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What's Shakin': Earthquake Research at Bridgewater

Robert C. Cicerone
Bridgewater State College, rcicerone@bridgew.edu

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Earthquake Research at Bridgewater

by Robert D. Cicerone

We are all very familiar with the phenomenon known as an earthquake. Whenever a catastrophic earthquake occurs in a densely populated city, we are inundated with news coverage showing scenes of destruction and human suffering. Indeed, earthquakes are among the most devastating geologic hazards. Fortunately, destructive earthquakes are relatively rare events.

A great deal of scientific and engineering study has been conducted to develop strategies to reduce the consequences of earthquakes. However, earthquakes are also important scientifically from a different perspective. Much of what scientists have learned about the internal structure of the Earth comes from the study of earthquakes.

If we look at a map showing the distribution of earthquakes in the world, it is readily apparent that earthquakes are not randomly distributed, but tend to occur in well-defined belts (see **Figure 1**). In fact, about 90% of the total amount of energy released by earthquakes occurs in the area around the Pacific Ocean. This area is also where most of the active volcanoes are located and is commonly referred to as the "Ring of Fire" by scientists. This is not a coincidence, but a manifestation of the fundamental mechanism of how the Earth works. This mechanism is known as *plate tectonics*.

Plate tectonics is a relatively recent theory in the earth sciences, having only gained widespread acceptance in the 1960s. However, the basic ideas of the theory date back to the 1600s, although they are most commonly identified with a German meteorologist named Alfred Wegener, who proposed a theory of continental drift in the early part of the twentieth century. It wasn't until the 1960s that scientists had accumulated enough geologic evidence to support the theory.

The basic idea of plate tectonics is simple. The earth's outer layer is relatively thin (about 100 kilometers, or 40 miles thick) and is referred to as the *lithosphere*. The lithosphere is actually broken up into about 14 "plates." A good analogy for the lithosphere would be a cracked eggshell. These plates are all moving with respect to each other, so there are places where the plates collide

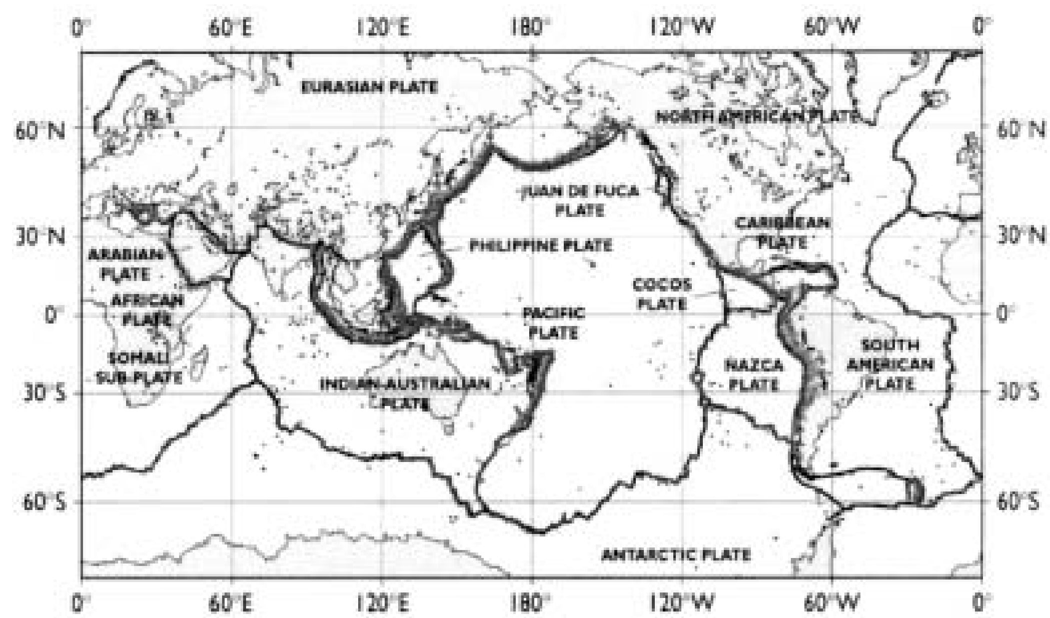


Figure 1. World Seismicity, 1963–2000. The dots represent the locations of earthquakes, and the heavy black lines represent the boundaries of the major plates. [From Understanding the Earth, 3rd edition, by Frank Press and Raymond Siever, W.H.Freeman and Company, 2001].

with each other, other places where plates move away from each other, and still other places where the plates slide past each other. It is at these plate boundaries where interesting geologic events occur.

Let's take another look at **Figure 1**. In addition to showing the locations of recent earthquake epicenters, the map also shows the boundaries between the various plates that make up the earth's lithosphere. You should notice that most of the earthquakes occur, not surprisingly, near plate boundaries (there are some earthquakes that don't occur near plate boundaries, but we'll talk about them later).

If the boundaries between plates were smooth, then the interaction between the plates would be relatively uneventful. It's the fact that the boundaries are rough and there is a lot of friction between the interacting plates that makes things interesting. As the plates try to move, the roughness of the surface between the plates and the friction that exists on the surfaces resists motion, so that strain energy builds up over time in the rocks on either side of the surface. Eventually, enough energy builds up that it either overcomes the frictional forces or causes one of these rough spots (referred to as asperities by scientists) to break. When this happens, there is a sudden movement of the plates on either side of the surface, causing a sudden release of all of this accumulated strain energy, producing the phenomenon that we call an earthquake.

Some of the energy that is released by the earthquake is converted to kinetic energy, causing the plates to move, some of the energy is actually dissipated as heat along the surface between the plates, and some is converted to waves. The waves then propagate through the earth, causing the ground to shake near the surface of the earth. This ground shaking at the surface of the earth leads to the destruction that typically accompanies a large earthquake. These waves also travel deep within the earth and re-emerge at the surface far away from the earthquake source. Scientists can record these re-emerging waves on instruments called seismometers. By measuring how long it takes these waves to travel to different points on the surface of the earth, scientists have been able to reconstruct an accurate physical model of the internal structure of the earth. In fact, the use of earthquake, or seismic, waves from artificial sources is routine in exploring for oil and gas and, more recently, has become an important technique in engineering and environmental applications where detailed knowledge of the subsurface structure of the earth is needed.

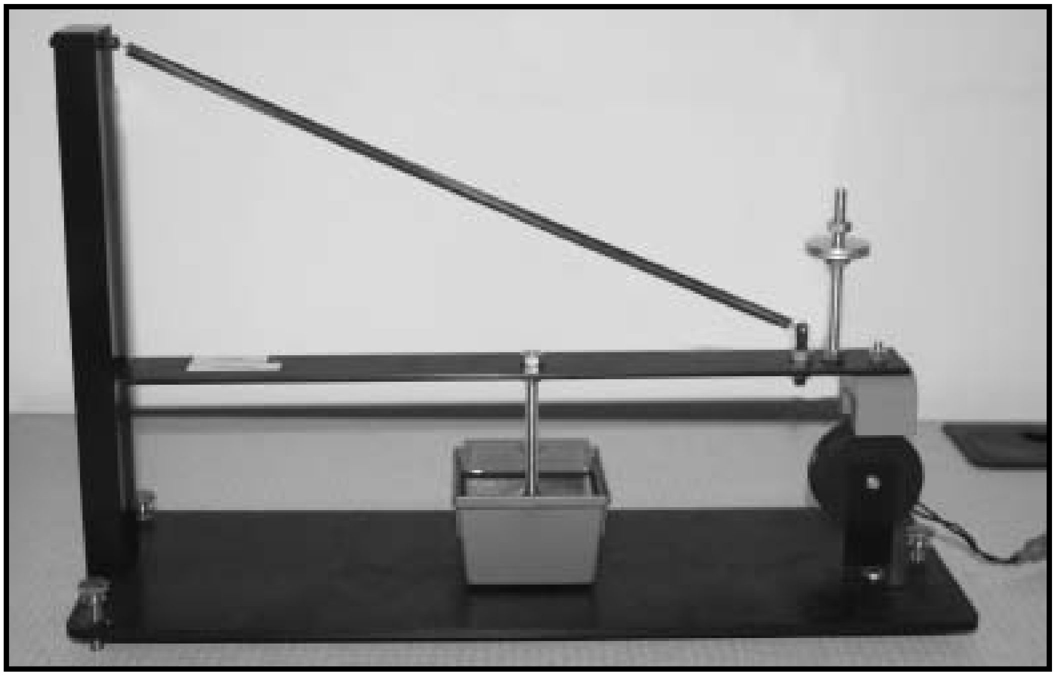
Over the past several years, I have been involved in research related to several different aspects of the earthquake hazard problem. One of the most elusive goals in earthquake hazard research is the ability to predict earthquakes on short enough time scales to provide useful information to local governments to aid in emergency measures such as evacuation.

In recent years, there has been a great deal of effort invested into the study of one aspect of the earthquake-prediction problem, the study of earthquake precursors. The term *earthquake precursor* refers to any physical phenomenon that occurs prior to an earthquake that may indicate the imminent occurrence of the earthquake. This includes electromagnetic field emissions, gas emissions, change in ground water levels, localized ground deformation, and changes in seismic activity. Unfortunately, there has been no systematic study of these phenomena, and observation of earthquake precursors has been serendipitous. For example, anomalous magnetic fields were recorded prior to the 1989 Loma Prieta earthquake in northern California by a magnetic-field sensor deployed to measure electromagnetic noise generated by electric trains of the San Francisco Bay Area transit system. More recently, however, Japanese scientists are currently installing networks to study these earthquake precursors in the area of the Tokai Gap, where the next great earthquake is expected to hit and could have devastating consequences to the metropolitan Tokyo area. This is a significant advance in the systematic study of earthquake precursors.

I have been working with a colleague at Boston College, Professor John Ebel, to systematically compile observations of earthquake precursors. As part of this continuing effort here at Bridgewater, I hope to study the magnetic field precursors from the Loma Prieta earthquake with an undergraduate student, Kathleen Gonsalves, who has received a grant from the ATP Summer Undergraduate Research Program at Bridgewater. The goal of the research is to find evidence to support a model of the physical process that generates the magnetic field and to develop more detailed models of the process for this particular earthquake.

A second area of research that I have been pursuing involves a study of the mechanisms of seismic wave attenuation, with specific application to New England and surrounding areas in the United States and Canada. The term attenuation refers to the dissipation, or reduction, of the energy in seismic waves as they travel through the earth.

Figure 2. Bridgewater State College's seismic recording instrument.



The importance of a better understanding of seismic wave attenuation can best be illustrated by an example. Imagine an earthquake of a given magnitude occurring in California. The area affected by the earthquake depends on the nature of the rocks in the vicinity of the earthquake and how effective they are in dissipating the energy released by the earthquake. California is relatively young geologically and the rocks are fairly broken up, so that the energy from earthquakes dissipates rapidly. Therefore, even though California is very active seismically, the affected area from any one earthquake is relatively limited.

In comparison, an earthquake of the same magnitude in New England or any part of the eastern or central United States would affect an area about five to ten times as large as the same earthquake in California. This is due to the fact that the rocks in the eastern and central parts of the United States are much older geologically and have had a longer time to fuse together, so that they are very efficient at transmitting seismic waves with little loss of energy. Therefore, even though earthquakes are more infrequent in the eastern and central United States, the affected area from any one earthquake can be very extensive.

I have been working with colleagues at the Earth Resources Laboratory at MIT to determine the attenuation characteristics of New England and adjacent areas using earthquakes recorded on the New England Seismic Network. New England experiences approximately ten earthquakes per year, with magnitudes usually ranging between 2 and 4. These earthquakes obviously occur away from any plate boundary and are examples of what scientists refer to as *intraplate* earthquakes. Our main objective in this study is to estimate the relative importance of two different mechanisms of attenuation. The first mechanism involves the actual dissipation of seismic energy as heat by internal friction within the rocks. The other mechanism is scattering, where the seismic energy is reflected by irregularities in the upper part of the earth. This mechanism does not actually dissipate energy, but it is a geometric effect that redistributes energy in the earth, creating an apparent attenuation effect. Our initial results indicate that scattering is the more important mechanism in New England. In addition, the effect appears to be most prominent in the shallowest part of the earth, possibly due to either fractures in the rock or due to the topography of the surface of the earth.

Another area of research that I have been pursuing involves a study of what scientists refer to as the magnitude-frequency relationship of earthquakes. If we look at the distribution of earthquakes over time in large areas, we find that there is a relationship between how often an earthquake occurs and it magnitude, which is a measure of the size of the earthquake. Simply put, small earthquakes occur much more frequently than larger ones. In general, there is a ten-fold decrease in the frequency of occurrence of an earthquake for every unit increase in magnitude. For example, earthquakes of magnitude 6 occur ten times more often than earthquake of magnitude 7 and one hundred times more often than earthquakes of magnitude 8. This magnitude-frequency relationship is referred to as the Gutenberg-Richter (GR) law, named after the two scientists, Beno Gutenberg and Charles Richter (the same Richter of Richter magnitude fame), who first discovered it in the 1950s. This law has been an important component of most earthquake hazard studies.

Recently, scientists have discovered that the GR law begins to break down as the area studied gets smaller. If we look at a single fault (a fracture in the earth that produces earthquakes), we see that the earthquakes occurring on that fault do not generally fit the GR law, but tend to be very similar to each other. Let's look at a specific example: the southern segment of the San Andreas Fault in California just east of Los Angeles. The last major earthquake to occur on this fault happened in 1857 and is referred to as the Fort Tejon earthquake. The estimated magnitude of this earthquake was about 8 (it occurred before seismic instrumentation had been developed). The estimated repeat time for this earthquake is between 150 and 200 years. This is the so-called "Big One" that many scientists believe is imminent in southern California.

If the GR law is valid, then the southern segment of the San Andreas Fault should have produced, in the time interval since the Fort Tejon earthquake, about ten earthquakes of magnitude 7, about one hundred earthquakes of magnitude six, about 1000 earthquakes of magnitude 5, and so on. Yet this has not happened: there has been only minor seismic activity on this segment of the fault.

Figure 3.

This discrepancy has led scientists to propose an alternative model to describe the magnitude-frequency distribution of earthquakes called the characteristic earthquake model. This model states that earthquake-generating faults tend to produce earthquakes of about the same magnitude over a regularly-repeating interval of time. So, when applied to our example above, the southern segment of the San Andreas Fault should produce an earthquake of magnitude 8 approximately every 150 to 200 years. Many scientists advocate the characteristic earthquake model, arguing that the GR law describes not the distribution of earthquake magnitudes, but the distribution of fault sizes in the earth.

I have been working with a colleague to develop software to calculate earthquake hazard maps using both the GR model and the characteristic-earthquake model of earthquake occurrence. We have already developed a computer simulation to generate a synthetic time history, or catalog, of earthquakes using either model assumption. We are presently developing software to use these catalogs as input to generate earthquake hazard maps. We are interested in the differences in the earthquake hazard maps that result from the different model assumptions.

Bridgewater State College has become very active in earthquake research. The college has recently applied for membership in IRIS (Incorporated Research Institutions for Seismology), a consortium of universities and government institutions undertaking research in seismology. The college has also installed an earthquake-recording instrument, or *seismometer,* in the basement of the Conant Science Building (**Figures 2 and 3**). The instrument is connected to a computer and provides a continuous display of earthquake data in real time and is capable of recording and storing data from individual earthquakes.

Earthquakes are complex physical phenomena and, in the last century, scientists have made a great deal of progress in understanding how and why earthquakes occur. However, there is still much that is not understood about earthquakes. The study of earthquakes has provided, and will continue to provide, a great benefit to society. It is a privilege for me to participate with Bridgewater in this fascinating endeavor.

—Robert D. Cicerone is Assistant Professor of Earth Sciences and Geography