on Hokkaido's coast (Figure 2).

[15] Although the paleo beach storm berms at Kiritappu have not been dated, we deduce that each berm represents one rapid uplift event associated with post seismic creep on the down dip extension of the seismogenic zone after a multi-segment earthquake, and that a new storm berm is formed each time a formerly active storm berm is uplifted above storm waves. If true, then an abrupt uplift leaves a geologic record of abandoned, inactive berms on open, prograding coastlines and buried peat deposits in protected tidal marshes.

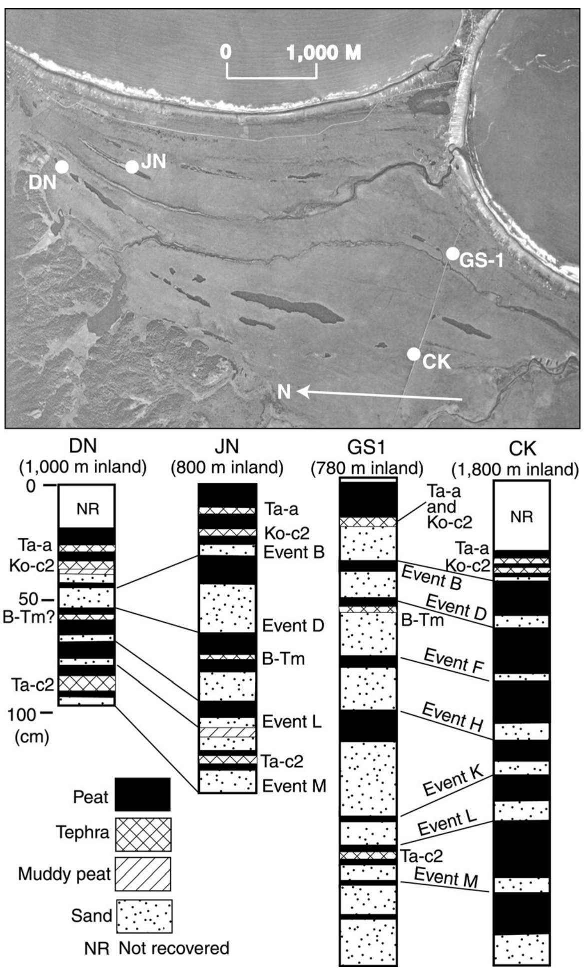

Figure 3. Aerial photograph of Kiritappu marsh, an emergent coastal plain built by seaward-prograding beach berms. Berms are separated by lower-elevation troughs occupied by ponded water or low gradient drainages. Cores (white dots) DN, JN, GS1 and CK show that the coastal plain has built up by tsunami sand and interbedded peat deposited on top of beach sand substrate (core GS1 from *Nanayama et al.* [2000]).

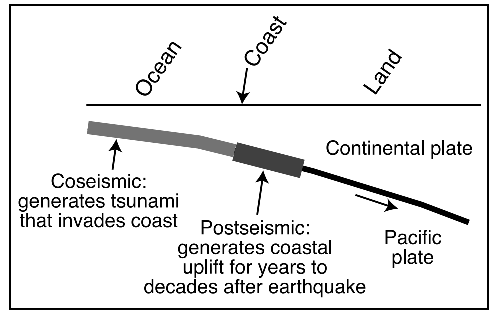

Figure 4. Summary schematic diagram showing the origin of recurrent tsunami and recurrent coastal uplift on Hokkaido's eastern shore caused by the coseismic and postseismic affects of multi-segment earthquakes on the Kuril subduction zone.

6. Multi-Segment Earthquake Origin of Recurrent Coastal Uplift on Hokkaido's Eastern Coast, Japan

[16] Recurrent coastal uplift and tsunami, recorded along Hokkaido's eastern shore, are triggered in response to multi-segment earthquakes on the Kurile subduction zone (Figure 4). Coastal uplift events, which are documented by deposition of wetland freshwater peat in abrupt contact above tidal mud [*Atwater et al.*, 2004; *Sawai et al.*, 2004], and unusually high tsunamis, which are documented by deposition of sheets of sand on relict beach berms [*Nanayama et al.*, 2003], both occur at the same frequency on this coast. Sequences of inactive beach berms on Kiritappu coastal plain probably also chronicle repeated uplift and abandonment of active coastal berms. Each coastal uplift event recurs on average every 500 years, occurs after a tsunami that is generated by coseismic uplift offshore, persists for years to decades, and is the product of post seismic deep slip on the down dip extension of the seismogenic plate boundary following an offshore multi-segment earthquake.

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