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Transient Uplift After a 17th-Century Earthquake Along the Kuril Subduction Zone

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In eastern Hokkaido, 60 to 80 kilometers above a subducting oceanic plate, tidal mudflats changed into freshwater forests during the first decades after a 17th-century tsunami. The mudflats gradually rose by a meter, as judged from fossil diatom assemblages. Both the tsunami and the ensuing uplift exceeded any in the region's 200 years of written history, and both resulted from a shallow plate-boundary earthquake of unusually large size along the Kuril subduction zone. This earthquake probably induced more creep farther down the plate boundary than did any of the region's historical events.

Large shallow earthquakes at subduction zones commonly warp Earth's surface. Although the most dramatic deformation accompanies the earthquakes, additional, transient warping can follow in response to fault creep, mantle relaxation, or both (1). Small post-seismic transients at subduction zones have produced days, weeks, months, or even years of horizontal motion detectable by satellite geodesy (2–4). The largest recorded transients, induced by giant earthquakes during the 1960s in Chile and Alaska, continue today and have thus far produced as much as a meter or two of gradual coastal uplift, according to eyewitnesses, tide gauges, and estuarine ecology (5–9).

Postseismic uplift has a long-recognized potential for resolving a glaring conflict between geologic uplift and geodetic subsidence along the Kuril subduction zone. The subduction zone conveys the Pacific plate beneath Asia at rates averaging 8 to 9 m per century (10) (Fig. 1A). In eastern Hokkaido, 60 to 80 km above the top of the subducting plate, uplifted marine terraces somehow coexist with subsiding tide gauges and bench marks. The geology requires 20 to 50 m of net uplift in the past

125,000 years (11), but the geodesy shows as much as 1 m of subsidence in the past 100 years (12, 13). The subsidence probably results from subduction; currently locked to the overriding plate (14), the subducting Pacific plate drags eastern Hokkaido downward. In 1973, when a shallow earthquake of moment magnitude (M_w) 7.8 broke the plate boundary offshore (Fig. 1B), geophysicists expected decimeters of rebound (15, 16). However, no onshore uplift coincided with the earthquake and less than 0.1 m followed (17). Similarly, an adjacent earthquake of M_w 8.0 in 2003 was accompanied by onshore subsidence and was followed by just centimeters of onshore uplift (18). Little, if any, other uplift

is known from the rest of eastern Hokkaido's written history, which includes an earthquake of M_w 8.2 in 1952 (19) and several other magnitude-8 events from the past 200 years (20).

Eastern Hokkaido's geologic history of the past 3000 years, however, indicates episodic uplift perhaps related to unusually large earthquakes. The uplift, which repeatedly changed muddy estuaries into lowland forests, amounted to about 1 m per episode (21–23). The outsize earthquakes, inferred from unusually large tsunamis that spread sand kilometers inland, probably resulted from seismic ruptures at least twice as long as those in 1973 and 2003 (24). Both for the episodic uplift and the outsize earthquakes, hundreds of years elapsed between events, and the most recent event occurred in the 17th century. Do unusually large plate-boundary earthquakes provide the long-sought mechanism for eastern Hokkaido's terrace uplift?

We address this question by using stratigraphy and paleoecology to learn whether the 17th-century uplift episode shortly followed the outsize 17th-century tsunami. The tsunami deposited a sand sheet, commonly 10 cm thick, on lowlands along the open Pacific coast. The sheet was previously unknown from the sheltered arms of estuaries where the 17th-century uplift is recorded by an upward change from tidal mud to forest peat. We recently found tsunami sand sheets within such mud-to-peat sequences at two estuaries beside the Pacific coast: Mochirippu (Fig. 2), described below, and the south end of Kiritappu marsh, described in supporting material (25) (fig. S1).

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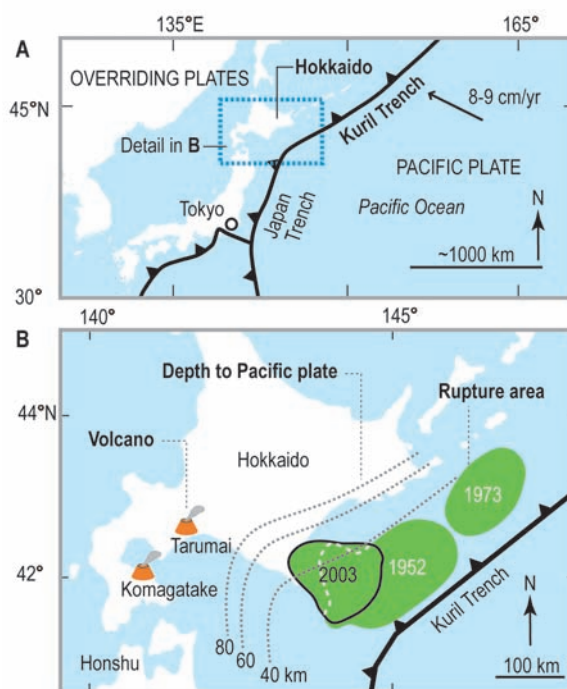


Fig. 1. Study area. (A) Kuril and Japan trenches. (B) Hokkaido, showing volcanoes responsible for tephra layers in Fig. 2 (26), depths to the Pacific plate (37), and rupture areas of instrumentally recorded earthquakes on the plate boundary off eastern Hokkaido (4, 19, 28). Heavy lines in (A) and (B) denote seafloor trenches, which mark seaward edges of subduction zones; triangles point down the fault plane.

Mochirippu consists of a bay and fringing tidal marshes that together extend 3 km inland from a narrow inlet through a beach berm (Fig. 2A). In dozens of cores 2.0 to 2.5 km inland from the beach, we found no sand from historical tsunamis. However, we consistently found two prehistoric tsunami sand sheets (Figs. 2B). The younger sheet, mainly 2 to 5 cm thick, is widely bounded by mud that contains tidal-flat diatom assemblages (Fig. 2, C and D). As much as 5 cm of mud overlies the younger sheet. This mud grades upward

into peat that formed on a forest floor. Dates of regional volcanic-ash layers (26) show that the tidal flat changed into the forest by 1667 and that the forest persisted through 1739 (Fig. 2C).

We quantify this 17th-century emergence at Mochirippu, and elsewhere, by means of diatom assemblages that we relate to modern environments through transfer functions (25, 27). The results imply several decimeters of gradual pre-tsunami subsidence, no detectable change around the

time of the tsunami, and at least 1 m of subsequent uplift (Fig. 2D). The uplift began around the time of the tsunami (which has not been dated exactly), continued to 1667, and ended by 1739. A core from the southern Kiritappu marsh shows a similar uplift history (fig. S1), as do sites elsewhere in eastern Hokkaido (red triangles in Fig. 3A). Written records provide evidence against more than 2 m of 17th-century uplift at Akkeshi-ko (23).

Stratigraphy and paleoecology thus imply that a 17th-century earthquake off eastern Hokkaido generated both an outside tsunami and an ensuing episode of gradual coastal uplift. Had the earthquake accompanied the uplift, the tsunami would have coincided with an abrupt change from tidal flat to lowland forest (Fig. 2E, left). Instead, the uplift happened gradually in the first decades after the tsunami (Fig. 2E, right).

How did the 17th-century earthquake induce uplift that historical earthquakes failed to trigger? In the most likely series of events, an unusually large earthquake broke the plate boundary offshore, and this rupture induced unusual amounts of postseismic slip farther down the plate boundary, beneath eastern Hokkaido. Satellite geodesy suggests that the plate boundary is currently locked beneath most of the continental shelf and slope. Modeled for an elastic Earth, the locked zone extends down the plate boundary to a depth of 55 km (14). The 1973 rupture broke this part of the plate boundary no deeper than about 30 km (28), and the 1952 and 2003 ruptures reached depths of 50 km along only a few tens of kilometers of rupture length (Fig. 1B). The 17th-century uplift, however, followed an earthquake that probably broke the combined areas of the 1952 and 1973 ruptures, for a rupture length of at least 300 km (24). We assume that such widespread rupture, if it reached the lower limit of the locked zone, would release the plate boundary for afterslip farther downdip, beneath eastern Hokkaido. In addition, because uplift usually occurs above the area of slip on a thrust fault (29), meters of plate-boundary creep beneath eastern Hokkaido should raise the coast, as simulated by the simple dislocation model in Fig. 3, B and C (30, 31). Such afterslip, on a much smaller scale, probably generated Hokkaido's postseismic uplift in 2003 (4, 18).

Relaxation of stress in the continental mantle also may have contributed to eastern Hokkaido's 17th-century uplift. During a shallow plate-boundary earthquake, seaward displacement of the overriding plate stresses the mantle wedge behind and below it. The mantle, as a viscoelastic material, then catches up with this displacement by flowing seaward and upward beneath the coast (1). This kind of deep deformation, be-

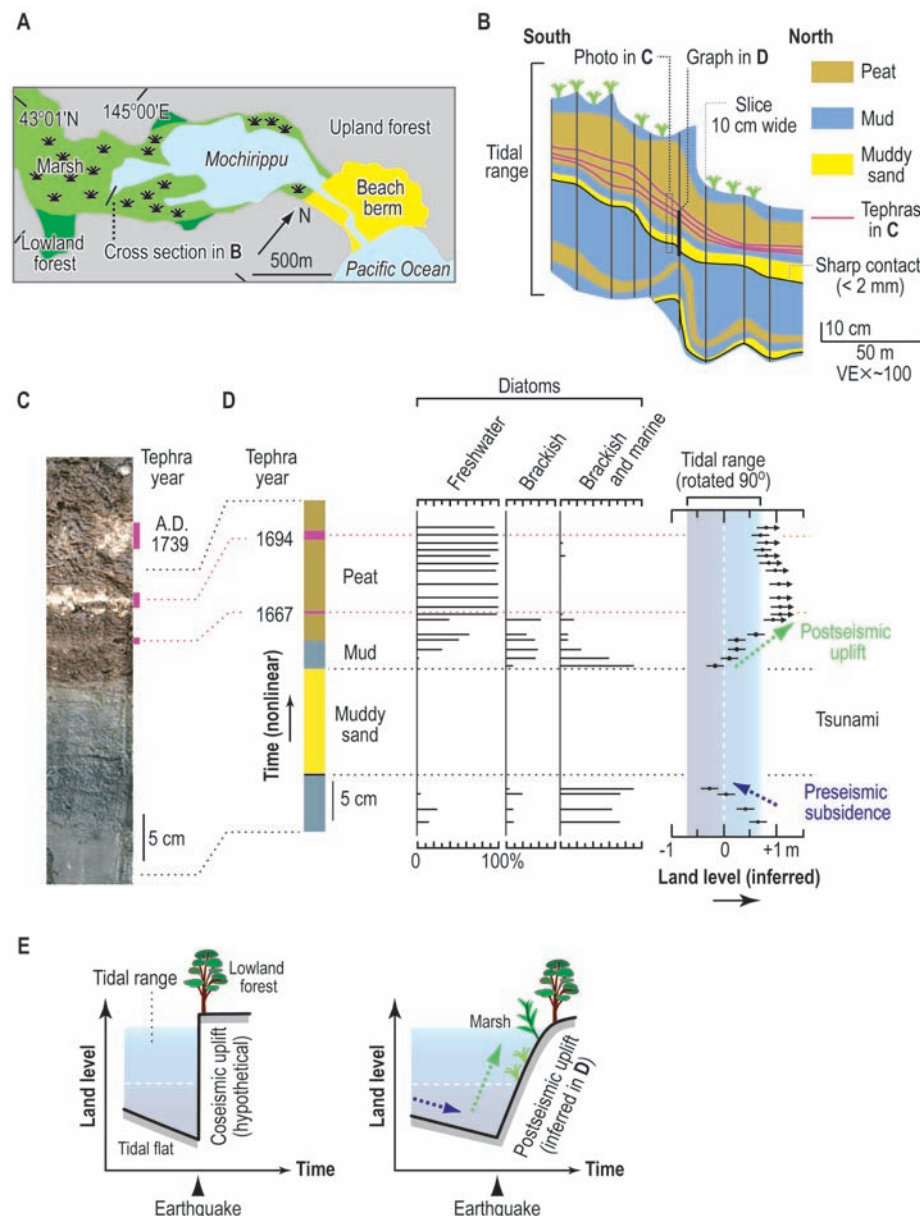


Fig. 2. Geologic evidence for postseismic coastal uplift at Mochirippu (location, Fig. 3A). (A) Index map. (B) Stratigraphic cross section. (See figs. S1 and S2 for additional cross sections.) (C) Example of change from tidal-flat mud to lowland-forest peat, punctuated by a tsunami deposit and by volcanic-ash layers. (D) Land-level changes inferred from diatom assemblages in a core near the one in (C). Stratigraphy (left) and relative abundance of diatoms, which are grouped by ecology, in a core near the one in (C) (middle), and land-level changes inferred from the diatom assemblages (right). Error bars for height estimates span 2 SD. Arrow in (D) denotes limiting-minimum height estimated from diatom assemblage typical of lowland forests above high tides (27). (E) Changes in land level and depositional environment in response to coseismic uplift (left) and postseismic uplift (right).

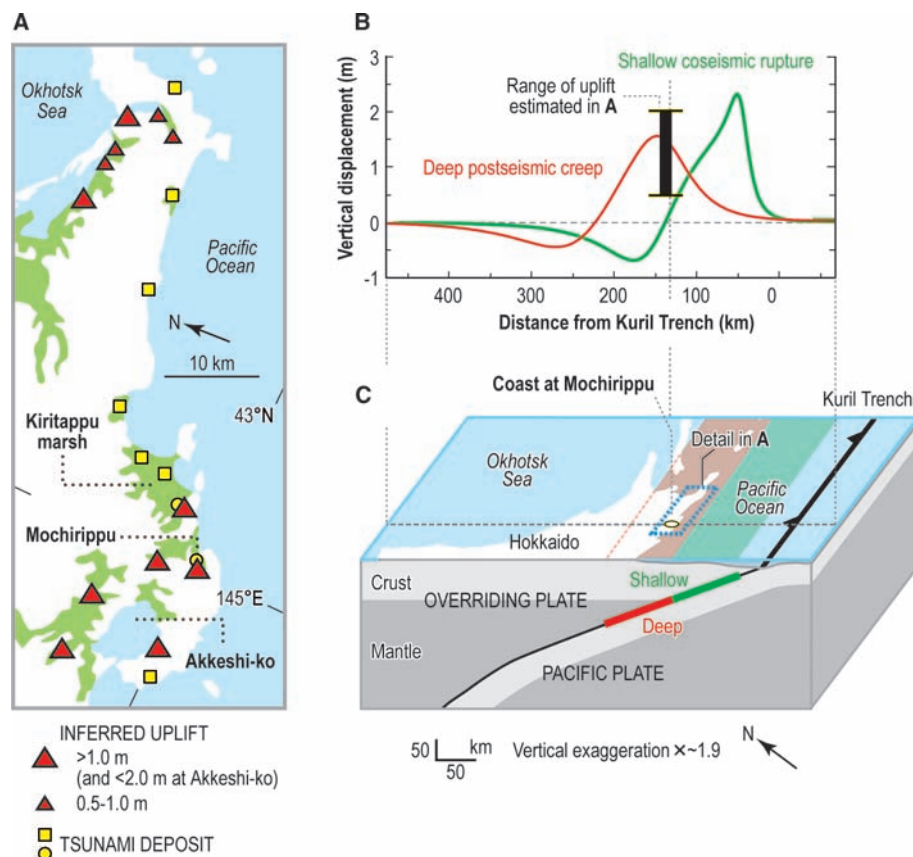


Fig. 3. Afterslip hypothesis for eastern Hokkaido. (A) Distribution of 17th-century evidence for an unusually large tsunami (yellow) and uplift (red). Tsunami sites shown by squares are from Nanayama *et al.* (24); circles, this study. Uplift amounts were estimated as in Fig. 2D and fig. S3C. (B) Vertical displacement computed by elastic-dislocation modeling (29) of fault slip assumed in (C). (C) Modeled slip at the plate boundary (front panel) and corresponding areas of computed uplift at Earth's surface (color bands viewed obliquely). Green, shallow seismic rupture of the interseismic locked zone (14) at 15 to 55 km depth. Red, deep afterslip at 55 to 85 km, down dip from full interplate coupling. Uplift profiles in (B).

lied to be going on today in the region of the 1960 Chile earthquake, can be difficult to distinguish observationally from after-slip (32).

Do the postseismic effects of outside earthquakes produce enough uplift to negate interseismic subsidence in eastern Hokkaido? An uplift deficit persists if the interseismic subsidence accumulates at nearly 1 m per 100 years and if the postseismic uplift averages just 1 to 2 m in 500 years. However, a definitive answer will require a clear picture of entire deformation cycles between outside earthquakes. That picture will depend on the interseismic subsidence rates (33, 34), land-level changes that accompany the outside earthquakes, the size and duration of ensuing transients, the coseismic and postseismic effects of lesser earthquakes, and the recurrence intervals of the various earthquakes themselves.

References and Notes

1. K. Wang, in *The Seismogenic Zone Experiment*, T. Dixon, Ed. (Columbia Univ. Press, New York, in press).
2. K. Heki, S. Miyazaki, H. Tsuji, *Nature* **386**, 595 (1997).

3. T. I. Melbourne, F. H. Webb, J. M. Stock, C. Reiger, *J. Geophys. Res.* **107**, 2241 (2002); <http://dx.doi.org/10.1029/2001JB000555>.
4. S. Ozawa, M. Kaidzu, M. Murakami, T. Imakiire, Y. Hatanaka, *Earth Planets Space* **56**, 675 (2004).
5. S. E. Barrientos, G. Pfaffner, E. Lorca, *Geophys. Res. Lett.* **19**, 701 (1992).
6. S. C. Cohen, J. T. Freymueller, *J. Geophys. Res.* **102**, 20479 (1997).
7. Y. Zong, I. Shennan, R. A. Combellick, S. L. Hamilton, M. M. Rutherford, *Holocene* **13**, 7 (2003).
8. J. P. Guilbault, J. J. Clague, M. Lapointe, *Quat. Sci. Rev.* **15**, 913 (1996).
9. Uplift since the 1964 Alaska earthquake, known mainly from tide-gauge records (6), is also evident as changes in diatom and pollen assemblages of estuarine deposits (7). Similarly, postseismic uplift induced by the 1700 Cascadia earthquake has been inferred from foraminifera (8). In both cases, and also in southwest Japan (10), the uplift occurred in areas that subsided during the earthquake, and the amount of coseismic subsidence exceeded the amount of postseismic uplift. The 17th-century uplift in eastern Hokkaido, by contrast, more nearly resembles the postseismic uplift in Chile (5) insofar as the Chilean uplift occurred arcward of the area of coseismic subsidence.
10. C. DeMets, *J. Geophys. Res.* **97**, 17,615 (1992).
11. K. Okumura, *Geog. Rep. Tokyo Metropol. Univ.* **31**, 19 (1996).
12. K. Shimazaki, *Phys. Earth Planet. Inter.* **8**, 148 (1974).
13. S. Ozawa, M. Hashimoto, T. Tada, *Bull. Geog. Surv. Inst.* **43**, 1 (1997).

14. S. Mazzotti, X. Le Pichon, P. Henry, S.-I. Miyazaki, *J. Geophys. Res.* **105**, 13159 (2000).
15. K. Shimazaki, *Phys. Earth Planet. Inter.* **9**, 314 (1974).
16. K. Kasahara, *Pure Appl. Geophys.* **113**, 127 (1975).
17. K. Kasahara, T. Kato, *Pure Appl. Geophys.* **119**, 392 (1980/1981).
18. Y. Yamanaka, M. Kikuchi, *Earth Planets Space* **55**, e21 (2003).
19. K. Hirata, E. L. Geist, K. Satake, Y. Tanioka, S. Yamaki, *J. Geophys. Res.* **108**, 2196 (2003); <http://dx.doi.org/10.1029/2002JB001976>.
20. An offshore earthquake in 1894 was followed, between 1894 and 1905, by as much as 0.2 m of coastal uplift in easternmost Hokkaido (15, 16). This estimate is based on incomplete records of a tide gauge.
21. Y. Sawai, *Quat. Res.* **56**, 231 (2001).
22. Y. Sawai, H. Nasu, Y. Yasuda, *J. Quat. Sci.* **17**, 602 (2002).
23. B. F. Atwater *et al.*, *Holocene* **14**, 487 (2004).
24. F. Nanayama *et al.*, *Nature* **424**, 660 (2003).
25. Materials and methods are available as supporting material on Science Online.
26. R. Furukawa, M. Yoshimoto, K. Yamagata, K. Wada, T. Ui, *Kazan* **42**, 269 (1997).
27. Y. Sawai, B. P. Horton, T. Nagumo, *Quat. Sci. Rev.* **23**, 2467 (2004); <http://dx.doi.org/10.1016/j.quascirev.2004.05.006>.
28. A. Nakanishi *et al.*, *J. Geophys. Res.* **109**, 5305 (2004); <http://dx.doi.org/10.1029/2003JB002574>.
29. J. C. Savage, *J. Geophys. Res.* **88**, 4984 (1983).
30. Y. Okada, *Bull. Seismol. Soc. Am.* **75**, 1135 (1985).
31. Vertical displacement of ground surface was computed for a dislocation model (29) in which the fault extends from 15 to 55 km depth on the subducting plate (dip angle 20°) for coseismic rupture and 55 to 85 km depth for deep postseismic creep. The average coseismic slip is 5 m (23), and the same amount is assumed for the deep postseismic slip.
32. Y. Hu, K. Wang, J. He, J. Klotz, G. Khazaradze, *J. Geophys. Res.*, in press.
33. The estimate of nearly 1 m per 100 years exaggerates eastern Hokkaido's 20th-century subsidence. At the region's two tide gauges, Hanasaki and Kushiro, the Pacific coast sank relative to the sea by 8 to 9 mm/year on average from 1958 to 1995 (13). However, sea level in northeast Japan has risen more than 2 mm/year, on average, in the past few decades (35, 36). Subtraction of sea-level rise from the tide-gauge rates decreases the amount of terrace uplift that remains to be explained.
34. Subduction erosion may also contribute to modern subsidence in eastern Hokkaido (36). However, if it has occurred steadily throughout the late Quaternary, subduction erosion does not diminish the amount of uplift needed to raise the region's marine terraces.
35. A. Cazenave, R. S. Nerem, *Rev. Geophys.* **42**, RG3001 (2004).
36. K. Heki, *Earth Planet. Sci. Lett.* **219**, 13 (2004).
37. K. Katsumata, N. Wada, M. Kasahara, *J. Geophys. Res.* **108**, 2565 (2003); <http://dx.doi.org/10.1029/2002JB002175>.
38. We thank K. Wang for improving the geophysical model, B. Sherrord for field help, J. Bourgeois, J. Clague, T. Kato, T. Sagiya, K. Shimazaki, H. Sekiguchi, Y. Tanioka, W. Thatcher, S. Toda, K. Wang, and two anonymous referees for reviews and E. Davis, A. J. Long, and I. Shennan for discussion. Part of the work was supported by grants from the Japanese Ministry of Education, Science, and Culture (nos. 10007549 and 13007536) to Y.S. Authors are grouped by affiliation in the by-line. Their responsibilities: field work, Y.S., T.K., H.N., M.Y.; diatom analysis, Y.S., T.N., B.H.; afterslip model, K.S., H.K.; manuscript preparation, B.A., K.S., Y.S.

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Materials and Methods
Fig. S1
References

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