FORUM

Growing Understanding of Subduction Dynamics Indicates Need to Rethink Seismic Hazards

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Tsunamigenic megathrust earthquakes, like the 2004 Sumatra-Andaman and 2011 Tohoku events, are the most dramatic consequences of subduction dynamics. The classical view is that megathrusts release elastic energy due to the rupture of a fault with a width of tens of kilometers in the down-dip direction and a length of hundreds to a thousand kilometers along the trench. However, recent research, particularly work on the Tohoku event, has suggested that the generation of huge tsunamis may require the release of gravitational energy as well as elastic energy [*George et al.*, 2011]. Our growing understanding of the role of gravitational energy in generating tsunamis following megathrust earthquakes points to the need to reevaluate earthquake and tsunami hazard assessments.

Looking at megathrusts worldwide, despite advances in numerical models of the lithosphere-mantle system, there are still many unexplained observations related to the kinematics. One of the largest uncertainties is the effective strength of subducting slabs. It is unclear why the age of the incoming plate (believed to control buoyancy and strength) is poorly related to subduction velocities and slab dip. Attempts to link large thrust events (magnitude ≥8.5) with slab edges, proximity to the continental upper plate, age gradient of the incoming plate, and sediment size have shown only a slight correlation [*Heuret et al.*, 2012]. The nature of megathrusts, their tsunamigenic potential, and the need for more advanced modeling were the subjects of intense discussion among seismologists, computational geodynamicists, and tsunami modelers at a recent conference, "Geophysics of Slab Dynamics," held in Jeju, South Korea, August 2012.

Ruff and Kanamori [1980] tried to relate the age and convergence velocity of each subducting slab to the maximum earthquake magnitude. However, both the Sumatra and Tohoku events violate Ruff and Kanamori's scaling, as well as every other suggested relationship. The megathrust events of the past decade have also shown that present hazard maps are inadequate due to questionable assumptions and the short time interval for which seismicity data are available [*Stein et al.*, 2012]. Emile Okal (Northwestern University) pointed out at Jeju that the Tohoku event even violates the standard scaling laws between rupture area, fault slip, and magnitude, applicable to most thrust quakes. These anomalies have led researchers to hypothesize a substantial involvement of the crustal wedge—either in the form of a giant landslide or the uplift of the entire wedge or the rigid motion of a crustal block sliding through the slip of a normal fault—in the subsequent tsunami generation [*Grilli et al.*, 2012].

While statistical analyses are important for testing hypotheses on the physics of seismic events, the limited set of observed megathrusts makes this approach inapplicable to the largest earthquakes, which can only be truly understood through a detailed, site-specific analysis of convergent zone crustal dynamics, with tsunami observations and numerical modeling providing additional strong constraints on the mechanism of tsunami generation. Moreover, if the tsunami magnitude also depends on the response of the crustal wedge, seismic hazard maps must be rethought. Presently, these maps are based on recent data that might not reflect the largest events. This viewpoint is supported by older historical and geological data, showing that large tsunamis occurred in the past in the region of the Tohoku event (e.g., the 869 earthquake in Japan's "Jogan" era). This reinforces the hypothesis that the coupled crustal wedge–megathrust mechanism might be general and suggests that crustal deformation near subduction zones will have to be monitored in detail to obtain the information needed for tsunami risk estimation.

Over the past decade, progress in geodynamic numerical modeling has moved us closer to simulating short- and long-term processes, with a resolution of tens of meters near thrust faults. However, it is an open question whether this will help us understand how megathrusts emerge from plate convergence. Revisiting the Sumatra event suggests that these efforts can be fruitful: the rupture involved 1200 kilometers of the trench and activated the southern portion of the arc, triggering four large quakes over 3 years, almost filling the entire arc. That cluster of events shows that within years of a major earthquake, the reorganization of stresses can contribute to triggering new events over thousands of kilometers of distance. The time scale is confirmed by a study of the asthenosphere flow after the Sumatra event [*Han et al.*, 2008]. Furthermore, numerical models of mantle flow near slabs, predicting velocities up to 1 meter per year [*Jadamec and Billen*, 2010], show that a slip of 10 meters, typical for megathrusts, is associated with a relaxation time of the stress inside the entire slab on the order of 10 years.

Earthquake source studies of thrust faults at subduction zones are evolving toward new models of seismic loading and stress release, but how such models will ultimately have to be modified from cyclical models remains unclear [*Kagan et al.*, 2012]. Geodynamicists who model subduction on the scale of the upper mantle (~1000 kilometers) scarcely interact with researchers who study the deformation of the crustal wedge. Participants at Jeju reached a consensus on moving toward integrating near-surface processes into

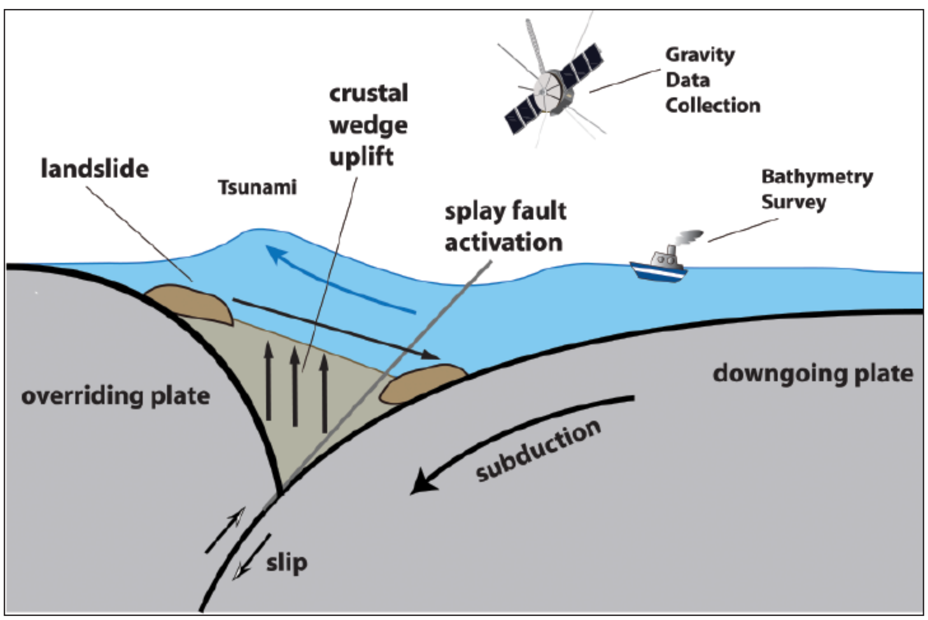

Fig. 1. Crustal wedge uplift, landslides, splay faults, and rigid block rotation caused by megathrust earthquakes can produce anomalously large tsunamis. Monitoring bathymetry and gravity before and after such events will help scientists to understand the phenomenology and estimate the associated risks.

subduction models, based on the substantial progress in our ability to integrate crustal evolution into nonlinear viscous mantle models. Models of mantle and subduction dynamics homogenize structural heterogeneities below the 1 kilometer scale, obtaining smooth elastic stress patterns and solving for the creeping flow of the lithosphere-mantle system. On the other hand, crustal studies typically model heterogeneous short-scale patterns in space and time, which are considered essential for capturing tectonic evolution and understanding stress accumulation before seismic events. Clearly, our ability to model such complex systems with high resolution in three dimensions near major faults will be enhanced as innovative strategies are developed for using high-performance computing.

Modeling crustal dynamics requires including physics that is now mostly missing in subduction models (e.g., free surface, faults, inertia). To test the hypothesis that the crustal forearc deforms or ruptures, possibly triggering tsunamis, immediately following large thrust earthquakes, future investigations will require a closer integration of models and observations (Figure 1). In particular, they will require monitoring of the forearc bathymetry before and after events; seismic/geodetic and tsunami inversions, which can be used to reconstruct tsunami generation mechanisms and model observed runups; and studies of the variation of the geodetic field in the years before and after the event [*Cambiotti and Sabadini*, 2013]. Although accurate and reliable earthquake prediction is impossible, high-resolution three-dimensional dynamic models of the forearc wedge can substantially help in forecasting hazards from the largest earthquakes on Earth.

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