Geophysical Research Abstracts
Vol. 12, EGU2010-2250, 2010
EGU General Assembly 2010

Gravity drives Great Earthquakes

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The most violent of Great Earthquakes are driven by ruptures on giant megathrusts adjacent to actively forming mountain belts. Current theory suggests that the seismic rupture harvests (and thus releases) elastic energy that has been previously stored in locked segments of the megathrust. The general belief, however, is that this energy was accumulated as the result of relative motion of the adjacent stiff elastic tectonic plates. This mechanism fails to explain many first order aspects of large earthquakes, however. The energy source for strain accumulation must also include gravitational collapse of orogenic crust and/or in the foundering (or roll-back) of an adjacent subducting lithospheric slab. Therefore we have conducted an analysis of the geometry of aftershocks, and report that this allows distinction of two types of failure on giant megathrusts. Mode I failure involves horizontal shortening, and is consistent with the classic view that megathrusts fail in compression, with motion analogous to that expected if accretion takes place against a rigid (or elastic) backstop. Mode II failure involves horizontal extension, and requires the over-riding plate to stretch during an earthquake. This process is likely to continue during the subsequent period of afterslip, and therefore will again be evident in aftershock patterns. Mode I behaviour may well have applied to the southern segment of the Sumatran megathrust, from whence emanated the rupture that drove the 2004 Great Earthquake. Mode II behaviour appears to apply to the northern segment of the same rupture, however. The geometry of aftershocks beneath the Andaman Sea suggest that the crust above the initial rupture failed in an extensional mode.

The edge of the Indian plate is foundering, with slab-hinge roll-back in a direction orthogonal to its motion vector. The only possible cause for this extension therefore is westward roll-back of the subducting Indian plate, and the consequent gravity-driven movement of the over-riding crust and mantle. This is possible for the crust and mantle above major subduction zones is mechanically weakened by the flux of heat and water associated with subduction zone processes. In consequence the lithosphere of the over-riding orogens can act more like a fluid than a rigid plate. Such fluid-like behaviour has been noted for the Himalaya and for the crust of the uplifted adjacent Tibetan Plateau, which appear to be collapsing. Similar conclusions as to the fluid-like behaviour of an orogen can also be reached for the crust and mantle of Myanmar and Indonesia, since here again, there is evidence for arc-normal motion adjacent to rolling-back subduction zones. Prior to the Great Sumatran Earthquake of 2004 we had postulated such movements on geological time-scales, describing them as 'surges' driven by the gravitational potential energy of the adjacent orogen. But we considered time-scales that were very different to those that apply in the lead up, or during and subsequent to a catastrophic seismic event. The Great Sumatran Earthquake taught us quite differently. Data from satellites support the hypothesis that extension took place in a discrete increment, which we interpret to be the result of a gravitationally driven surge of the Indonesian crust westward over the weakened rupture during and after the earthquake.

Mode II megathrusts are tsunamigenic for one very simple reason: the crust has been attenuated as the result of ongoing extension, so they can be overlain by large tracts of water, and they have a long rupture run time, allowing a succession of stress accumulations to be harvested. The after-slip beneath the Andaman Sea was also significant (in terms of moment) although non-seismogenic in its character. Operation of a Mode II megathrust prior to catastrophic failure may involve relatively quiescent motion with a mixture of normal faults and reverse faults, much like south of Java today. Ductile yield may produce steadily increasing (and accelerating) subsidence (on decadal time scales) as roll-back deepens the trench and adjacent fore-arc basins. This suggests a relatively simple (and cost effective) strategy that would allow precursor motions on Mode II megathrusts to be precisely monitored.