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Challenges of anticipating the 2011 Tohoku earthquake and tsunami using coastal geology

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[1] Can the magnitude of a giant earthquake be estimated from paleoseismological data alone? Attempts to estimate the size of the Jogan earthquake of AD 869, whose tsunami affected much of the same coast as the 2011 Tohoku tsunami, offers an excellent opportunity to address this question, which is fundamental to assessing earthquake and tsunami hazards at subduction zones. Between 2004 and 2010, examining stratigraphy at 399 locations beneath paddy fields along 180 km of coast mainly south of Sendai, we learned that a tsunami deposit associated with the AD 869 Jogan earthquake had run inland at least 1.5 km across multiple coastal lowlands, and that one of the lowlands had subsided during the Jogan earthquake and an earlier earthquake as well. Radiocarbon ages just below/above sand deposits left by the pre-Jogan tsunamis suggested recurrence intervals in the range of 500 to 800 years. Modeling inundation and subsidence, we estimated size of the Jogan earthquake as moment magnitude 8.4 or larger and a fault rupture area 200 km long. We did not consider a longer rupture, like the one in 2011, because coastal landform and absence of a volcanic ash layer make any Jogan layer difficult to identify along the Sanriku coast. Still, Sendai tsunami geology might have reduced casualties by improving evacuation maps and informing public-awareness campaigns. **Citation:** Sawai, Y., Y. Namegaya, Y. Okamura, K. Satake, and M. Shishikura (2012), Challenges of anticipating the 2011 Tohoku earthquake and tsunami using coastal geology, *Geophys. Res. Lett.*, *39*, L21309, doi:10.1029/2012GL053692.

1. Introduction

[2] In the region of the giant (magnitude-9) 2011 Tohoku earthquake and tsunami in northcentral Japan, stratigraphic studies of past tsunamis began nearly a quarter-century ago with the discovery of a sand sheet linked to the Jogan earthquake and tsunami of July AD 869 [*Abe et al.*, 1990; *Minoura and Nakaya*, 1991; *Minoura et al.*, 2001; *Sugawara et al.*, 2011] (Figures 1 and 2). Historical documents and the distribution of the sand sheet on the Sendai plain both showed that the Jogan tsunami ran inland kilometers farther than did any later tsunamis–until 2011 (Figures S1 and S2 and Table S1 in Text S1 in the auxiliary material).[1] However, a Japanese national seismic hazard map dated May 2010 showed no hazard to the Sendai area from subduction earthquakes along the Japan Trench larger than those of the past 400 years [*The Headquarters for Earthquake Research Promotion*, 2010].

[3] This apparent contradiction in recognized hazard reflects uncertainty, which persists today, about the size of the Jogan earthquake and the intervals at which such earthquakes recur. We sought to address these unknowns through coastal geological studies and geophysical modeling that began in 2004. Our results, first reported in preliminary Japanese-language publications in 2007–2010 [*Namegaya et al.*, 2010; *Satake et al.*, 2008; *Sawai et al.*, 2008b; *Shishikura et al.*, 2007], are presented here in English for the first time. Also reported here are findings from Odaka and Juo that have not been published previously in any language.

2. Methods

[4] Previous studies had identified Jogan tsunami deposits in the outskirts of Sendai (Figure 2a). To test the size of past earthquakes and tsunamis, we searched beneath coastal lowlands north and south of Sendai for the Jogan and other sandy tsunami deposits and for stratigraphic signs of coseismic subsidence. Such signs of long-lasting subsidence commonly record the greatest earthquakes at other subduction zones [*Satake and Atwater*, 2007]. We studied sediment samples with a handheld gouge corer and 15–40-cm-wide, rectangular geoslicer at 399 locations along seven leveled transects in Sendai plain and nine transects in other multiple coastal lowlands facing the Japan Trench (Table S2 in Text S1). We used diatom assemblages to infer changes in environment and elevation following methods described by *Sawai* [2001] (Figure 3 and Figure S10 in Text S1). A widely mapped ash bed deposited in AD 915, identified in the field and through chemical analysis (To-a (Towada) ash of *Aoki and Machida* [2006]) (Table S3 in Text S1), helped us trace tsunami deposits. To date tsunamis and subsidence we analyzed 159 materials (plant macrofossils, insects, and charcoals), mostly from peaty beds, with routine AMS ^{14}C methods (Table S4 in Text S1).

[5] We further assessed earthquake size by modeling tsunamis that could explain the mapped sand sheets, following the method of *Satake et al.* [2008] (Table S5 in Text S1).

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Nonlinear shallow-water equations were solved with a finite-difference method applied to bathymetry and topography. We used various data sources to model present-day bathymetry and topography, then reconstructed the Jogan shoreline in AD 869. Details on sites, stratigraphy, data sources, and methods are in the auxiliary material.

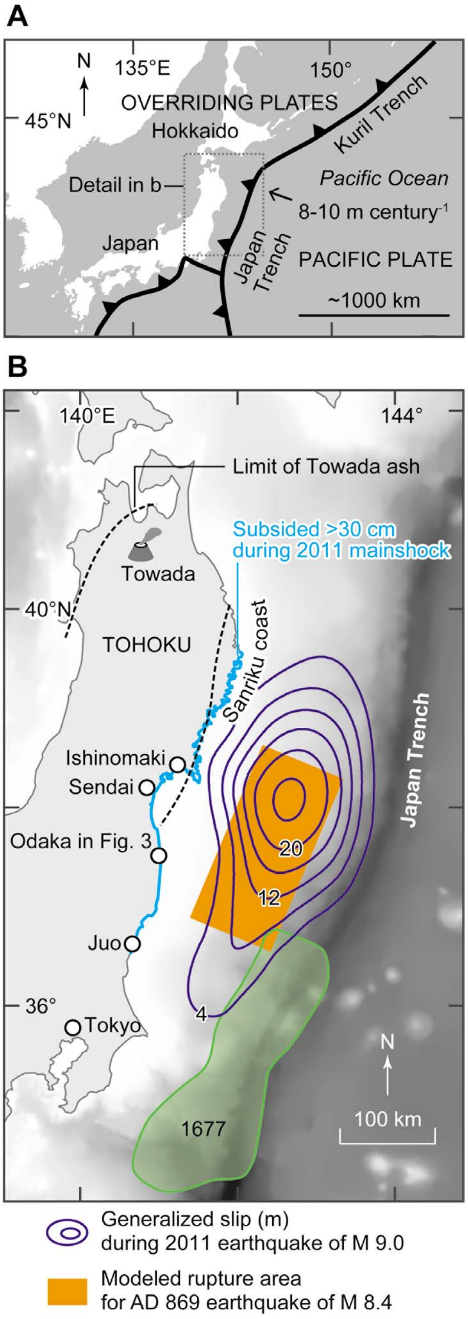

Figure 1. Location map. (a) Barbed line shows seaward edge of subduction zone. (b) Northeastern Honshu, showing limit of Towada ash of AD 915 [*Machida and Arai*, 2003], the estimated rupture area of 1677 earthquake [*Takeuchi et al.*, 2007], coastal coseismic subsidence in 2011, generalized 2011 fault-rupture area and slip inferred from GPS data [*Ozawa et al.*, 2011], and the rupture area of a hypothetical AD 869 Jogan earthquake of M 8.4 that can explain the inundation area inferred from the Jogan sand sheet (Figure S12 in Text S1).

3. Evidence for Historical and Prehistoric Tsunamis

[6] We mapped five extensive sand deposits in sediments spanning 3,000 years along seven transects perpendicular to the shoreline in the Sendai area (Figures 2–4 and Figures S3–S7 in Text S1). From old to young the deposits are labeled A, B (Jogan), C, D, and K (Keicho 1611). All sand deposits were bounded by peaty deposits that accumulated in a freshwater swamp or marsh. The deposits show single or multiple vertical upward-fining beds and are laterally continuous for more than 0.5–1.5 km.

[7] The three sand deposits 1,000–3,000 years old are widely preserved along a 100-km-long stretch of coast that includes the Sendai plain. A sheltered lowland in Odaka, 70 km south of Sendai, retains three sand deposits interbedded with peat and mud (Figures 3a–3c and Figure S8 in Text S1). As on the Sendai plain, the deposits fine upward, commonly in multiple beds or laminations. We could not trace sand B more than 1.8 km from the present shoreline. Using 130 radiocarbon ages, we correlate the Odaka sand deposits with sands B, C, and D in the Sendai plain (Figure 4 and Figure S11 and Table S4 in Text S1).

[8] Lithology, sedimentary structures, and paleoecology suggest that the sand deposits were laid down during rapid marine incursions. Most deposits have abrupt lower contacts and taper landward over hundreds of meters. Internal structures of the deposits include multiple graded beds, parallel laminae, rip-up clasts, and flame structures, all features consistent with deposition by tsunamis [*Morton et al.*, 2007]. We ruled out fluvial deposition as a possible origin for the deposits because they contain many marine and brackish diatoms (Figure S10 in Text S1).

[9] Three of the five sand deposits can be matched with tsunamis known from written records. We correlated sand B with the Jogan tsunami by means of radiocarbon ages just below and above sand B and by its position just below the Towada ash of AD 915 (To-a, Figure 2c and Table S3 in Text S1). Beneath seaward parts of the Sendai plain we found evidence for two tsunamis younger than Jogan: sand A, which may correlate with an earthquake in 1454 (Figures 2c and 4b); and sand K, which may represent a tsunami in 1611 that had its greatest reported effects farther north, on the Sanriku coast (location, Figure 1b) [*Imamura*, 1934]. Radiocarbon ages suggest time intervals of about 800 years between sands D and C, and about 500 years between sands C and B—shorter than the 1,000 year average recurrence interval inferred previously [*Minoura et al.*, 2001] for unusually large tsunamis near Sendai.

[10] In Juo, near the southern Tohoku, we were not able to find correlatives of the tsunami deposits identified in Sendai plain and Odaka (Figure 4 and Figure S9 in Text S1). Radiocarbon ages show that three sand deposits within freshwater peaty sediment (sands H, J, and M) are younger

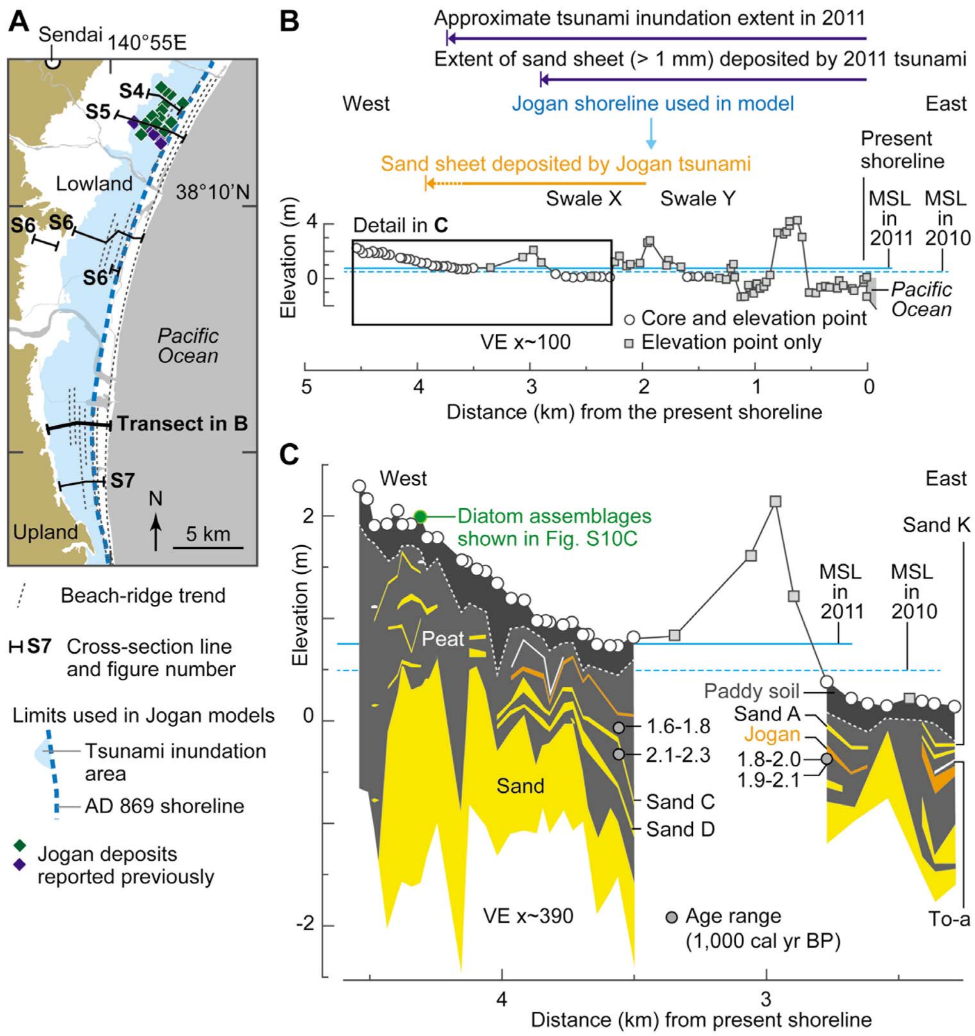

Figure 2. Evidence for unusually large tsunamis on the Sendai plain. (a) Index map. Evidence reported previously plotted as diamonds (green, *Sugawara et al.* [2011]; blue, *Abe et al.* [1990] and *Minoura and Nakaya* [1991]). (b) Topographic profile across southern Sendai lowland (location in Figure 2a). Inundation by 2011 tsunami estimated from airphotographs by the Geographical Survey Institute. We measured the extent of the 2011 sand sheet along this profile in the first two days after the tsunami. Mean tidal level (MTL) in 2011 was calculated using data taken after April 2011. VE, vertical exaggeration. (c) Stratigraphic cross section of swales along profile in Figure 2b.

than the Jogan tsunami. One sand may record the tsunami of 1677 (Figure 4) [*Takeuchi et al.*, 2007].

4. Evidence for Coseismic Subsidence

[11] At Odaka, we found diatom evidence for coseismic subsidence coincident with sand deposition that we correlate by stratigraphic sequence and radiocarbon age with sands C and B (Figures 3 and 4). In each case the diatom assemblage below a sand deposit contains more freshwater taxa, and fewer marine taxa, than does the assemblage above it (Figure 3d).

[12] The inferred subsidence helps define the tsunami sources in two ways. First, subsidence coincident with a sand deposit implicates a nearby Japanese earthquake, not a large storm or a tsunami from a distant source. Second, if at least partly tectonic, not just a result of shaking-induced compaction, coseismic subsidence can help constrain the fault-rupture model of the earthquake. As we show in the next section, the inferred coastal subsidence shows that a fault rupture on the subduction plate boundary was located directly offshore from sand deposits, as illustrated by the coastal subsidence that accompanied the 2011 earthquake (Figure 1b).

5. Modeling the Jogan Rupture

[13] We used tsunami simulation models, constrained in part by evidence for coseismic subsidence, to reproduce inundation by the Jogan tsunami of AD 869. Of the eight tsunami deposits identified in this study, we knew best the lateral and inland distribution of the AD 869 Jogan deposit and the position of its contemporaneous shoreline. To estimate parameters of the Jogan rupture, we computed tsunami inundation for 14 different fault models, including plate-boundary ruptures with various lengths and widths, and some with slip on outer-rise normal faults like an earthquake along Japan Trench in 1933. We then

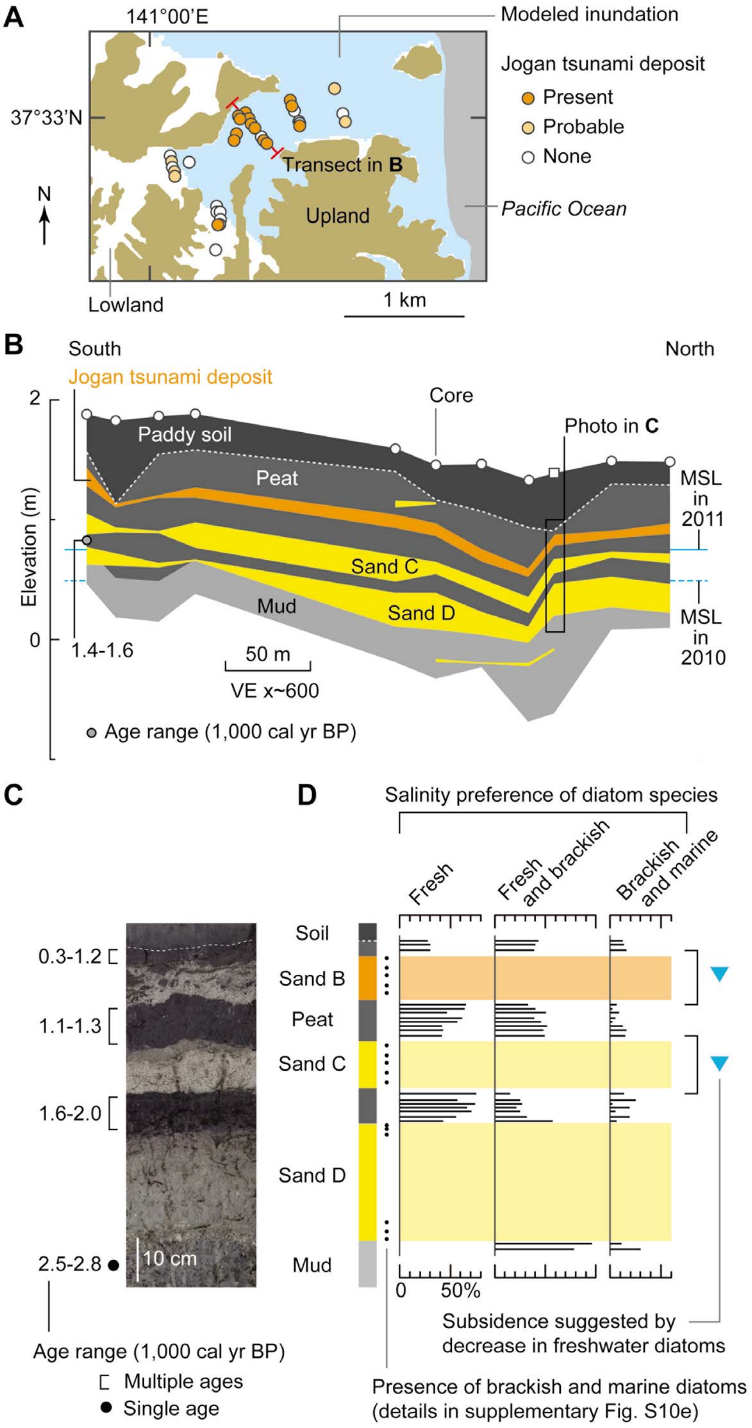

Figure 3. Evidence that coastal subsidence accompanied two of the unusually large tsunamis at Odaka. (a) Index map showing Odaka. (b) Cross section along line in Figure 3a. (c) Photograph of vertical slice. (d) Vertical changes in diatom assemblages in this slice.

compared our inundation results with the inundation areas inferred from mapping the distribution of the Jogan tsunami deposit in the Sendai plain and at Ishinomaki and Odaka (Figures S12–S14 in Text S1).

[14] To help define inundation limits for modeling, we first needed to estimate changes in the shoreline of the Sendai plain during the past few thousand years. The estimates are most confident for the Jogan shoreline because the AD 915 ash covered the lowland shortly after the tsunami. The ash tends to be preserved best in swales between the lowland's beach ridges. We thus drew the Jogan shoreline between the most seaward swale that contains both the ash and the Jogan tsunami deposit, sand B (swale X in Figure 2b), and the most landward swale containing only the ash (swale Y in Figure 2b). We then estimated the minimum inundation distance by mapping sand B to its landward limit. The

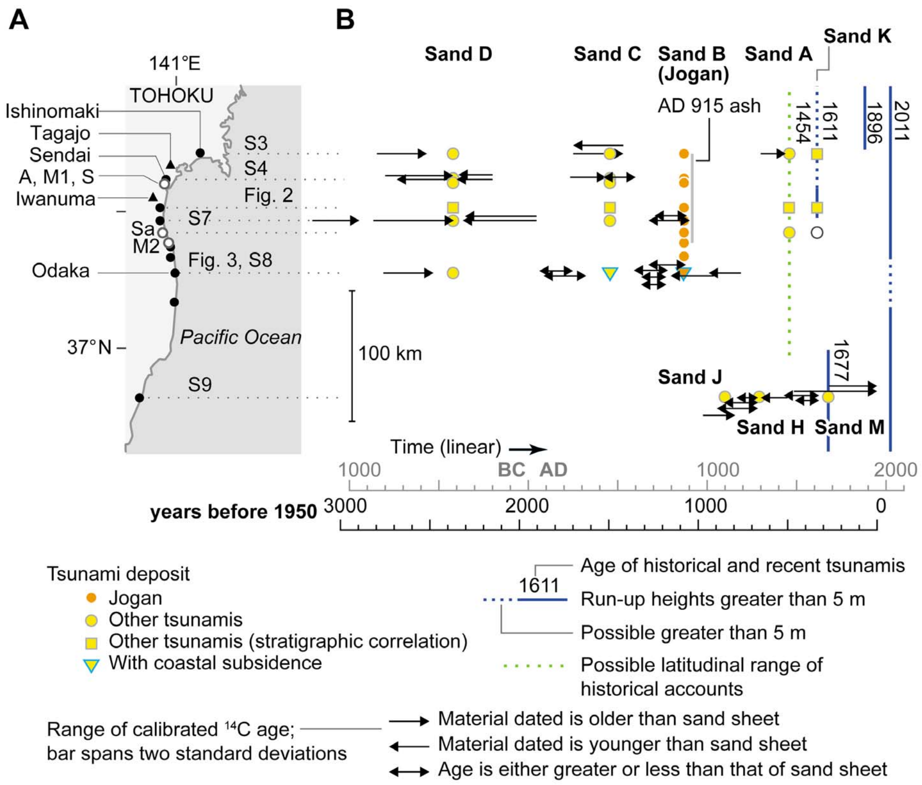

Figure 4. Age constraints on tsunami inundation and associated subsidence near Sendai. (a) Index map. Black and white circles show study sites of this paper and previous studies, respectively (A; *Abe et al.* [1990], M1; *Minoura and Nakaya* [1991], M2; *Minoura et al.* [2001], Sa; *Sawai et al.* [2008a], Su; *Sugawara et al.* [2011]). S, see auxiliary material. (b) Time-distance diagram. Data from written records is from *Imamura* [1934] and *Takeuchi et al.* [2007].

Jogan tsunami probably ran beyond this limit by analogy with the 2011 tsunami, which outran its sand deposit on the Sendai plain (Figure 2b and Table S6 in Text S1).

[15] We found that a plate-boundary rupture at least 100 km wide is needed to yield the long tsunami wavelength implied by the inland tsunami penetration minimally estimated from the distribution of sand B. The best model is a fault rupture 200 km long and 100 km wide, with an average slip of 7 m. The earthquake magnitude inferred from this model, Mw 8.4, thus incorporates assumptions about tsunami inundation that tend to minimize the estimated magnitude. Tsunamis produced by large slip on a narrow fault rupture near the trench axis have shorter wavelengths than our best model, and a correspondingly narrower zone of coastal inundation [*Satake et al.*, 2008]. A 100-km-wide rupture also produces a wider zone of subsidence that helps explain the coseismic subsidence at Odaka.

[16] All the models used estimates of fault-rupture length that are probably minimums for the Jogan earthquake. Few of the models extend more than 50 km south of Odaka. This southern limit sufficed to account for the tsunami inundation and coseismic subsidence that we inferred from stratigraphy and diatoms near Odaka (Figures 3 and 4), but we do not know how much farther south the inundation and subsidence extended. In the northward direction, the modeled ruptures extend to an area offshore of Ishinomaki. This latitude is close to the northern limit, as of 2010, of documented tsunami deposits that have been correlated with the Jogan tsunami on the basis of stratigraphic position beneath the AD 915 ash.

6. Discussion

[17] It is an open question whether Earth science could have forewarned of the enormity of the 2011 earthquake and tsunami. Even with the advantage of post-2011 hindsight, the magnitude of the Jogan earthquake remains unknown [*Sugawara et al.*, 2012]. To have shown that it attained magnitude 9, coastal geologists would have needed to correlate evidence for tsunami inundation and coseismic subsidence southward past Juo, northward along the Sanriku coast, or both. The search in both directions would have been impeded by the eastern limit of the AD 915 ash (Figure 1b). Moreover, as in our radiocarbon-aided correlations between the Sendai plain and Odaka, geologic dating rarely has the precision to distinguish between a single long fault rupture and a swift series of shorter ones [*Nelson et al.*, 1995]. It would also have been difficult to estimate, in the manner of Figure 2b, the inland limits of tsunamis on parts of the mountainous Sanriku coast where tsunamis of many sizes must have filled narrow valleys wall to wall. Finally, the huge slip near the Japan Trench axis, which contributed to the enormous size of the 2011 earthquake, cannot be resolved from tsunami inundation modeling. The 2011 tsunami inundation areas can be reproduced without such huge offshore fault slip [*Satake et al.*, 2012].

[18] Still, tsunami geology had the potential to provide estimates of the recurrence of past great Tohoku earthquakes and the minimum inland extent of their accompanying tsunamis [*Satake and Atwater*, 2007], with consideration of the uncertainties mentioned above. It might also have reduced the 2011 casualties through tsunami awareness. Our mapping and dating of tsunami deposits as described here (inundation maps in auxiliary material) could have focused emergency planning, improved evacuation maps, and informed public-awareness campaigns.

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