**Japan’s Earthquakes and Tectonic Setting**

And a Tale of Two Earthquakes

80% of earthquakes worldwide occur around the circum-Pacific region chiefly along the subduction-zone boundaries, known as the “Pacific Ring of Fire”, so named because of the more than 400 active volcanoes that occur there. The earthquake and volcano belt sweeps through Japan where about 20% of worldwide measured earthquakes occur. There are more than 100,000 earthquakes recorded in Japan every year. Of those about 1,500 are strong enough for people to notice. By examining the pattern of seismic activity of all earthquakes greater than magnitude 4 since 2011, we see the expected patterns of shallow to deep earthquakes along the subduction zones.

Over 100 major earthquakes of M7 or larger have occurred in the past century~~.~~ Japan also has over 100 active volcanoes. along a volcanic arc that lies parallel to oceanic trenches, both distinctive features of convergent margins.

Earthquakes, volcanoes, and trenches all result from Japan being wedged among four major tectonic plates. The Pacific Plate subducts beneath the Okhotsk Plate at the Japan Trench. The rate of convergence is 8.3 cm/yr at the location shown. The Philippine Sea Plate subducts beneath central and southwest Japan at the Sagami Trough, the Nankai Trough, and the Ryukyu Trench. At the location shown, subduction is somewhat oblique at 4.5 cm/yr. A complex structure accommodates slow east-west convergence between the Okhotsk and Eurasian plates.

Northwest-directed forces due to subduction, plus East-West-oriented compression between the Eurasian and Okhokst plates. complicate the region.”

Lets go back millions of years and exaggerate the tectonics. Now we can see Oblique subduction pushing a forearc crustal block to the west at a rate of about one half cm/yr). A right-lateral strike-slip fault, called the Median Tectonic Line, accommodates most of that motion within the Eurasian Plate.

In this region that includes Kyoto, the Imperial Capital of Japan for more than one thousand years, the earthquake history since the mid-1800s demonstrates that major crustal-fault earthquakes in this region occur about every 15 years. The most recent example is The Great Hanshin earthquake of 1995, commonly referred to as the Kobe earthquake.”

Before dawn on January 17, 1995, a right-lateral strike-slip fault ruptured 20 km to the southwest and 30 km to the northeast from a hypocenter at about 15 km depth. Fault displacement was 3 meters at the hypocenter and 1 meter at 10 km depth beneath Kobe, a port city with population of 1.5 million.

Although this magnitude 6.9 earthquake released less than 1/1000 th of the energy released during the **2011** Tohoku-oki subduction zone earthquake, Severe ground shaking and resulting damage was concentrated at locations underlain by weak, water-saturated sediment and artificial Fill along and within Osaka Bay.

Traditional style houses with a heavy clay-tile roof were vulnerable to collapse while failures of individual stories or the entire structure affected some multistory buildings. Hundreds of fires ignited and firefighting efforts were hampered by failures of the water supply and transportation system. Over 100,000 buildings were destroyed leaving 300,000 homeless. Sections of the elevated Hanshin Expressway that opened in 1962 collapsed. Most structures completed *after* 1981 when building codes were updated, survived with minimal damage. This earthquake forced a reassessment for tall buildings and transportation infrastructure.

Now let’s look at cross sections of the subduction zones. In northernmost Honshu, the oceanic Pacific Plate dives beneath the continental Okhotsk Plate. Here we see how earthquakes outline the subduction geometry. To 70 km depth, thrust-faulting earthquakes are concentrated at the contact between the plates where megathrust events, often associated with tsunamis, are generated. Deformation of the overriding plate generates shallow *intra*-plate earthquakes. Below 70 km depth, earthquakes occur only within the subducting plate. Earthquakes in this subduction zone reach extreme depths of over 500+ km because the Pacific Plate is ~150 Ma old and therefore very cold when it starts to subduct. Plus, the rate of subduction is fairly rapid at over 8 cm/yr so the oceanic plate is still cool and brittle at depth.

A cross section through central Honshu shows a slightly steeper subduction angle, thus the volcanoes are closer to the trench. At the Ryukyu Trench, the angle of subduction is similar to Central Honshu , but the subduction rate is slower, and the max depth of earthquakes is only 300 km.

“By the late 1800s, written accounts and the beginnings of seismology provide reasonably accurate information on the location and size of earthquakes off the northeast coast of Honshu.  Running at five years per second, this animation shows the earthquake history of magnitude 7.4 or larger earthquakes on the subduction zone boundary between the Pacific and Okhotsk plates from 1896 through 2010.  This history led to the impression that earthquakes on this plate boundary do not exceed magnitude 8.2.  That maximum earthquake magnitude and associated tsunami size became the basis for emergency management, including coastal tsunami defenses.”

Some geoscientists observed that the displacement between the Pacific and Okhotsk plates during earthquakes of the past few centuries was much less than the relative plate motion.  They were concerned the subduction zone might be storing elastic energy over many centuries that could be released in a massive earthquake.

On March 11 2011, the Tohoku-oki magnitude 9 earthquake ruptured a 500-kilometer-long by 200-kilometer-wide area of the plate boundary over an interval of three minutes. Extreme ground shaking affected coastal towns of northeastern Honshu and strong shaking lasted for 6 minutes in Tokyo.

Superior construction practices and earthquake preparedness impressively mitigated damage from ground shaking during this earthquake confirming that Japanese cities often shake but they rarely topple. Unfortunately, the tsunami generated by the Tohoku-oki earthquake reached greater heights and much farther inland than had been anticipated for tsunamis in this area.

To understand the 2011 tsunami, let’s view the earthquake rupture process in cross section. Rupture initiated at the hypocenter, 24 km beneath the seafloor, then propagated both up-dip to the east and down-dip to the west. Maximum fault displacement reached 40 meters at a location 50 km from the Japan trench then decreased to 20 m at the trench. These are the largest fault displacements documented for any earthquake in history. Elastic rebound during the earthquake caused stations along the coast nearest the epicenter to jump east by as much as 4.4 meters or 14.5 feet. Seafloor uplift reached 7 meters above the zone of maximum fault displacement while the seafloor dropped by 2 meters between the epicenter and the coast. Most of the coastal area subsided during the earthquake. That vertical displacement of the ocean floor produced the tsunami that rushed onshore within 20 minutes of the earthquake. In coastal areas where seafloor bathymetry and onshore topography focused wave energy, the tsunami reached elevations of 40 meters, or 130 feet, above sea level. Although 96% of citizens successfully evacuated the tsunami inundation zone, nearly 20,000 lives were lost in this, the most costly natural disaster in Japan’s history.

Centuries of written accounts from this region reported earthquakes and tsunamis, but gave only vague hints about past events as large as the 2011 event.  However, a decade before, geoscientists searching sedimentary layers upslope of the coast reported tsunami geology evidence for a similar earthquake in 869 A.D.. Unfortunately, debate about this tsunami geology was still ongoing when the 2011 earthquake and tsunami struck. This painful lesson taught us that the subduction zone between the Pacific and Okhotsk plates, and probably others worldwide, can store elastic energy over 1000-year intervals then release that energy in just a few minutes during massive earthquakes. As towns in northeast Honshu devastated by the 2011 tsunami are being rebuilt, changes in coastal land-use practices are being implemented to decrease the number of people living and working in vulnerable near-shore areas. In this and many other ways, Japan continues to advance earthquake and tsunami preparedness.