At not quite 3 o’clock in the afternoon local time on March 11, 2011, 30 kilometers below the ocean floor roughly 130 km east of Tohoku (the northeast region of Japan’s largest island, Honshu), the earth cracked. A portion of the earth more than 400 km long and 150 km wide moved upwards—in places as much as 20 or 30 meters, the height of a six-story building. Measured at magnitude 9.0, the Tohoku earthquake was among the largest in recorded history and the largest to strike Japan since modern instrumentation began to be used 130 years ago.

Within 15 minutes the earthquake was followed by a wall of water that rose as high as ten meters in places along Japan’s coast. More than the violent shaking of the earth, the tsunami caused the greatest damage. More than 125,000 buildings were damaged or destroyed; roads, railways, and water and power lines were made unusable; industry and commerce were halted for months; at least 16,000 people were killed.

**STRESS TRANSFER**
Seismologists have long known that the rupture of large-magnitude earthquakes like Tohoku affects the stress borne by other faults nearby (for at least several hundred kilometers). When hundred kilometer-long sections of the earth’s crust move by as much as they did in the Tohoku earthquake, the state of stress on nearby faults will be altered, thereby potentially impacting their tectonic stability either positively or negatively. In effect, stress is transferred from one fault to others.

Thus, one question that has risen repeatedly since the Tohoku rupture is: what effect has the earthquake had on the numerous other crustal faults and subduction zones that comprise the tectonic setting of Japan? In particular, will the transfer of stress by the March 11th Tohoku earthquake hasten the occurrence of new ruptures—especially in the vicinity of relatively nearby Tokyo, where a significant proportion of Japan’s population, administrative authority, economic activity, communications outlets, and insured property is concentrated?

This article describes how scientists think about and try to answer these questions. Attempting to quantify changes in fault rupture probabilities is one of the most daunting challenges for seismologists. In the case of Tohoku, the task is made more challenging by the complexity of Japan’s seismicity, which arises from the interaction of multiple tectonic plates moving in different directions at different rates, and the presence of hundreds of crustal faults (some undoubtedly still undiscovered).
It is difficult, if not impossible, to estimate an exact value for Coulomb stress on a fault because the necessary calculations require detailed information about the active tectonic shear stress (stresses parallel to the fault plane), effective normal stress (stresses perpendicular to the fault plane), and the effective coefficient of friction on the fault—that is, the extent to which a fault is “locked.” Unfortunately, this information is not known. However, when a large magnitude earthquake occurs, changes in the shear and normal stresses on neighboring faults can be estimated, and from this information the related Coulomb stress changes can be calculated.

To do this, certain information about both the causative fault and the affected faults is needed. This includes, but is not limited to:

- The geometry of the causative fault plane
- The slip distribution and slip direction on the causative fault plane
- The geometry of the affected faults, including specifically:
  - Strike
  - Dip
  - Fault depth
  - The slip direction of the expected future earthquakes on the affected faults
- The effective coefficient of friction on affected faults

This information, in theory, would be sufficient to estimate the scale of Coulomb stress change on faults. However, there are large uncertainties in the values of these parameters that could strongly affect the results of the calculations. The most important sources of uncertainty are the state of friction on the affected faults and the geometry and slip direction of the future earthquake on those faults. Further, in trying to develop a complete and realistic picture of what might be happening at depth, issues like a potential depth dependency of Coulomb stress change over the entire fault plane need to be addressed. For example, should the rupture probability analysis use an averaged Coulomb stress change or, given that stress typically is not uniform along a fault plane, use local maxima instead?

Inset in Figure 1 is a map of central Honshu and its known faults. Next to it are four idealized Coulomb stress change...
diagrams of the same region (west and south of Tokyo). Each diagram reflects different assumed characteristics (dip angle, rupture mechanism) of a representative fault. Clearly what we know—or don’t know—about the particulars of any given fault have enormous implications for any estimate of stress transfer.

**DETERMINING RATES OF LONG-TERM STRESS BUILDUP**

The operation for determining the amount of Coulomb stress change just described yields a measure of how much stress is added to (or perhaps relieved from) a fault by an event like the Tohoku earthquake. The wider question, however, is how that change in stress will affect the fault: will the fault fail sooner or later than would otherwise be expected? How much sooner or later? What is the time-shift caused by the change in stress?

To answer this question, information about two other aspects of a fault that has undergone stress transfer must be known: the fault’s recurrence rate—how regularly it has ruptured in the past—and the fault’s yearly rate of stress accumulation.

**RECURRENT RATE**

With respect to a fault’s recurrence rate, if a fault has been identified, usually it is because it has been documented in historical records or an historical record has been developed or augmented for it through paleoseismic findings. Thus, the recurrence rate of most identified faults (however approximate in many instances) is understood to be the average number of years between earthquakes—which, in turn, is assumed to be the length of time needed for sufficient stress to build up on the fault to cause it to fail, or rupture.

**RATE OF STRESS ACCUMULATION**

To determine a fault’s yearly rate of stress accumulation, however, is more complicated. This usually requires constructing an elaborate three-dimensional mathematical model of the fault’s entire seismic region, a model that would include all of the tectonic forces at work in that region. However, it is possible for researchers to use a less data intensive, but still relatively reliable method for determining a useful stress accumulation rate for a fault—one that employs “stress drop.”

“Stress drop” refers to the change in shear stress on a fault from the moment just before it ruptures to the moment just after. That difference, which can be determined using the data recorded by modern seismic monitoring instruments, is assumed to be the threshold amount of stress that causes the fault to fail. Thus, by dividing an earthquake’s stress drop (presumably the total amount of stress the fault has accumulated between ruptures) by its recurrence rate, an estimate of its yearly rate of stress accumulation is determined. For example, assume that the stress drop on a particular fault is 40 bars. Say that it is known that that fault ruptured in 1950, 1827, and 1699—and thus it’s recurrence rate is about 125 years. Accordingly, this fault’s yearly stress accumulation rate would be 0.32 bars per year (40 bars ÷ 125 years = 0.32 bars per year).

Performing these operations yields the two pieces of information necessary to estimate the potential time-shift presumably caused by Tohoku on the example fault: the change in stress on the fault brought about by Tohoku (which for purposes of demonstration can arbitrarily be said to be 2 bars), and the fault’s yearly rate of stress accumulation (0.32 bars per year). By dividing the one by the other (dividing stress change by rate of accumulation), the example fault’s time-shift is determined: 6.25 years in this instance.

**RUPTURE PROBABILITIES**

What, however, does such a time-shift actually mean—or, rather, how should it be used to estimate rupture probability? Because the rupture histories of faults are incomplete and because there is insufficient data available for a detailed physical modeling of the rupture process,
Seismologists use what are known as “renewal” models to develop probabilistic time-dependent rupture forecast analyses. The two most important parameters in all renewal models are the mean recurrence interval and the elapsed time since the last rupture. Thus, in the framework of a renewal model, the time-shift can be applied either to the elapsed time or the mean recurrence interval.

Three models are most commonly used by researchers to resolve the question of rupture probability. One model translates the calculated time-shift to a re-setting of a fault’s rupture-clock. A second model applies the time-shift to a fault’s mean recurrence interval. The third model places the time-shift estimate into a physical model of earthquake genesis known as a “rate-state model.” This model requires a great deal of data about the state of a fault’s specific geology to perform robustly. In general, it shows a larger probability for a fault rupturing immediately after experiencing positive stress transfer from another earthquake, with the probability then decreasing with time.

Large magnitude earthquakes do change the state of stress on regional faults. Physical models can provide useful information concerning changes in the degree of Coulomb stress experienced by faults. These changes are a function of the geometry, slip, coefficient of friction, and many other factors. However, there are large uncertainties regarding these parameters, and they need to be taken into account in all such efforts at analysis.

It also should be noted that the mechanics of how a particular fault ruptures is extremely complex and depends upon numerous factors at depth that are not well understood or not known at all. This lack of knowledge adds another layer of uncertainty when trying to interpret Coulomb stress changes and their application to quantifying fault rupture probabilities. Not long after the Tohoku earthquake ruptured, a joint effort between the U. S. Geological Survey and Kyoto University (Toda, et al; 2011) produced a preliminary qualitative investigation of the increase or decrease in stress on nearby faults. The researchers reported areas and faults where they found that the Tohoku event had increased or decreased the state of stress, but they refrained from quantifying potential changes to the rupture probabilities.

It will take many more months and possibly even years before revised rupture probabilities can reliably be estimated. AIR researchers, along with hundreds of others in the wider scientific community, are hard at work trying to overcome the many uncertainties to achieve this. Given the potential implications for the Tokyo metropolitan area, the importance of such work cannot be overestimated.

Charles-Augustin de Coulomb (1736-1806), the 18th century French scientist who first articulated one of the three basic laws of

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**Closing Comment**

Our discussion of stress transfer leads to several conclusions:
FRICTION; FRICTION PLAYS AN IMPORTANT ROLE IN THE IMPOSITION OF STRESS ON FAULTS.

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