Superquakes and Supercycles: Implications for the GEM Seismic Hazard Model

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The recent Mw=9 superquake off Tohoku Japan, and the 2004 Sumatra-Andaman earthquake have humbled many in earthquake research. Neither region was thought capable of earthquakes of magnitudes exceeding Mw~8.4. Appealing proposed relationships such as that between plate age and convergence rate and plate coupling based on anchored slabs, at least have many exceptions, and may not be valid. Both earthquakes occurred where the plate age was quite old, ~ 50-130 my. The role of thick sediments on the downgoing plate has also been considered a contributing factor, and relates well to many recent great earthquakes. The 2011 Tohoku event is also contrary to this hypothesis. Clearly much remains to be learned about these great events, so much so that most subduction plate boundaries should be considered suspect, and perhaps other fault systems as well. The issue is clearly hampered by short historical, and even shorter instrumental records. In NE Japan, the Quaternary rate of horizontal shortening is estimated at 5-7 mm/yr. This indicates that only a fraction (< 10%) of plate convergence is accommodated in the Japan arc as inelastic, permanent deformation. The uplift rate averaged over the Northeast Japan arc in late Quaternary time is 0.22-0.36 mm/yr. The rate of crustal shortening determined from the regional uplift data (assuming isostatic balance) is < 6-8 mm/yr, similar to the rate deduced from active faults and folds. Geodetically observed, short-term deformation of the Northeast Japan arc is, however, significantly different from long-term deformation. Triangulation, trilateration and GPS observations during the last ~100 years revealed that the Japan arc has contracted in an east-west direction at a rate as high as several tens of mm/yr. This rate is nearly one order of magnitude greater than geologically observed shortening rates, and is comparable to the rate of plate convergence at the Japan Trench. Along the Pacific coast, abnormally high rates (several to 10 mm/yr.) of subsidence have been observed by tide level observations during the last ~80 years. These data strongly suggested that the strain accumulated must be released in earthquakes stronger than those in the historical record (Ikeda, 2003). The Jogan tsunami of 869 is the only event in the historical record that could have been equivalent to the March 2011 earthquake, and paleotsunami deposits indicate that the Jogan event had several predecessors at ~ 1000 year intervals (Minoura et al., 2001).

In Cascadia, paleoseismology based on turbidites offshore has established a very long earthquake record that includes segmented ruptures, a heterogeneous time series with clusters of events and gaps of as long as 1000 years, and also several outsized events. Goldfinger et al. (2011) compared the mass of correlated turbidite deposits along strike, and found strong correlation between disparate sites. From this they conclude the earthquake magnitude and turbidite mass are related for many of the Cascadia events. There are in the record several events that are considerably larger in terms of the turbidite deposits. The obviously larger events are the 11th and 16th events back in time, known as T11 and T16 that took place 5960 +/- 140 and 8810 +/- 160 years ago. These events are consistently larger at core sites along the length of Cascadia (mass correlation of 0.57-0.72, coarse fraction pulse correlation 0.85-0.95. These likely larger events are approximately two to five times the average turbidite mass for Holocene events. Goldfinger et al. estimate Mw for T11 and T16 as 9.13 and 9.1 respectively using parameters calibrated to the AD 1700 event, and setting that event equal to 9.0 based on Satake et al.

With the unique long term record in Cascadia, we suggest that it is possible to explore the long term cycling of kinetic energy. We scale turbidite mass (energy release) to balance plate convergence (energy gain) to generate a 10ka energy time series for Cascadia. Although the scaling is undoubtedly crude and includes many unknowns, a relatively robust pattern is observed, and includes long term increases and declines in stored "energy state" which we term "supercycles". When the energy state reaches a relative low point, there is a tendency for a long temporal gap in earthquakes, thus the supercycles are related to temporal clustering as well. What is suggested by this pattern is that some events release less (slip deficit) while others release more (slip excess) energy than available from plate convergence alone. The difference, deficit or excess, appears to allow for long term growth and decay in the state of potential energy available for earthquakes.

A related example is the Haiyuan fault in Gansu Province, China, the source of an earthquake in 1920 with a rupture length of 237 km and a loss of life exceeding 220,000 people. An extensive paleoseismic trenching program along the entire length of the fault divided the 1920 rupture into three segments and dated surface-rupturing earthquakes in each segment over the past 6000 yrs. Some earthquakes ruptured one segment, and some ruptured two, but only one pre-historic earthquake (6100-6200 yrs. BP) ruptured all three segments and was a duplicate of the 1920 event (Ran et al. 1997, Yonkang et al., 1997). In this example, the most recent earthquake was the largest, and prior to trenching, there was a tendency to regard the 1920 earthquake as the characteristic earthquake, when the majority of the paleoseismic examples were much smaller. The two largest events had much greater net slip (5.6 and 7.0 m respectively for the ~6150 BP and AD 1920 events) than the intervening events which averaged 1.5-2 meters for seven measured single segment ruptures (6 additional single and one three segment rupture could not be determined).

Collectively, these data from a variety of sources raise a number of important issues. First, it is becoming even more clear that our short instrumental and historical records are inadequate to characterize the seismic behavior of subduction zones and other major fault systems.

Given recent predictive failures of universal models of great earthquake recurrence, we must consider that there may not be reliable predictive factors available for such purposes at present, or in the immediate future. Paleoseismology offers a relatively simple method of determining the long term behavior of a fault system, illuminating not just the time series of event occurrences, but segmentation, clustering, magnitude, stress transfer, and strain supercycles. For the short term problem of seismic hazards, we suggest that characterization of the maximum considered earthquake, required for planning of critical facilities in populated areas, may require earthquake records as long as 10,000 years.

We suspect that elastic strain may accumulate at even very small rates in settings previously considered unfavorable, and that any such fault may be capable of eventually generating a very large earthquake from incremental strain accumulation over many “normal” seismic cycles. Such long-term cycling is suggested for Cascadia, one of a very few localities where enough events are recognized to test such models. Not enough data exist to test such a models elsewhere, but a mismatch between recurrence time and earthquake size has been observed in Chile in the 1960 rupture zone (Cisternas et al., 2005), and this type of cycling could also partially explain the periodic occurrence of the observed outsized events in Sumatra, Hokkaido and Tohoku.

At a minimum, the Tohoku earthquake implies that other comparable subduction zones may be capable of similar behavior. Put in terms of relatively old subduction plate systems previously discounted as M9 producers, much of South America (represented by the 1868 Arica earthquake (Dorbath et al., 1990), the remainder of the Japan trench, the Kuriles, the western Aleutians, the Philippine, Manila and Sulu trenches, Java, the Makran and Hikurangi may be capable of similar behavior. Island arc subduction systems form a group that may also be suspect as suggested by McCaffrey (2008), however these systems have no direct analogy to NE japan, and currently have no known evidence of past superquakes.