Seismotectonics of Japan's Subduction Zones

Danielle Verdugo, Tania Gonzalez and Eldon Gath, Earth Consultants International

Tectonic Overview of Japan

Japan lies on one of the most complex and better-studied tectonic regions in the world, defined by the interaction of four tectonic plates that come together under or near the Japanese archipelago (Figure 1). Honshu, Japan's main island, resides on two different plates: its southwestern half rides on the eastern edge of the Eurasian Plate, whereas its northeastern half is on the southern tip of the Okhotsk Plate. This plate boundary is defined by the north-northwest-trending Itoigawa-Shizuoka Tectonic Line (ISTL), marked conspicuously by Mount Fuji just southwest of Tokyo (Taira, 2001).

Southwest of the ISTL, Honshu and the islands of Shikoku and Kyushu ride the Eurasian plate while two plates subduct beneath their shores. The Philippine Sea Plate subducts shallowly beneath the Eurasian Plate along the Nankai Trough at a rate of 4 cm/yr, and this is responsible for the majority of the seismogenic and tsunamogenic hazards to southern Japan. Farther east, in the Pacific Ocean, the Pacific Plate subducts steeply beneath the Philippine Sea Plate along the Izu-Bonin Trench at a rate of 8 cm/yr, extending to depths between 250–600 km below sea level directly under southern Honshu and the island of Shikoku.

Northeast of the ISTL, the Okhotsk Plate, carrying the northeastern half of Honshu and the island of Hokkaido, is being squeezed between the Eurasian Plate to the west, and the Pacific Plate to the east. The Pacific Plate is subducting beneath the Okhotsk Plate at a rate of over 8 cm/yr along the Japan Trench east of and beneath Honshu, and along the Kuril Trench east of and beneath Hokkaido. The 11 March 2011 M_w 9.0 Tohoku-oki earthquake occurred along the Japan Trench when an over 300 km-long (along-strike) by 150 km-wide (down-dip) patch (red shaded area in Figure 1) of the Pacific Plate thrust 30-40 m under the Okhotsk Plate.

All four subduction zones defined by the Nankai Trough, and the Izu-Bonin, Kuril, and Northeast Japan trenches, have produced many historical, large plate boundary earthquakes off Japan's east coast. Aside from subduction zone earthquakes, Japan experiences other types of earthquakes including, but not limited to, intra- and inter-plate earthquakes, and shallow crustal earthquakes (Figure 2). This article focuses mainly on inter-plate (plate boundary) earthquakes occurring at the subduction zones listed above.

First we will focus on southern Japan, where the historical earthquake record along the Nankai subduction zone is longest of its kind on Earth. Next, we head out to sea in the east to the Izu-Bonin subduction zone to explore how earthquakes on the Pacific Plate also affect southern Honshu. Then we move north to the Kuril subduction zone, where the Pacific Plate also subducts offshore Hokkaido at the Kuril subduction zone. This should complete our understanding of the surrounding seismotectonic framework before focusing on the Japan subduction zone and the historical earthquakes preceding March's Tohoku-oki earthquake.

Nankai Subduction Zone

The earthquake history of the Nankai subduction zone is relatively well known because of Japan's extensive 13-centuries-long historical record. The distribution of these earthquakes permits the division of the Nankai subduction zone into five segments. These fore-arc segments usually rupture individually, in pairs, or triplets, with complete rupture of the entire subduction zone thought to have occurred in the 1498 Meio, 1605 Keicho, and 1707 Hoei earthquakes (Figures 1 and 2).

The earliest historical earthquakes struck in AD 684 and 887, two other earthquakes occurred in AD 1096 and 1099, and at least one earthquake occurred in AD 1361. Combined, these events resolve into a repeat time of, at a minimum, two centuries. However, the historical record may be incomplete, especially during the earlier period when there was disunity in Japan during "the warring states period." In fact, archeological evidence suggests additional earthquakes between AD 887 and 1099, and AD 1099 and 1361 (Sangawa, 1997). Tsunami deposits described by Takada et al. (2002) document six events prior to the tsunami deposit marking the 1605 Keicho earthquake, indicating a recurrence interval for Nankai subduction-zone earthquakes on the order of 100–120 years. This repeat time, roughly 100 years, is consistent with the historical, better-documented record for the past four centuries that includes earthquakes in 1498, 1605, 1707, 1854, 1944 and 1946 (Sykes and Menke, 2006). If this recurrence interval holds true and Nankai subduction zone earthquakes keep on schedule, the next earthquake is due in the mid-21st century, within the next 40–50 years.

Interestingly, the most recent two event sequences fully ruptured all but the easternmost Tokai segment of the Nankai Trough in the two Ansei earthquakes of 1854 (occurring 32 hours apart) and the Showa earthquakes of 1944 and 1946, with magnitudes around M_w 8.1 (Yeats and Sieh, 1997). The lack of rupture to the Tokai segment has given rise to the controversial Tokai Gap Hypothesis—the expected rupture of the Tokai segment (Figure 1) with some of the adjoining segments to the west. And as such, the Japanese have instrumented and prepared for the upcoming Tokai event ala the expected Parkfield rupture on the San Andreas fault.

Izu-Bonin Subduction Zone

Southeast of Tokyo, the Sagami Trough separates the northeastern Japan subduction zone from the Izu-Bonin subduction zone (Figure 1). The Japan subduction zone typically generates larger earthquakes than the Izu-Bonin zone. The Wadati-Benioff (W-B) zone, a zone of seismicity that represents the inter-plate interface between two tectonic plates at a subduction zone, dips more steeply in the Izu-Bonin subduction zone than it does in the Northeast Japan subduction zone. As a result, the convergence rate at the Izu-Bonin Trench is slower and the plate interface is more poorly coupled than that at the Northeast Japan Trench (Yeats and Sieh, 1997).

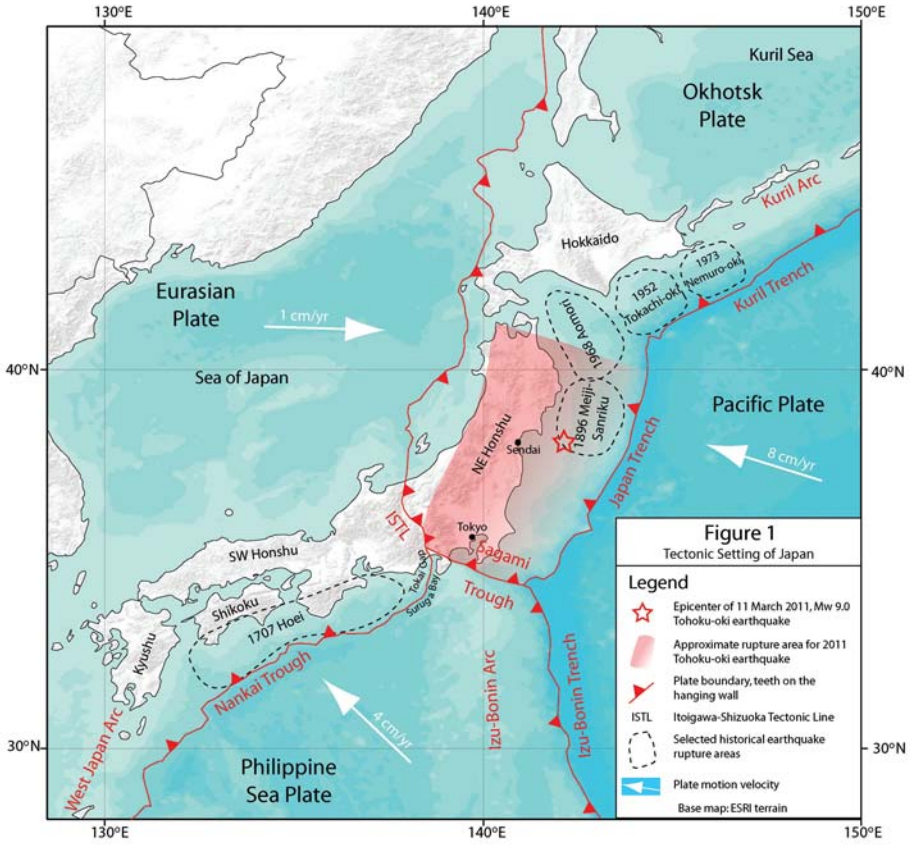

Figure 1 – Japan Tectonic Setting

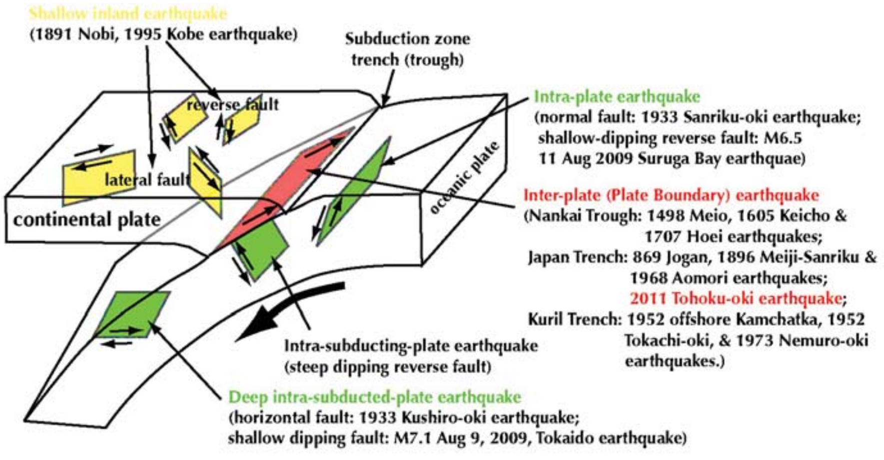

Figure 2. Different types of earthquakes that occur in Japan with recent and historical examples. [Redrawn and modified from HERP Bulletin, 1999.]

Figure 2 – Japan EQ types

A worldwide study of subduction-zone earthquakes by Ruff and Kanamori (1980), and Heaton and Kanamori (1984), showed that the maximum magnitude earthquake expected on a subducting plate boundary is dependent on the age of the plate being subducted and the rate at which the plates are converging on each other. The Pacific Plate is 150 million years old at the Izu-Bonin Trench and is converging on the Philippine Sea Plate at a rate of 6 cm/yr, leading to an estimate of maximum moment magnitude (M_w) of 7.2.

In contrast, the Philippine Sea Plate is 20 million years old at the Nankai Trough and is converging toward the west-northwest on the Japanese Islands at a rate of 4 cm/yr, resulting in an M_w 8.6 maximum magnitude earthquake. Although both the Pacific and Philippine Sea plates directly underlie southern Honshu, the main earthquake hazard to Honshu is from the Philippine Sea Plate. Two reasons account for this fact. First, the top of the Philippine Sea Plate is only 15 km beneath southwestern Honshu, whereas the top of the Pacific Plate is 250 km deep. An earthquake at the boundary between the Philippine Sea Plate and the overlying continental crust would not attenuate over the short distance between the mainshock and the surface, whereas strong ground motions from an earthquake at the top of the Pacific Plate would lose most of their energy in the 250 km they would have to travel to reach the surface. This is illustrated by the August 2009, deep-focus Tokaido earthquake (Figure 2), which had a magnitude only slightly less than that of the maximum estimated plate boundary earthquake, but which, due to attenuation, was not highly destructive. Second, the maximum size of a Nankai subduction-zone earthquake is M_w 8.6, larger than the estimated M_w 7.2 on an inter-plate (or plate boundary) earthquake occurring at the top of the Pacific Plate and base of the Philippine Sea Plate. The reason for this difference is that young oceanic crust at the Nankai Trench is much hotter than oceanic crust at the Izu-Bonin Trench, making the young crust much more buoyant, and therefore more strongly coupled to the overlying Eurasian plate.

Kuril Subduction Zone

The Kuril subduction zone stretches from offshore Hokkaido to the Russian Kamchatka peninsula and has produced one of the largest earthquakes since 1900, the 1952 M_w 9.0 earthquake off Kamchatka (McCann et al., 1979 in Yeats and Sieh, 1997). The southernmost section of the Kuril Trench has two segments, Tokachi-oki and Nemuro-oki, both off Hokkaido's eastern shore. Tokachi-oki has experienced three earthquakes in the last 170 years, in 1843, 1952 and 2003, with magnitudes ranging from 8.0 to 8.2 (Figure 1). Farther north, the Nemuro-oki segment has ruptured in two earthquakes, 1894 and 1973, with magnitudes of 8.2 and 7.8 respectively (Figure 1, Nanayama et al., 2003). Both segments have widely variable recurrence intervals in the order of 50–100 years. While these more frequent, single-segment ruptures are considered the typical type along the southern Kuril trench, longer geologic records garnered from tsunami-deposit studies on Hokkaido indicate that events larger than the historically recorded earthquakes occurred between about 2000 and 7000 years ago. These larger events appear to have a recurrence interval of about 500 years, and the most recent event occurred 350 years ago (Nanayama et al., 2003). The distribution of tsunami deposits representing the larger subduction zone events would likely require the simultaneous rupture of both the Tokachi-oki and Nemuro-oki segments (Okumura, 2011) in an event similar in size to the March 2011 earthquake to the south.

Japan Subduction Zone

Prior to the Tohoku-oki earthquake in March, the Japan subduction zone was thought to generate mostly great interplate earthquakes like the M_w 8.2 Aomori earthquake of 16 May 1968 (Figures 1 and 2), and normal-fault earthquakes like the M_w 8.3 Sanriku-oki of 3 March 1933 on the outer rise that generated a large tsunami on the coast of northeast Japan (Figure 2). The 1933 event was the largest earthquake in the region prior to the 11 March 2011 event and an intra-plate earthquake, presumably a result of bending moment on the Pacific Plate that is under horizontal compression at the subduction zone. This makes it an object lesson that the largest earthquake at a subduction zone may not be at the plate boundary.

Another inter-plate subduction zone event on the Japan Trench includes the M_w 7.6 Meiji-Sanriku earthquake of 1896 (Figure 1) that created a 38-m tsunami and killed 27,000 (USGS summary). While these events were large and created tsunamis, they aren't large enough to be considered analogs to the March 2011 earthquake. In 2001, Minoura and others reported finding evidence that the AD 869 Jogan earthquake deposited tsunami sands 4 km *or more* inland on the Sendai plain—2 km farther inland than any tsunami since that time. According to their search in historical records, the tsunami felled structures in an 8th to 9th century castle town and killed 1000 people. The 869 event was likely the 2011 analogue, but unfortunately for the victims of the 2011 tsunami, its impacts had been forgotten.

Considering how complex the seismic hazard is in Japan, it is remarkably well understood both spatially and temporally, and Japanese earthquake preparedness is the best in the world. Nevertheless, the population and infrastructure density of Japan means that damage will still occur, injuries and fatalities will be large, and emergency response will be stretched when a large earthquake occurs. In the case of the 2011 Tohoku-oki event, the magnitude of the earthquake and the height of the resultant tsunami exceeded structural design and community protection thresholds. If the geological findings of Minoura and others had been understood and acted upon in time, perhaps the damage and casualties could have been reduced. The past is the key to the present and the future, and geology is how we read that past and use those findings to predict the future.

References

Heaton, T.H., and Kanamori, H., 1984, Seismic potential associated with subduction in the northwestern United States: *Seismological Society of America Bulletin 74*:933–941.

McCann, W.R., Nishenko, S.P., Sykes, L.R. and Krause, J., 1979, Seismic gaps and plate tectonics: Seismic potential for major boundaries: *Pure and Applied Geophysics*, Vol. 117, pp. 1090–1147.

Minoura, K., Imamura, F., Sugawara, D., Kono, Y., and Iwashita, T., 2001, The 869 Jogan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan: *Journal of Natural Disaster Science*, Vol. 23, No. 2, pp. 83–88.

Nanayama, F., Satake, K., Furukawa, R., Shimokawa, K., Atwater, B., Shigeno, K. and Tamaki, S., 2003, Unusually large earthquakes inferred from tsunami deposits along the Kuril trench: *Nature*, Vol. 424, No. 6949, pp. 660–663.

Okumura, K., 2011, Interplate megathrust earthquakes and tsunamis along the Japan Trench offshore Northeast Japan, accessed online: http://www.igu-online.org/site/?p=806

Ruff, L., and Kanamori, H., 1980, Seismicity and the subduction process: *Physics of the Earth and Planetary Interiors*, Vol. 23, pp. 240–252.

Sangawa, A., 1997, Seismological Archeology: History of Earthquakes Narrated by Archeological Sites: Dohosha, Tokyo, Japan.

Sykes, L.R., and Menke, W., 2006, Repeat times of large earthquakes: Implications for earthquake mechanisms and long-term prediction: Seismological Society of America Bulletin, Vol. 96, pp. 1569-1596.

Taira, A., 2001, Tectonic Evolution of the Japanese Island Arc System: Annual Reviews in Earth and Planetary Sciences, Vol. 2, pp. 109–134.

Takada, K., Satake, K., Sangawa, A., Shimokawa, K., Kumagai, H., Goto, K. and Haraguchi, T., 2002, Survey of tsunami deposits at an archaeological site along the eastern Nankai trough: Chikyu Monthly, 24, 736–742 (in Japanese).

USGS summary, 2011, March 11, 2011 Mw 9.0 Tohoku-oki earthquake, accessed online: http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/usc0001xgp.php

AEG NEWS

ASSOCIATION OF ENVIRONMENTAL & ENGINEERING GEOLOGISTS

Connecting Professionals, Practice and the Public

June 2011

Vol. 54, No. 2