

## FORUM

## The Size of the 2011 Tohoku Earthquake Need Not Have Been a Surprise

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The devastating 11 March 2011 magnitude 9.1 earthquake along the Tohoku coast of northeastern Japan reminded seismologists again of the adage, “It ain’t what you don’t know that gets you into trouble—it’s what you know for sure that just ain’t so.”

Many seismologists—and hence disaster planners—thought that such huge earthquakes could not occur on this subduction zone [Chang, 2011; Geller, 2011]. Great earthquakes—magnitude 8—were expected and planned for. However, a giant magnitude 9 earthquake, which would release 30 times more energy, was not considered.

As illustrated in Figure 1a, a magnitude 9 earthquake involves more slip on a larger fault area, resulting in a larger tsunami because the maximum tsunami runup height is typically about twice the fault slip [Okal and Synolakis, 2004]. Thus, the March earthquake generated a huge tsunami that overtopped even 10-meter seawalls, causing enormous damage including crippling nuclear power plants.

With the wisdom of hindsight, it is worth considering why such a huge earthquake was not anticipated. The available history had no record of such earthquakes. This seemed plausible, given an analysis in 1980 of the largest known earthquakes at different subduction zones [Ruff and Kanamori, 1980]. These data (Figure 1b) showed a striking pattern: Magnitude 9 earthquakes occurred only where lithosphere younger than 80 million years old was subducting rapidly, faster than 50 millimeters per year. This result made intuitive sense, because both young age and speed could favor strong mechanical coupling at the interface between the two plates (Figure 1c). Because oceanic lithosphere cools as it moves away from a ridge and ages, young lithosphere is less dense and thus more buoyant. Similar, faster subducting lithosphere should increase friction at the interface. The stronger coupling was, in turn, assumed to give rise to larger earthquakes when the interface eventually slipped in a great thrust fault earthquake. By using the model, the maximum expected earthquake size could be predicted.

This model was widely accepted until the 26 December 2004 magnitude 9.3 Sumatra earthquake that generated the giant Indian Ocean tsunami. According to the model, this trench should have generated at most a magnitude 8 earthquake. However, reanalysis found a quite different picture [Stein and Okal, 2007]. The newer data set differed for several reasons. Better rates of plate motion were

available from new GPS data. Additional information on maximum earthquake sizes came from new observations, including paleoseismic estimates of the size of older earthquakes such as the 1700 C.E. event at the Cascadia subduction zone [Satake and Atwater, 2007]. Moreover, it was recognized that although the largest trench earthquakes are typically thrust fault events, this is not always the case. With the newer data the proposed correlation vanished, as the 2011 Tohoku earthquake subsequently confirmed (Figure 1d).

Thus, instead of only some subduction zones being able to generate magnitude 9s, it now looks like many or all can [McCaffrey, 2008].

The apparent pattern resulted from the fact that magnitude 9s are so rare, on average, fewer than one per decade [Stein and Wysession, 2003]. These are about 10 times rarer than magnitude 8s. Thus, the short seismological record (the seismometer was invented in the 1880s) misled seismologists into assuming that the largest earthquakes known on a particular subduction zone were the largest that would happen.

This does not work, because subduction zone earthquakes rupture portions of a trench called segments. This effect is shown in Figure 1e for a portion of the trench south of Tohoku. Sometimes one segment ruptures, and other times more than one does. The more segments that rupture, the bigger the earthquake.

Thus, before December 2004, seismologists knew only of earthquakes with magnitude

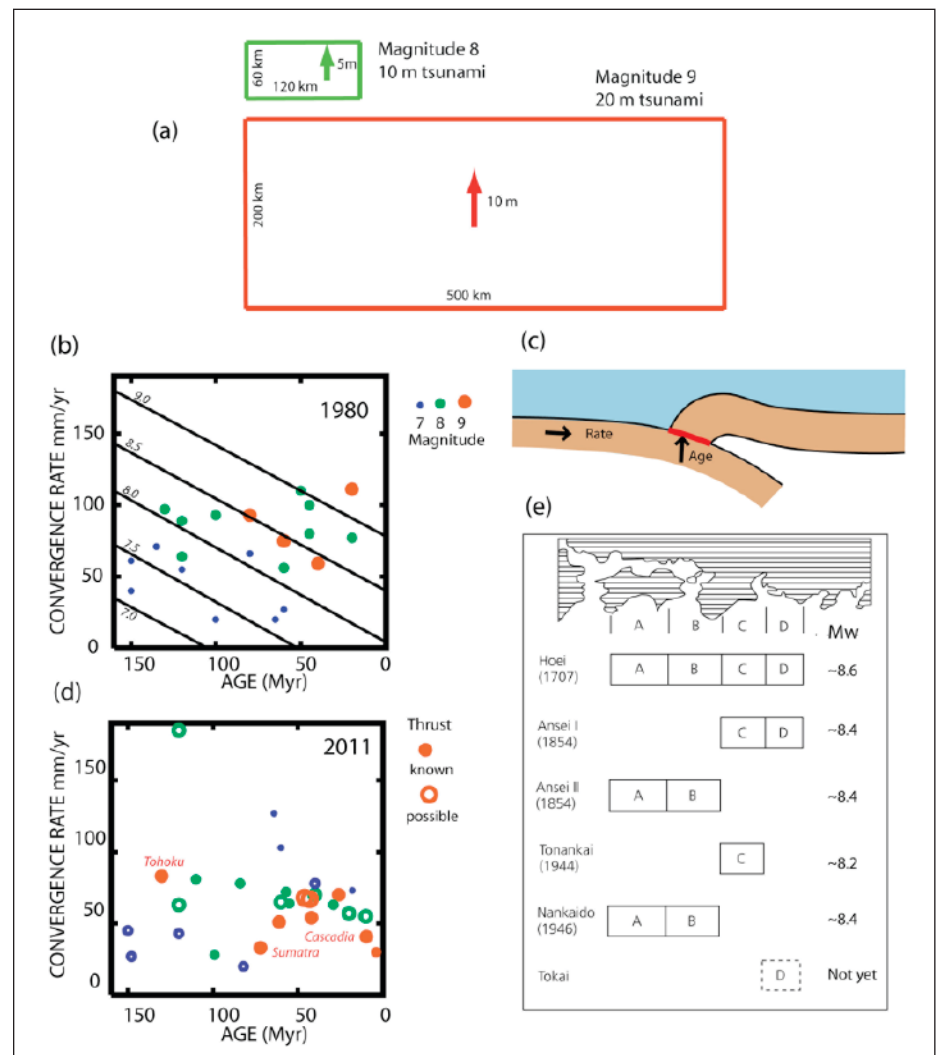


Fig. 1. (a) Illustration of possible relative fault dimensions, average fault slip, and average tsunami runup for magnitude 8 and 9 earthquakes. (b) Data available in 1980 showing the largest earthquake known at various subduction zones. Magnitude 9 earthquakes occurred only where young lithosphere subducts rapidly. Diagonal lines show predicted maximum earthquake magnitude [Ruff and Kanamori, 1980]. (c) Physical interpretation of this result in terms of strong mechanical coupling and thus large earthquakes at the trench interface. (d) Data available today, updated from Stein and Okal [2007] by including 2011 Tohoku earthquake. (e) Earthquake history for the Nankai trough area [Ando, 1975] illustrating how the rupturing of different segments causes earthquakes of different magnitudes.

less than 8 [Bilham *et al.*, 2005] due to short ruptures along the Sumatra trench, making the much bigger multisegment rupture a surprise. Plate motion calculations show that earthquakes like 2004's would happen about 500 years apart [Stein and Okal, 2005], so the short history available did not include them. Paleoseismic studies have since found deposits from a huge tsunami about 600 years ago [Monecke *et al.*, 2008].

Similar variability is found at other trenches [Satake and Atwater, 2007]. For example, the 1960 magnitude 9.5 Chilean earthquake, the largest ever seismologically recorded, was a multisegment rupture much bigger than typical on that trench. Similarly, it appears that the very large Cascadia subduction zone earthquake in 1700 C.E. was a multisegment rupture and that smaller ones happen between the big ones [Kelsey *et al.*, 2005].

A striking comparison with Tohoku is what happens on the Kurile trench just to the north. The largest seismologically recorded earthquakes there are magnitude 8, which only account for about one third of the plate motion. Hence it had been assumed that most of the subduction there occurred aseismically [Kanamori, 1977].

However, more recently discovered deposits from ancient tsunamis show that much larger earthquakes had happened in the past [Nanayama *et al.*, 2003], accounting for much of the subduction that had been thought to occur aseismically. Thus, it is not surprising that the same thing just happened off Tohoku.

Seismologists recognized that large subduction earthquakes had occurred off Tohoku and would occur again [Kanamori, 1977; Seno, 1979]. Increasing attention was also being paid to data showing that large tsunamis had struck the area in 869 [Mino-ura *et al.*, 2001], 1896, and 1933 C.E. GPS

data were showing that the plate interface was accumulating more strain than would be expected if a large fraction of the subduction occurred aseismically [Loveless and Meade, 2010]. However, the revised ideas about maximum earthquake and tsunami size were new enough that they weren't fully appreciated. Moreover, it takes a long time for new scientific results to be translated into actual hazard mitigation practices. Usually, this is not a problem, because huge earthquakes are very rare. In this case, the devastating earthquake came too soon.

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