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PERSPECTIVES

Megathrust aftermath. Tsunami produced by the 2011 magnitude 9 Tohoku subduction earthquake.

GEOPHYSICS

Weak subduction makes great quakes

Small earthquakes reveal low stress levels at megathrust zones and in surrounding crust

By **Roland Bürgmann**

The world's greatest earthquakes, producing catastrophic shaking and tsunamis, occur in subduction zones. Here oceanic plates dive below adjoining regions along megathrust faults (see the figure). The recent magnitude ~9 megathrust earthquakes in Sumatra, Chile, and Japan, with fault displacements of several tens of meters, were stark reminders of the destructive power of these events. On page 1213 of this issue, Hardebeck (*1*) uses the orientations of fault planes of thousands of smaller earthquakes near and above the world's megathrusts to evaluate the state of stress driving these great events. The general conclusion made is that all faults in subduction zones, including the megathrusts, are unusually weak.

Plate tectonic forces drive the subduction process and earthquakes. Stress at a particular point can be fully described by the orientations and magnitudes of three mutually perpendicular, principal (maximum, intermediate, and minimum) compressive stresses. By definition, shear stress is zero on planes perpendicular to the principal stresses. As Earth's free surface cannot support shear stress, the principal stresses in the shallow crust are expected to be parallel and perpendicular to the surface, a state of stress referred to as Andersonian (*2*).

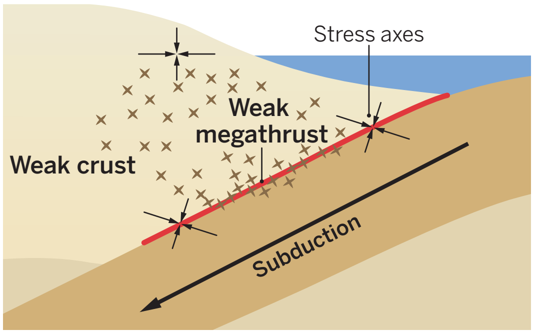
The magnitude of stresses in the brittle crust is bounded by the frictional strength of faults. The coefficient of friction determines the strength of a fault as a linear function of the fault-perpendicular normal stress. Laboratory-derived estimates of friction coefficients for most rock types suggest that fault strength and stress will linearly increase with increasing rock overburden within Earth, reaching several hundred megapascals (MPa) at depths where subduction earthquakes occur (*3*).

Our knowledge of the actual stresses driving earthquake faulting remains limited and is based on indirect or incomplete measures of stress. It is nearly impossible to directly measure absolute stress where earthquakes occur, as this requires observations in costly deep boreholes (*4*). A number

Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA. E-mail: burgmann@seismo.berkeley.edu

of geophysical studies in some subduction zones have suggested that fault friction values and stress may be much lower than expected from laboratory experiments. Such studies have relied on estimates of frictional heat generated by faulting (*5*, *6*), the orientation of stresses estimated from the geometry of aftershock fault planes (*7*), as well as the apparent large rotation in principal stress orientations from before to after the 2011 Tohoku earthquake in Japan (*8*, *9*).

Hardebeck focuses on using the fault plane geometry of small earthquakes near and above the megathrust of global subduction zones to determine the orientations of the principal stresses and constrain their magnitudes. The orientation of the maximum principal stress with respect to the megathrust provides information about the relative strength of the fault and surrounding crust. If the megathrust is weak (low friction) in an otherwise strong crust,



Weak subduction zones. The orientation of compressive stress inferred from the geometry of many small earthquake fault planes suggests a weak megathrust in a weak surrounding crust.

we would expect the principal stresses to be nearly perpendicular and aligned with the fault, similar to the case for the free Earth's surface. If both the megathrust and surrounding material are either weak or strong, we would expect the maximum compressive stress to be oriented at an oblique angle (20° to 60°) from the fault.

Contrary to expectations, Hardebeck finds that the orientation of maximum compressive stress near most subduction thrusts plunges toward the trench at angles of 10° to 50°. This indicates that the state of stress is not Andersonian and that the maximum compressive stress is oriented roughly 30° from the megathrust. This orientation is expected for faults with frictional strength similar to that of the surrounding crust; that is, they are either both strong or both weak. Using evidence of absolute megathrust weakness from studies documenting low frictional heat production (*5*, *6*), stress rotations due to great earthquakes (*8*, *9*), and high fluid pressures in fault zones (*10*), Hardebeck argues that both the megathrust and surrounding crust must be weak, with only a few exceptions. Stresses are likely no higher than a few tens of MPa, rather than hundreds of MPa expected from standard friction theory. Apparently, not that much stress is required to make a great earthquake fault slip, and when it does, it drops the ambient stress to extremely low levels.

Hardebeck suggests that most faults in the world's subduction zones are weak. What might produce such weakness? Possible explanations include intrinsically low friction of fault zone materials composed of clays and talc (*11*), high fluid pressures that push against the normal stress on faults (*10*), and dynamic shear weakening during earthquake fault slip (*12*). It is important to remember that the inference of stress is indirect and depends on the accuracy of the fault plane orientations and various assumptions made when inferring stress orientations from the fault slip data. To improve our knowledge of the magnitude and orientation of stress in subduction zones and the factors determining their variations in space and time, we need much-improved observations. More detailed observations of small earthquakes and their fault plane orientations near the megathrust require seafloor seismic sensors. Seafloor geodetic measurements can capture the strain associated with evolving stress (*13*). Improved in situ observations are possible by drilling into a megathrust at greater depths to directly observe the composition, stress, and conditions in the fault zone (*14*). The distribution of absolute stress in space and time is probably the most important quantity in solid earth sciences that we know the least about. The analysis reported in Hardebeck's paper takes an important step toward changing that. ■

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EVOLUTION

How single cells work together

Are single-celled symbioses organelle evolution in action?

By **Jonathan P. Zehr**

Symbiotic interactions are fundamental to life on Earth and were critical for the evolution of organelles that led to the success of eukaryotes on the planet. Such mutualistic interactions between unicellular microorganisms and multicellular plants and animals are pervasive in natural and agricultural ecosystems (*1*). In contrast, very little is known about symbiotic interactions between unicellular partners. Recent studies have revealed single-celled nitrogen-fixing symbioses that require different mechanisms to maintain symbiosis than seen in multicellular systems.

In aquatic environments, there are many examples of protists that acquire endosymbionts or plastids (*2*). These types of symbioses are analogous to the evolution of organelles, such as the photosynthetic organelle of the unicellular eukaryote *Paulinella* (*3*). Other unicellular mutualistic associations are nitrogen-fixing symbioses—for example, between filamentous cyanobacteria and marine diatoms (see the figure, panel A) (*4*). The filamentous cyanobacteria in these associations develop specialized cells (heterocysts) that allow them to separate the oxygen generated by photosynthesis from the oxygen-sensitive nitrogen fixation enzymes. In these symbioses, the intracellular cyanobacteria coordinate growth and division and are transmitted through different life stages (*5*). More recent studies have found evidence for nitrogen-fixing symbioses between unicellular cyanobacteria and single-celled protists that do not involve the development of specialized cells.

One example is a nitrogen-fixing symbiosis between the single-celled cyanobacterium UCYN-A (unicellular cyanobacteria nitrogen-fixing "group A") and a prymnesiophyte microalga (see the figure, panel B)

Department of Ocean Sciences, University of California, Santa Cruz, Santa Cruz, CA 95064, USA. E-mail: zehrj@ucsc.edu