Scientific brief on the March 2011 M9 Tohoku-oki Earthquake (Japan)

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1 What happened?

On 11th March 2011, a magnitude 9.0 earthquake (a one in 20 year event, globally) struck the east coast of Japan. The earthquake is the 4th largest measured since records began in the early 20th century. Earthquakes are caused by the movement of the Earth's tectonic plates; huge rigid areas of the Earth's surface that are 1000's of km wide. Although these plates are constantly moving on the surface of the Earth, their edges become stuck by friction as the plates try to push past one another, and pressure (stress) builds up along these plate boundaries. Eventually the friction is overcome and the ground on either side of the boundary suddenly moves, with the built-up energy released in seconds as an earthquake.

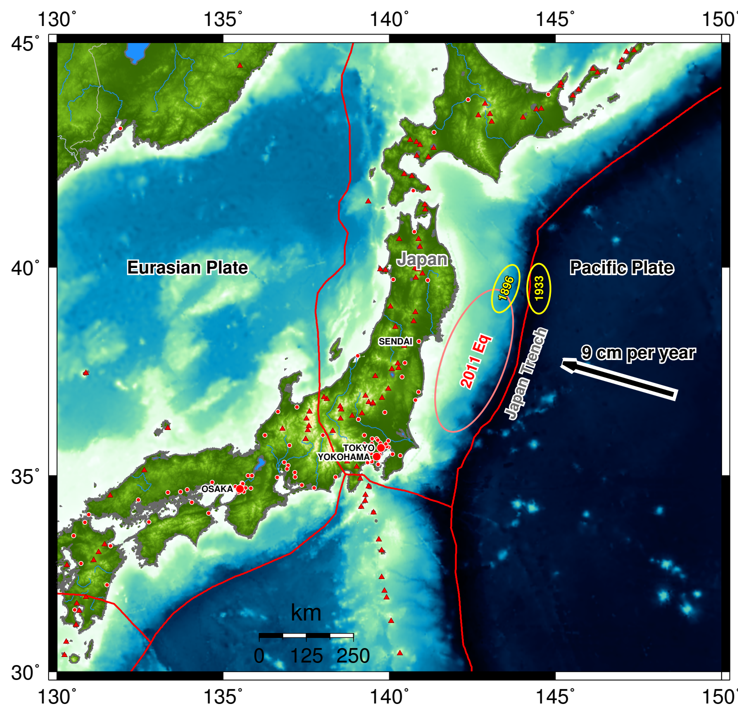

Figure 1: Map of Japan showing movement of the Pacific Plate towards the Eurasian Plate, and location of the 2011, 1933 and 1896 earthquakes (red and yellow ellipses). Plate boundaries are marked by red lines (Bird, 2003).

Off the east coast of Japan, the dense rock that makes up the Pacific Plate sinks below the Eurasian Plate (on which Japan sits, see Figure 1) in a process known as 'subduction' (Figure 2). As it does so, the Pacific Plate moves towards Japan at a rate of ~9 cm each year (DeMets et al., 2010). It is well-known that stress builds up along subduction plate boundaries such as this one, but the exact timing of when this stress will be released in earthquakes cannot be predicted.

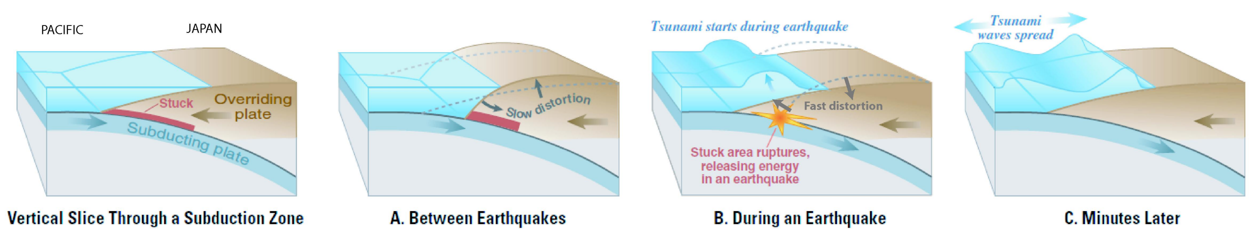

Figure 2: How subduction earthquakes occur and tsunamis are generated. Adapted from http://pubs.usgs.gov/circ/c1187/

The subduction plate boundary runs approximately parallel to Japan's coastline and the earthquake on 11th March was caused by the Pacific Plate suddenly sliding under Japan by tens of metres along a ∼300 km section of this boundary. The magnitude of an earthquake represents the energy that it releases. It is determined by the area of the plate boundary along which the two plates move in the earthquake, and by the amount that they move. The boundary between the two plates is deep underwater off the coast of Japan, so the sudden vertical motion of the seafloor displaces a huge mass of seawater, also in a line ∼300 km long. This caused a tsunami as the displaced water rushed both out into the Pacific and towards Japan, at speeds of around 500 km an hour. Out in the deep ocean, wave heights were only around 1 m higher than usual, but when the tsunami approached the shore where the water is shallower, the waves bunched together and increased in height, leading to the observed 10–15 m tsunami that struck the Japanese coast. The size of a tsunami is determined by the size of the preceding earthquake, and by how close the earthquake occurs to the Earth's surface. The 11th March earthquake had both a shallow depth and a large magnitude. In addition to lifting up a portion of the seafloor, the coast of the Sendai region was also dropped down by around half a metre by the earthquake.

#	Location	Mag.	Year
1.	Chile	M9.5	1960
2.	Alaska	M9.2	1964
3.	Sumatra	M9.1	2004
4.	Japan	M9.0	2011
5.	Kamchatka	M9.0	1952

Table 1: Largest 5 Earthquakes on record. Source USGS

Subduction regions such as the east coast of Japan generate the world's largest earthquakes. The 5 largest earthquakes on record (Table 1) have all been subduction earthquakes similar to the recent Japanese earthquake, and all generated damaging tsunamis. Big earthquakes with magnitudes of 8 or more are necessary to relieve the stress that builds up during the decades in between earthquakes. As the earthquake magnitude scale is not linear (i.e. a magnitude 9 earthquake releases 32 times more energy than a magnitude 8, and 1000 times more energy than a magnitude 7) small earthquakes are essentially unimportant in terms of relieving stress build-up, even though there are many more small earthquakes. There have been many aftershocks following the main shock, and they will continue for some time, generally decreasing in frequency and magnitude. These aftershocks are unlikely to be large enough to generate tsunamis, but may cause damage to buildings pre-weakened by the main earthquake.

2 Recent earthquake history

Japan has a long history of large and damaging earthquakes, many of which were subduction earthquakes, and many of which were associated with tsunamis. There are two particularly important earthquakes in the historical record that occurred in the same region as the recent earthquake, one in 1896 and one in 1933. Both of these earthquakes, despite being smaller in magnitude than the recent earthquake, caused tsunamis of at least 10 m that resulted in significant loss of life (USGS website). However, the 1933 earthquake was a different type of earthquake (Kanamori, 1971) that resulted from the bending of the Pacific Plate as it is dragged under Japan. This means that the 1896 earthquake was the last equivalent big earthquake to break the same region. This suggests that we might expect similar scale earthquakes along this section of the plate boundary every ∼100 years.

Year	Mag.	Deaths	Notes
1891	M8.0	7,300	
1896	M8.5	27,000	Tsunami in Sendai region
1923	M7.9	143,000	Great Kanto Eq
1927	M7.6	3,000	
1933	M8.4	3,000	Tsunami in Sendai region
1943	M7.4	1,200	
1944	M8.1	1,200	
1945	M7.1	2,000	
1946	M8.1	1,300	
1948	M7.3	3,800	
1995	M6.9	5,500	Kobe Eq

Table 2: Post-1890 Japanese earthquakes with greater than 1000 fatalities. Source USGS

3 Future concerns

However, even if the recent magnitude 9 earthquake relieved all the stress that had been building up on the Sendai portion of the plate boundary, the regions immediately to the north and south have not been relieved. And in addition, simple calculations show that when an earthquake happens, it increases the likelihood of further earthquakes in the neighbouring sections (i.e. in this case, to the north and south, see right panel in Figure 3) (Lin & Stein, 2004). Unlike the simplified picture we drew earlier of the entire plate boundary sticking and building up stress, in reality friction varies across the plate boundary, allowing some patches to move more freely than others. In the left panel of Figure 3, the red areas are those that are thought to be completely stuck and so are capable of generating earthquakes, whilst the blue areas are those that are thought to have low friction, and so move freely and are unlikely to generate big earthquakes. The recent earthquake broke the middle red patch (approximately shown by black contour lines), but not the northern or southern red patches.

So whilst earthquake prediction is currently impossible, we cannot rule out the possibility that the plate boundary is still capable of producing a magnitude ∼8 earthquake on the section closest to Tokyo in the near future. If such an earthquake were to occur, a tsunami might or might not be generated, depending on the size and depth of the earthquake. It is worth considering that there is a precedent to this scenario. Sumatra is essentially in an identical tectonic setting to Japan, and the 2004 M 9.2 earthquake (which generated the Indian Ocean tsunami) was followed by a M 8.6 earthquake in 2005 and by two large earthquakes, a M 8.4 and a M 7.9 in 2007 (Konca et al., 2008). Therefore, there is still concern that Japan could be struck again by a large earthquake (and potentially also a tsunami) in the months to decades ahead.

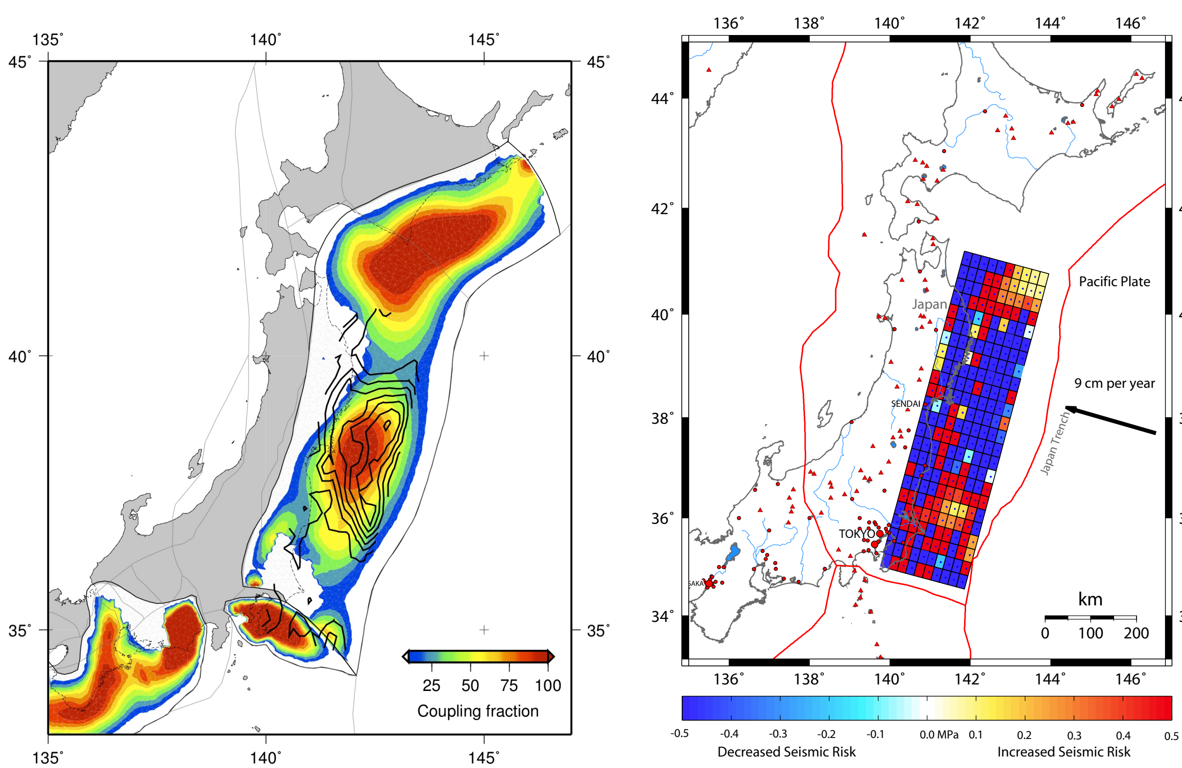

Figure 3: (*left*) Map showing regions of plate boundary stuck by friction (Loveless & Meade (2010), http://supersites.earthobservations.org/sendai.php). Red areas are places where the Pacific Plate gets stuck trying to move westwards under the Eurasian Plate at 9 cm per year. These areas can generate large earthquakes. Blue areas are patches not stuck and don't generate large earthquakes. The black contour lines shows the location of the recent earthquake rupture from Gavin Hayes of the USGS. (*right*) Map showing the plate boundary regions that now have a reduced seismic hazard (blue) and the regions that now have an increased hazard (red). Note in particular the large portion of red nearest to Tokyo.

References

Bird, P., 2003. An updated digital model of plate boundaries, *Geochemistry, Geophysics, and Geosystems*, **4**(3).

DeMets, C., Gordon, R. G., & Argus, D. F., 2010. Geologically current plate motions, *Geophysical Journal International*, **181**, 1–80.

Kanamori, H., 1971. Seismological evidence for a lithospheric normal faulting – the Sanriku earthquake of 1933, *Physics of the Earth and Planetary Interiors*, **4**(4), 289 – 300.

Konca, A. O., Avouac, J., Sladen, A., Meltzner, A. J., Sieh, K., Fang, P., Li, Z., Galetzka, J., Genrich, J., Chlieh, M., Natawidjaja, D. H., Bock, Y., Fielding, E. J., Ji, C., & Helmberger, D. V., 2008. Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence, *Nature*, **456**, 631–635.

Lin, J. & Stein, R. S., 2004. Stress triggering in thrust and subduction earthquakes and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults, *Journal of Geophysical Research*, **109**.

Loveless, J. P. & Meade, B. J., 2010. Geodetic imaging of plate motions, slip rates, and partitioning of deformation in Japan, *Journal of Geophysical Research*, **115**.