GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF EARTH AND ATMOSPHERIC SCIENCES

Tsunami Generation from Earthquakes: The Role of the Shallow Trench

Andrew V. Newman, *anewman@gatech.edu*
School of Earth and Atmospheric Sciences, Georgia Institute of Technology

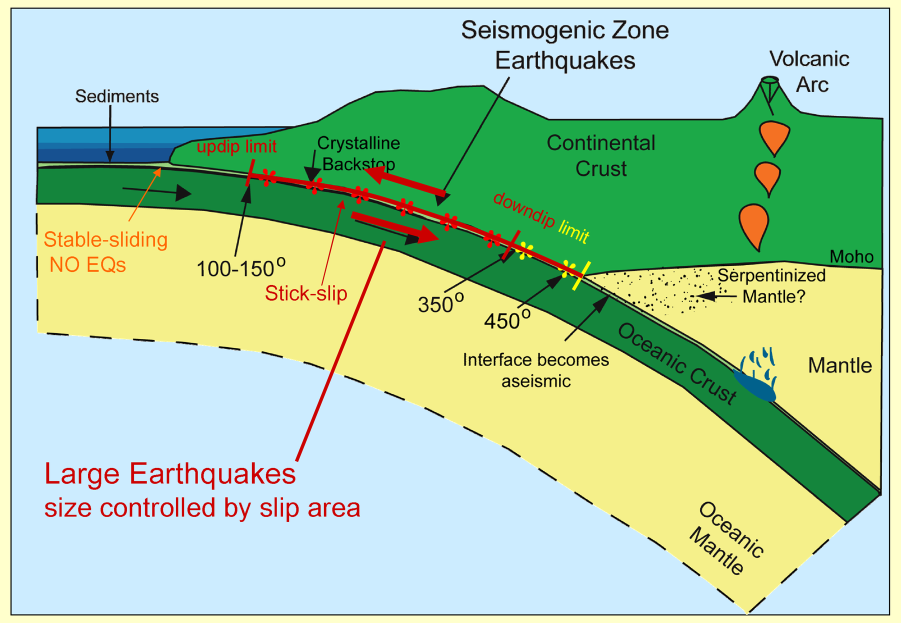
Plate Interface Seismicity in Subduction Zones

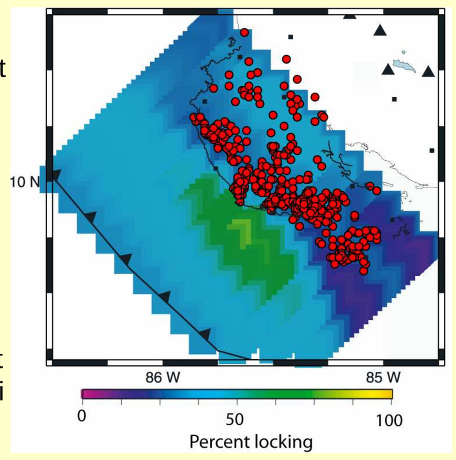
Because they are the primary source of numerous small and large tsunamis and ~90% of all seismic moment release occurs along the subduction interface, it is important to understand how it works.

Our current arguments for processes that allow subduction zone seismogenesis are as follows:

When the oceanic plate subducts, the interface heats through contact with the overriding plate by conduction & frictional heating. Such that at between 10-20 km depth, when the plate interface heats beyond ~100-150°C, brittle failure can occur because of dehydration reactions that transform abundant smectite and opal (both with low coefficients of friction) to illite and quartz (with more friction), thus allowing stick-slip behavior. A later transition back to stable-sliding occurs down-dip, about 40-50 km depth, due to further increased temperatures or contact with the mantle wedge, but is not important for tsunamigenesis.

Though this description works well for most subduction interface events, it is clear that at times earthquakes occur well above this 100° isotherm. In fact, when these earthquakes do not obey this "updip limit", they become much more likely to generate tsunamis because of geometry and reduced rupture velocity. Determining where these events may next occur is a challenge that will require a global evaluation of strain accumulation in the shallow trench.

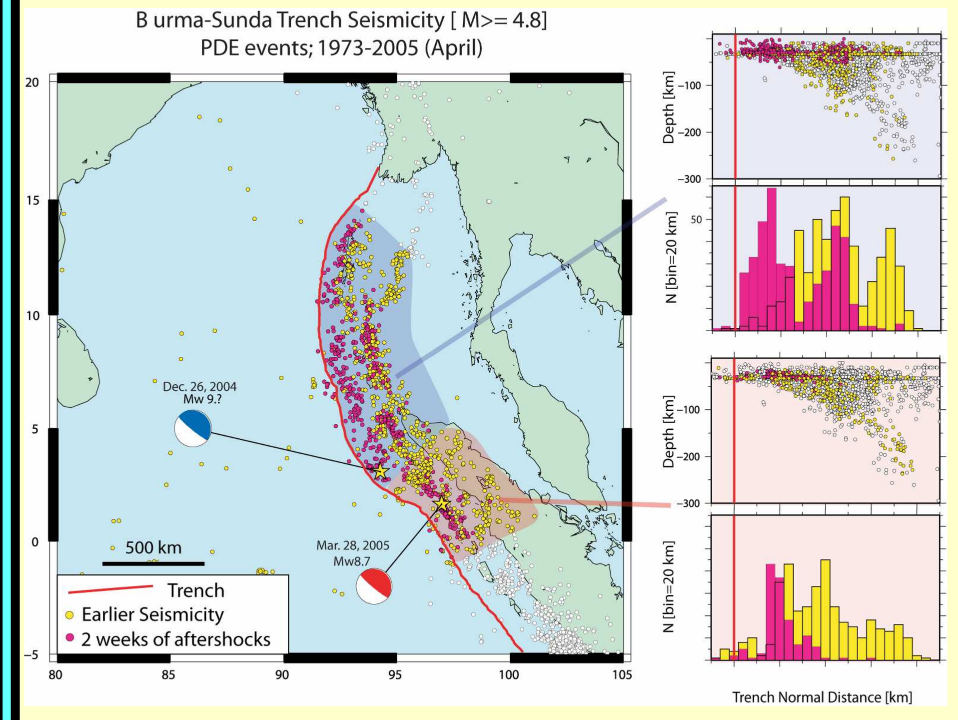


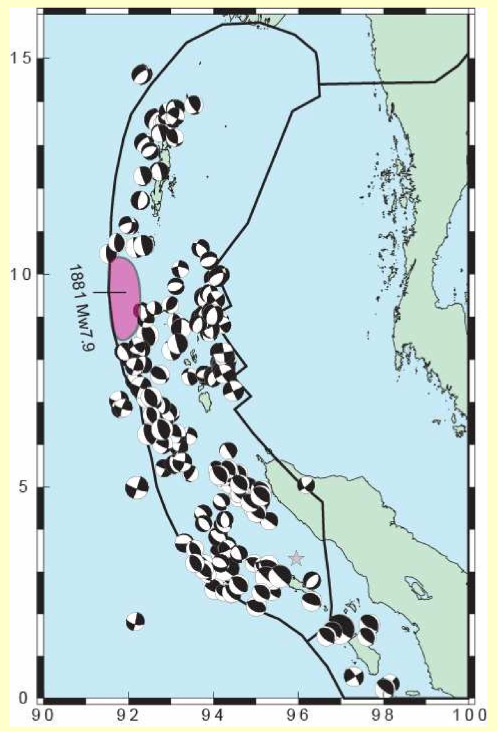


A comparison of locally detected microseismicity defining the "updip" limit in Nicoya Peninsula, Costa Rica [Newman et al., 2002], and interface locking as determined by GPS for the same period [Norabuena et al., 2004]. The unique character of this peninsula allows land-based geodetic studiesgain resolution in the otherwise unreachable shallow interface. The region of strong locking in the shallow trench is adjacent to the rupture area of the 1992 Tsunami Earthquake in Nicaragua.

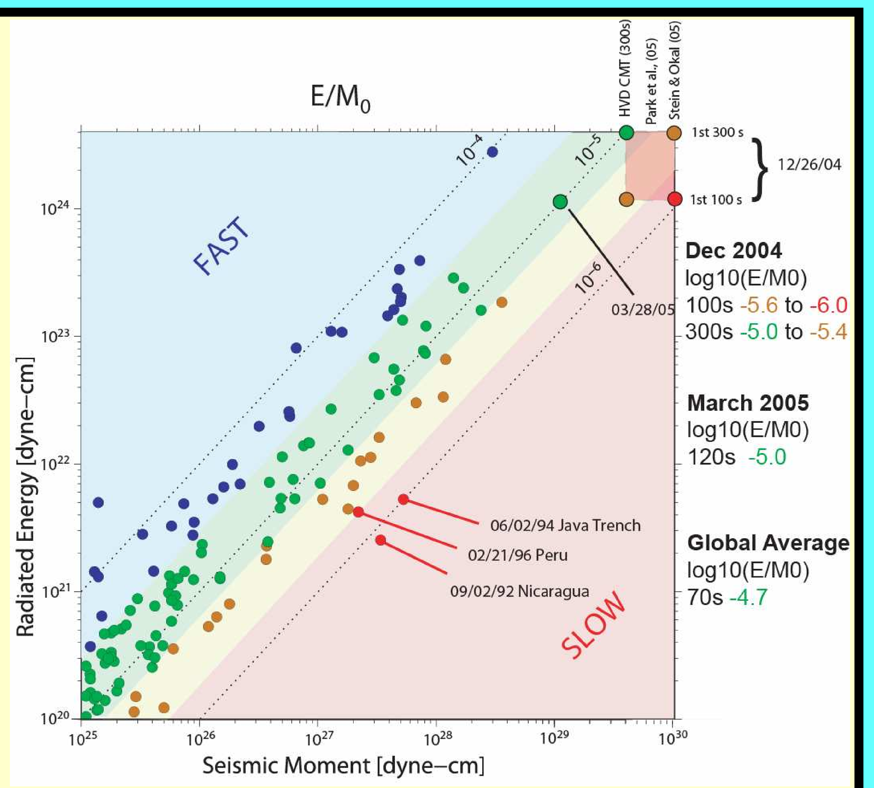
Sumatran Earthquakes (12/26/04, 3/28/05)

Similar events, very different tsunamigenesis





Regional maps showing locations of the 12/26/04 and 3/28/05 Mainshock and aftershocks [top], and their Harvard CMT focal mechanisms for larger events [right]. The December event activated aftershocks along almost the entirety of the Burma microplate, however a near-trench void exists at the latitude of the 1881 Mw7.9 tsunamigenic earthquake [Ortiz and Bilham, 2000], from likely insufficient strain accumulation since event. While aftershocks from the December event went to the shallow trench region, those form the March event only occurred along a comparatively narrow swath of the Sunda sub-plate.

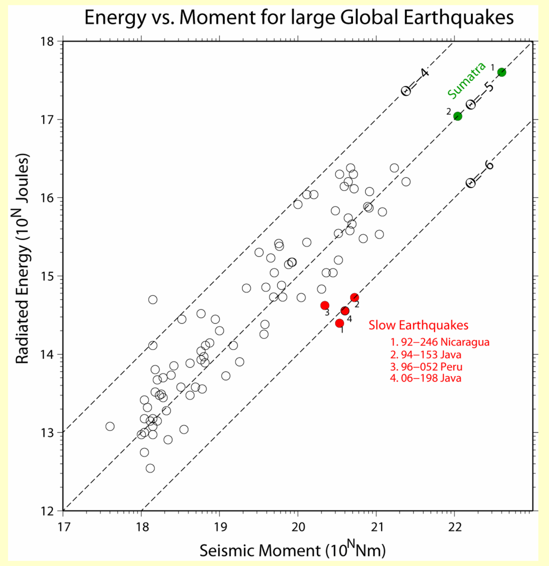


Earthquake energy to seismic moment distribution for large shallow global earthquakes [after Newman and Okal, 1998] While the March 2005 event does not appear to be deficient in high frequency energy, the December 2004 event appear to be somewhat- to very deficient depending on the duration of data used for the energy calculation and seismic moment estimate.

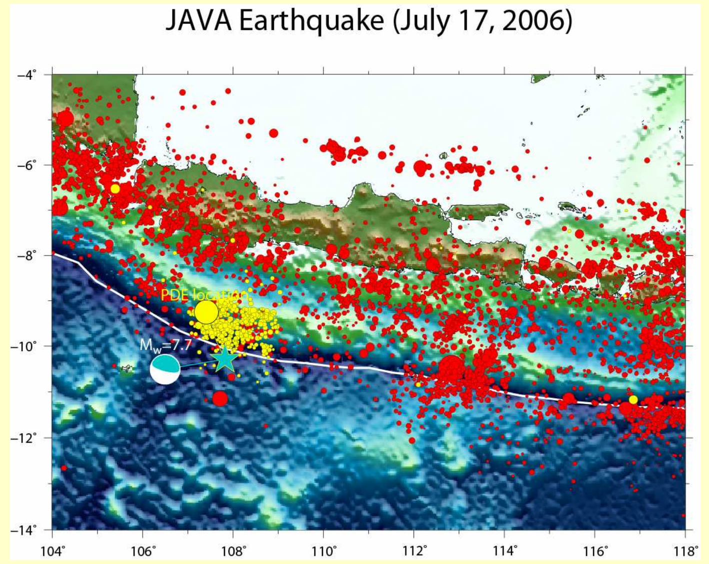
Due to the long rupture of the December event, these estimates are problematic as hey do not sample the entire rupture and have an additional energy contribution from later arrivals. Thus, the energy information alone does not uniquely identify a tsunami earthquake component.

Java Earthquake (7/17/2006)

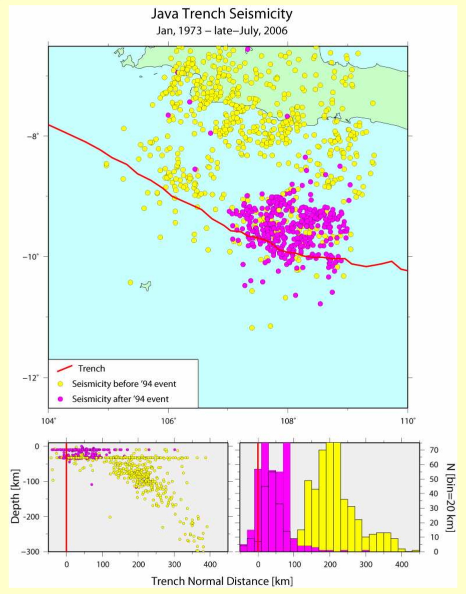
- Recent Java earthquake, which created a locally devastating tsunami, clearly ruptured in the very near trench region (as identified by early aftershocks. This event could be rapidly identified as a slow-source "Tsunami Earthquake" by utilizing the deficient character of radiated body-wave energy, when compared to its seismic moment.
  - This was the 1st observed in "tsunami earthquake" globally in the last 10 years, and may have more than a coincidental relationship with a similar event approximately 500 km east in 1994.
- Shallow rupture is likely contributor to both slow source and tsunamigenesis



Comparison of radiated energy to seismic moment [updated from Newman and Okal, 1998] (see above). The recent Java even clearly clusters with other known "tsunami earthquake".



PDE and recent seismicity in the Java Region surrounding the recent and 1994 "tsunami Earthquakes". PDE Mainshock and 1 month of aftershock activity is shown in yellow. 1994 Mainshock and aftershocks are apparent as a dense cluster of red events near the trench at about 113°E.



Focused examination of early and recent activity in the region surrounding the 2006 event highlights the near-trench nature of the event. Earlier near-trench events do not appear to cluster in time (time-distribution not shown)

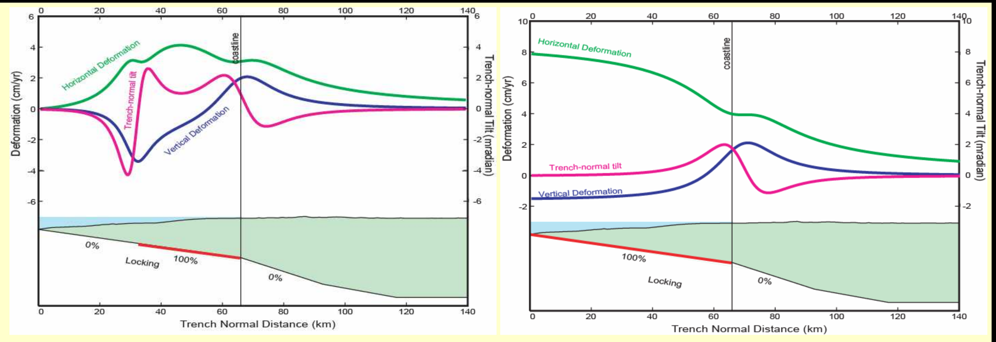
Near-trench rupture and tsunami excitation

Slower slip near trench (due to reduced rigidity?) can enhance tsunami excitation by several potential methods:

+ Earthquake Rupture is closer to natural period of tsunami waves then normal high-frequency ruptures, thus putting more energy in tsunami generation.
+ Enhanced earthquake slip due to conservation of rupture energy may occur because of the reduced volume of slip during the upward propagation of rupture into the margin wedge (similar to tsunami run-up near shore).
+ Increased slip due to elastic resistance to rupture in shallow region going to zero at trench.

A need for sea-floor geodesy

With low-cost and reliable sea-floor geodetic techniques it may become possible to identify locked regions, especially near-trench, that are invisible to land-based methods and most effective at generating tsunamis in large earthquakes.
The measurements would additionally be useful for a host of other natural and anthropogenic activities.



Predicted deformation for shallow dipping (Cocos Subduction), 9 cm/yr convergence with (a) 50% and (b) 100% locking across the offshore subduction interface. While the two models vary dramatically locally relative differences onshore are very small suggesting land-based techniques alone are unsuitable for determining the state of locking in the up-dip region.

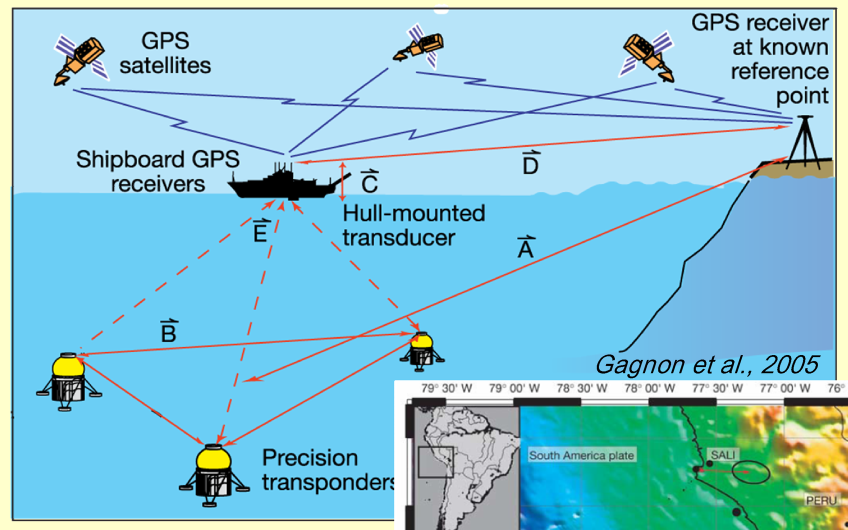
Tools

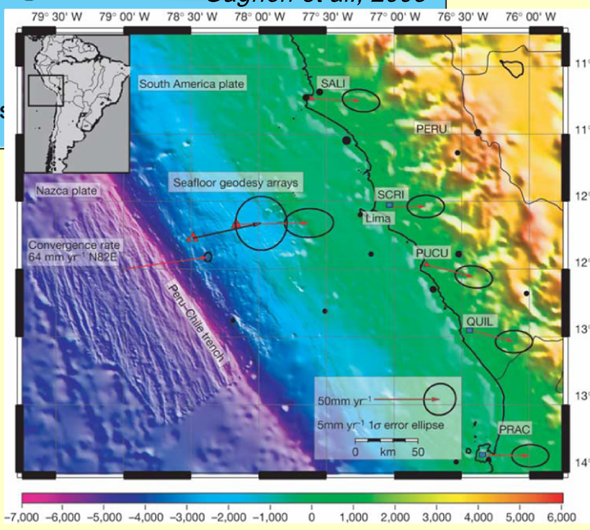
Seafloor geodesy is a relatively new, challenging, and expensive field.
The 2004 Earthquake and tsunami highlighted the need for the community renew efforts in determining the feasibility, cost effectiveness, and applicability of new seafloor geodetic methods capable of accuracy between 1-10 cm/yr.

These can include existing and new tools:

+ GPS-acoustic systems (H, a) [e.g., Spies et al., 1998; Gagnon et al., 2005]
+ Fully acoustic systems (LoS, r) [e.g., Fujimoto et al., 1998]
+ Pressure sensors (V,r, a?) [e.g., Fox,1990; Chadwick et al., 2005]
+ Tiltmeters (T, r) [Tolstoy et al., 1998; Anderson et al., 1997]
+ Gravity meters (V, r, a?) [Zumberge and Canuteson, 1994]
+ Fiber-optic extensometers (LoS, r) [Zumberge, Ocean Eng.,1997]
+ Bathymetric interferometry (LoS, r) (similar to InSAR)
+ Borehole strainmeters, and dilatometers (deviatoric and volumetric strain)

H, V, T = Horizontal, Vertical and Tilt Deformation
LoS = Line-of-Sight
a, r = Absolute and Relative measurements





Recent results [Gagnon et al., 2005] from a combined GPS-acoustic system (a) developed by Scripps showing shallow margin-wedge motions very similar to that of the incoming plate (b). These results suggest very strong near-trench locking in a region just south of the 1996 Peruvian slow-rupturing "tsunami earthquake".

Technical Challenges

In most all of these systems there are numerous issues that need to be considered including:

+ Cost ($$$)
+ Relative/absolute measurements
+ Power consumption/generation
+ Signal attenuation and scatter
+ Changes in path velocity
+ Data relay
+ Monumentation and retrieval
+ System lifespan