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GEOPHYSICS: The Next Great Earthquake

Robert McCaffrey, *et al.*

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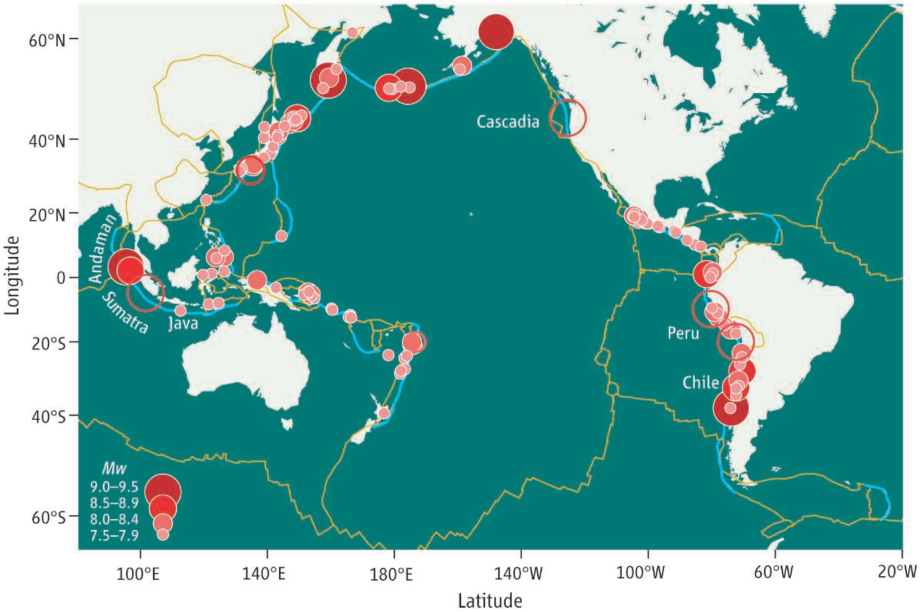
GEOPHYSICS

The Next Great Earthquake

Robert McCaffrey

The 2004 Sumatra-Andaman earthquake occurred at a surprising time and place; the lessons learned may help costal communities in the future.

Earthquakes with a magnitude 9 (M9) or larger occur very infrequently but can cause widespread damage and loss of life, as we saw with the Sumatra-Andaman earthquake in December 2004. Most of these earthquakes occur at the type of tectonic boundaries where one plate slides at a gentle angle beneath another (a process known as subduction). Because they happen mostly beneath the ocean, they often generate destructive tsunami waves.



Danger zones. Subduction zone segments (blue curves) and tectonic plate boundaries (brown curves) with filled circles showing locations of known earthquakes of M7.5 or greater since 1900. Open circles show incomplete sample of inferred largest earthquakes from 1700 to 1900 (*6*). Some segments that are free of M9 earthquakes in the past 100 years had them in the previous 200 years.

There are more than 40,000 km of subduction boundaries (see the figure). The rupture of any one contiguous segment ~800 km or more in length can produce an M9 earthquake. Seismologists have long tried to determine which segments are more likely than others to break. Yet, the M9 earthquake of 2004 ruptured a segment that was thought to be among the least likely to go. What governs the frequency of these massive quakes, and are all subduction segments capable of producing one?

Earthquake frequency can be estimated on the basis of plate tectonics. An M9 earthquake accounts for about 20 meters of slip on the boundary between two plates, which converge at 0.02 to 0.10 meters per year; thus, an average time between them is 200 to 1000 years, assuming all the slip is by M9 quakes. If some slip occurs through smaller quakes or creep, the interval will be longer.

From an observational standpoint, this long interval is problematic, because in most places, reliable records of earthquakes date back only a century. Historic accounts and geologic observations can be used to extend the record, but they lack detail.

In places where long histories are available, the times between great earthquakes appear to be highly irregular. In Cascadia, for example, disturbances of the soft sediments by shaking and deposits of sand by tsunamis, both suggestive of past great earthquakes, show an average time between events of 600 years (*1*). However, the actual times range from 200 to 1500 years, revealing a very large randomness to when the margin breaks.

The world's major subduction zones can be divided into several segments based on natural geologic changes or earthquake histories (see the figure). Each segment is long enough to produce an M9 quake. Five have had M9 quakes in the past century; many others have not produced quakes greater than M8 in recorded history. In the past few decades, seismologists have focused on trying to correlate this variable earthquake behavior with other properties of the different subduction zones. An underlying premise was that, as a result of geologic factors, some subduction zones are intrinsically incapable of generating an M9 quake. If true, this would be important to know.

According to an early idea, the age and speed of the subducting plate were important: If the subducting plate was geologically young (and therefore warm and buoyant), or moving quickly, or both, then its shallow trajectory into the mantle would make it stick more to the plate above it, leading to bigger quakes (*2*). This idea had empirical support from the 100-year historical earthquake record (*3*). Other similar suggestions based on plate mechanics were that the lateral motion of the subducted plate in Earth's mantle modified stress on the plate boundary (*4*) and that thick sediments in the trench lubricated the fault (*5*). The Sumatra-Andaman earthquake occurred in a very unlikely region, according to these explanations (*6*).

In contrast to mechanical processes, subduction of young, hot lithosphere heats the fault zone, and earthquakes may be inhibited in this setting because high temperatures within Earth promote ductile over brittle deformation (*7*). Regressions relating earthquake behavior to fault-zone temperatures gave similar statistical fits as the mechanical models (*8*). However, thermal considerations put the Andaman subduction-zone fault in the high-magnitude class: Its average temperature is probably close to that of central Chile, where the largest known subduction-zone earthquake (M9.5) occurred in 1960 (*9*).

The rate of convergence between plates can affect the generation of great earthquakes in another way. Theoretically, the frequency of earthquakes of a given size increases with the rate of the relative plate motion (*10*). If we observe the earthquake process for a finite time, it stands to reason that subduction zones with faster slip rates and, hence, more fre-

The author is in the Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180, USA. E-mail: mccafr@rpi.edu

quent M9s will have more M9s than those that are slow. Indeed, the number of M9 earthquakes that have occurred in the past 100 years (five) is within one of those expected at random if we take into account only the rate-predicted intervals between them (*11*). This recurrence-time concept explains some of the earlier positive correlations of earthquake size with slip rate. However, it differs fundamentally from the mechanical and thermal explanations, in that the latter predict some subduction zones to be incapable of having an M9, whereas the former holds that they are merely improbable.

The Sumatra-Andaman earthquake surprised many Earth scientists by occurring in an unexpected place. Earth gave us a stark reminder of the important difference between improbability and impossibility. Our understanding of where and when the next great earthquake will happen is in its infancy at best. We have not had enough time to decipher M9 earthquake behavior. It will take many more centuries, or many more quakes, or both, to understand the pattern, if one exists.

For policy purposes, one lesson we should take away from the Sumatra-Andaman earthquake is that every subduction zone is potentially locked, loaded, and dangerous. To focus on some and ignore others may be folly. Several are near densely populated land areas, and the potential impacts of shaking and tsunamis cannot be overstated. We learned that great earthquakes pose a unique hazard to distant coasts: The long rupture generated tsunami waves that traveled over vast oceans with little loss of amplitude due to spreading.

The great reach of the 2004 tsunami (*12*), and the expected long time interval between such events, requires that these lessons persist over a wide expanse of time and space. A small amount of knowledge in the right place can save many lives, as in the story of the 10-year-old British girl who had learned of tsunamis in school and warned fellow sunbathers in Thailand to run for higher ground, probably saving them (*13*).

Even while we develop technology-based global warning systems, we should, by sustained education, embed the lessons of 2004 in the cultural memories of all coastal communities.

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BOTANY

A Plant Receptor with a Big Family

A hormone that controls plant development and survival acts through a member of a receptor family whose other members are pervasive in animal cells.

Erwin Grill and Alexander Christmann

The largest known family of proteins is also, not surprisingly, involved in a wide range of biological processes in the animal world. Vital physiological functions such as vision, taste, and olfaction recruit G protein–coupled receptors to relay external signals into cells, to elicit the appropriate responses. Likewise, G protein–coupled receptors mediate responses to endogenous signals encoded by peptides, nucleotides, or lipids, to adjust cell growth and differentiation, metabolism, embryogenesis, and development to current physiological demands. The human genome encodes more than 800 G protein–coupled receptors. In contrast to this pervasiveness, plants seem not to have evolved such a dependence on these receptors. The genome of the plant *Arabidopsis thaliana* encodes about 25 "candidate" G protein–coupled receptors—plasma membrane–localized proteins with a seven-transmembrane topology that characterizes this receptor family. Moreover, not a single ligand for a candidate plant G protein–coupled receptor has been known. Now Liu *et al*., on page 1712 in this issue (*1*), report that a candidate G protein–coupled receptor of *Arabidopsis* is the receptor for the phytohormone abscisic acid. This is satisfying not only because it establishes the first functional member of this receptor family in the plant world, but it also identifies a long sought after receptor for an important plant developmental hormone.

Abscisic acid serves as a plant-specific signal during development and in response to environmental stresses such as cold, drought, and high concentrations of salt in the soil. The physiological responses it elicits include the closure of leaf stomatal pores to restrict transpiration, adjustment of metabolism to tolerate desiccation and cold temperatures, and inhibition of seed germination and seedling growth. Biochemical and electrophysiological studies provide evidence for both extracellular and intracellular perception of the hormone (*2*, *3*). Recently, the nuclear RNA-binding protein FCA, which controls flowering time (*4*), and the Mg-chelatase subunit H located in chloroplasts (*5*), were identified as intracellular abscisic acid receptors. Liu *et al.* now show that GCR2 is a plasma membrane–localized G protein–coupled receptor that specifically binds to naturally occurring abscisic acid, but not to the physiologically inactive isomer (trans-abscisic acid), to control stomatal closure, seed germination, and seedling growth.

In addition to seven-transmembrane domains, a G protein–coupled receptor has a cytosolic domain that acts as a guanine-nucleotide exchange factor for heterotrimeric GTP-binding proteins (G proteins). Upon binding to a ligand, the receptor promotes the exchange of bound GDP for GTP in an associated G protein; this results in receptor dissociation from the G protein. The G protein itself dissociates into $G\alpha$ and $G\beta\gamma$ complexes that then target downstream effectors such as guanylyl cyclase, protein kinases, or phospholipases. There is only one canonical $G\alpha$, one $G\beta$, and two $G\gamma$ subunits expressed in *Arabidopsis*. Previous functional analysis of plant G protein subunits implicated their involvement in phytohormone responses, including abscisic acid signaling (*6*). In mutant plants lacking $G\alpha$ (GPA1), regulation of stomatal movement is impaired and germination is hypersensitive to abscisic acid (*7*).

The authors are in the Department of Plant Science, Technical University Munich, Am Hochanger 4, 85350 Freising-Weihenstephan, Germany. E-mail: erwin.grill@wzw.tum.de