Intensity is a measure of the strength of ground shaking. It is very important in understanding damage and designing structures to withstand earthquakes. But it doesn’t say much about the size of the earthquake source or the total amount of energy released.

Almost everyone has heard of the *Richter Scale* and magnitude, but there is a lot of confusion about what magnitude is and what it means. That's not too surprising considering that there are several different magnitude scales in general use in the United States and all of them tend to be called "The Richter Scale" by the media. When Richter developed his original magnitude scale in 1935, he was looking for an empirical way to classify the relative size of small to moderate earthquakes in California. The scale was based on the peak amplitude, or wave height, recorded on a standard seismograph commonly deployed for locating local earthquakes in California at that time. Richter's scale was not initially related to energy, not could it be used for large earthquakes far away. The instruments that Richter used are no longer in common use, although we still have two of them in the basement of Founder's Hall at Humboldt State University.

The original Richter magnitude

Richter’s idea was to measure the largest amplitude anywhere on a Wood-Anderson seismograph. Wood-Andersons were developed in the 1920s and by the 1930s when Charles Richter, a seismologist at Cal Tech, began thinking about the magnitude problem. Wood-Anderson seismographs measured horizontal ground motion typically in either an East-West or North-South orientation. They magnified ground motion exactly 2800 times and were very good at picking up the signals from moderate earthquakes no more than a few hundred miles from the source.

Richter, who had always been interested in astronomy, drew inspiration from brightness scale astronomers assign to stars. He arbitrarily chose zero on his scale to be an earthquake that would show a maximum horizontal amplitude of 1 μm (0.00004 inch) on a seismogram recorded using a Wood-Anderson torsion seismograph located exactly 100 km (62 mi) from the epicenter. He chose this value because he thought it would preclude the assignment of negative magnitudes. He also wanted the scale to be able to cover all earthquakes using single digits, restricting his magnitudes to 10 or less. He was aware of the enormous range in earthquake size so defined his magnitude on a logarithmic scale:

Magnitude = logarithm maximum amplitude measured in μm
(Wood-Anderson Seismograph exactly 100 km from epicenter)

Using this definition, a magnitude 3 earthquake, would have a peak amplitude of 1 mm, a magnitude 4 earthquake, 1 cm, and a magnitude 5, 10 cm. Figure 1 illustrates the logarithmic relationship of amplitude and magnitude. You can barely see the magnitude 3.3 earthquake at the top. The amplitude is only a little more than a millimeter. The M 4.0 earthquake is easier to see with an amplitude of 10 mm or 1 cm. The magnitude 5.2 is easy to see with an amplitude of a bit more than 10 cm.

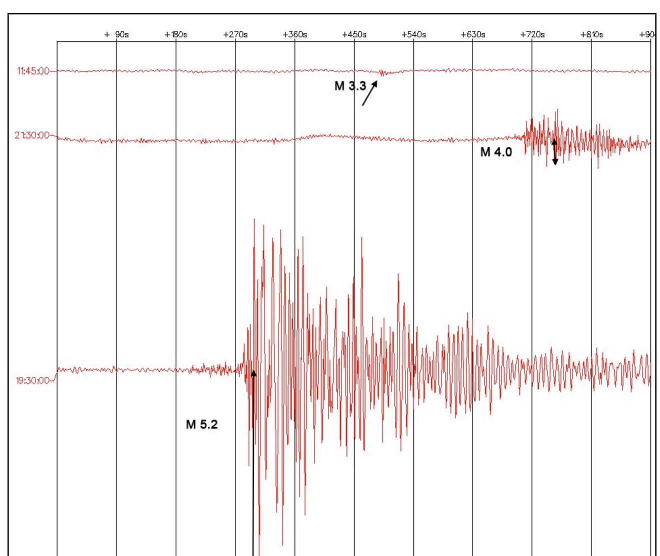

Figure 1. Illustration of magnitude and amplitude.

One problem with Richter's original formulation is that it is very unlikely to find a seismic station exactly 100 km away from every earthquake. Richter realized this and added or subtracted a factor to adjust for stations closer or further away from the epicenter. You are using this relationship in Part III of Home Problem 4.

Richter's formulation was quickly adopted by the seismological community and expanded to include global earthquakes. The Wood Anderson instruments couldn't record teleseisms (large earthquakes from far away) well. Richter and other seismologists adapted the method to other seismographs. Body wave magnitudes (m_b) are based on the amplitude of the initial P-wave signal and surface wave magnitudes (M_S) are determined using the peak amplitude of longer period (20 sec.) surface waves.

Types of Magnitudes

M_L **Local Magnitude** (original "Richter magnitude")

Magnitude scale originally developed by Charles Richter at Cal Tech in 1935 using the maximum amplitude of any phase (usually S) on a standard Wood Anderson seismograph. Richter defined the logarithmic framework for magnitudes – each increment of 1 on the magnitude scale corresponded to a ten-fold increase in the amplitude on the Wood Anderson seismograph. This magnitude scale is still used by seismologists today to compare the size of modern earthquakes to older ones and to estimate magnitudes of earthquakes in the magnitude 3 range that are often too small for moment magnitude (the current state-of-the-art) determinations. Modern broadband seismographs can simulate the response of these early instruments and seismologists can still calculate a magnitude essentially identical to Richter's original scale (now called local magnitude or M_L).

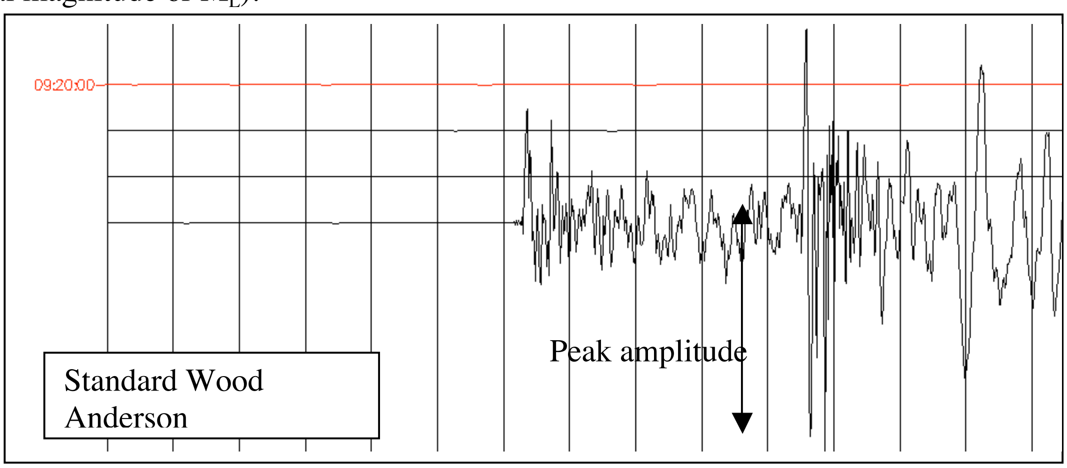

Figure 2. The response of a Wood-Anderson seismograph can be duplicated with modern instruments. This seismogram illustrates how the Local Magnitude is based on the largest amplitude signal on the seismogram.

M_S **Surface Wave Magnitude**

Charles Richter and Beno Gutenburg expanded Richter's magnitude concept to include larger earthquakes recorded on longer period seismographs. They measured the largest amplitude of a 20 second surface wave and calibrated the result to agree on average with the local magnitude estimates. This used to be the standard magnitude used by the USGS (and reported by the media) for large earthquakes but has been generally replaced by the moment magnitude scale. It is still often the first magnitude reported for large earthquakes as it takes less time to estimate accurately than moment magnitude. It is also used to distinguish between underground explosions and earthquakes.

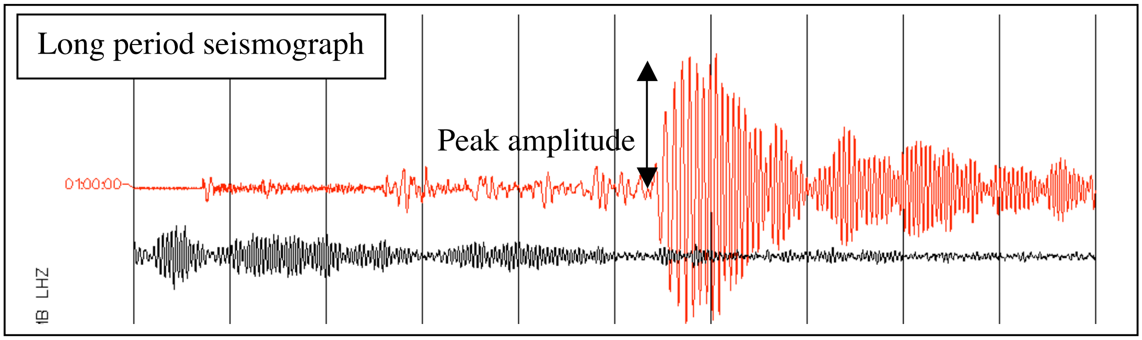

Figure 3. Surface wave magnitudes M_s are based on the maximum amplitude of surface waves with a 20 second period.

m_b Body Wave Magnitude

The body wave magnitude scale was developed to measure the size of deep earthquakes that produced weak surface waves (figure 4). It is based on the amplitude of the first P wave cycle. It is now used primarily along with M_s to discriminate between underground nuclear explosions and earthquakes. Explosions have a larger m_b/M_s ratio than earthquakes. Mare about this in NOTES: 21 – Energy and Underground Nuclear explosions.

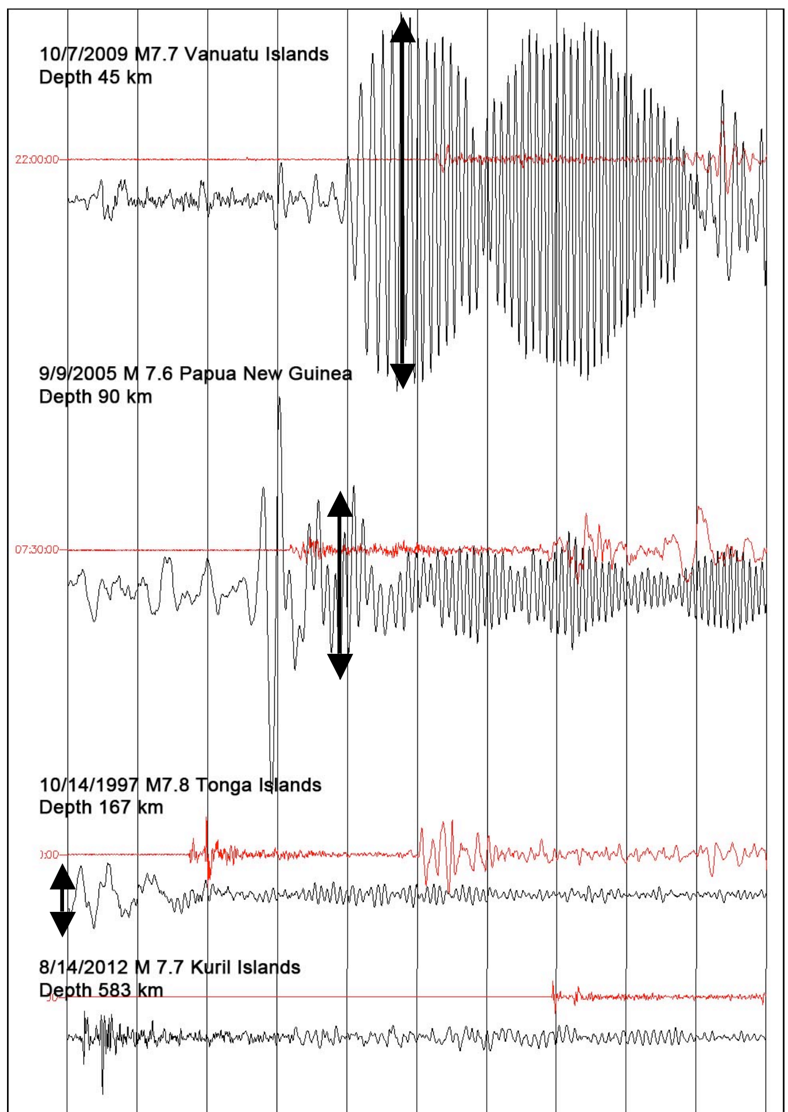

Figure 4. The body wave magnitude scale was developed to estimate the magnitude of deep earthquakes. The four seismograms to the right all have magnitudes between 7.6 – 7.8 but the amplitude of the surface waves (peak amplitude shown by arrows) is very different. The top earthquake is a typical shallow earthquake, centered at a depth of 45 km beneath the surface. The body waves (on the first line and the first half of the second line) are much smaller than the surface waves. Surface waves can still be seen on the second seismogram (90 km depth) but are only about half the size of the shallower earthquake. At a depth of 167 km, the surface waves can barely be seen and in the bottom record, the surface waves are not present.

M_{coda} Coda length Magnitude (sometimes called M_D, Duration Magnitude)

This is an automated magnitude estimated made by computers based only on the duration of the detectable signal. The length of the recording correlates with the magnitude of the earthquake. It is usually the first magnitude reported by the Real-time USGS earthquake postings and is qualified by the statement: *This is a computer-generated message -- this event has not yet been reviewed by a seismologist*. Large earthquakes or widely felt earthquakes are always reviewed by seismologists but many earthquakes in the magnitude 2 and smaller range are never examined more closely and are given coda magnitudes only.

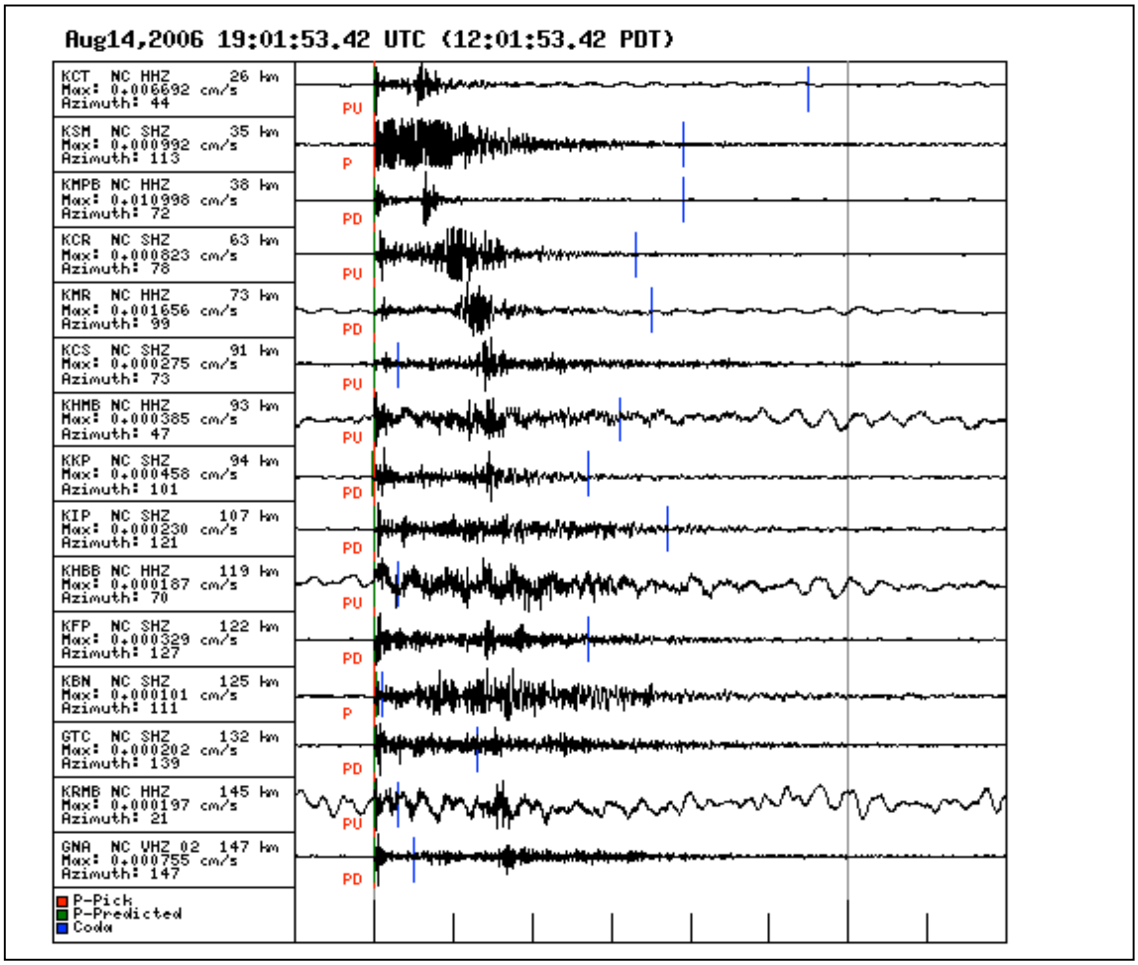

Figure 5. Automated computer coda length picks (blue vertical lines) for 15 stations that recorded a magnitude 2.8 earthquake offshore of Cape Mendocino, August 14, 2006.

M_{fa} Felt Area Magnitude

For earthquakes prior to the instrumental era, none of the previous techniques can be used to determine magnitude. Several seismologists have developed methods to estimate magnitude from isoseismal maps. These methods usually use the area of a particular isoseismal zone such as MMI VII to estimate magnitude. The method is only used for earthquakes that occurred before the 20th century.

In the 1970s, a number of weaknesses in the above types of magnitudes became apparent. The magnitude techniques were not based on the underlying physics of the earthquake source, but arbitrary relationships between peak amplitude and size, scaled to a particular seismograph.

Different methods and different instruments were used for different groups of earthquakes. It was not unusual for three different magnitudes to be released to the public, differing by a half a magnitude value or more. An even bigger problem was that all of the commonly used magnitude scales used in the 1960s and 1970s saturated for the biggest earthquakes. For example, the 1906 San Francisco earthquake had a surface wave magnitude of 8.3, the 1960 Chile earthquake an 8.5 and the 1964 Alaska earthquake an 8.4 (Table 1), making them appear very similar in size. But when one looks at the size of the fault ruptures in these earthquakes, the duration of shaking, and the area of impacts, it's very clear that San Francisco was much smaller than the other two. The problem is that the amplitude just can't become any larger after a certain size of fault rupture and so any magnitude method that relies on peak amplitude "tops out" at a certain level. For Body Wave magnitudes, that saturation point is about 6.8. For Surface Wave magnitudes, it's about 7.5.

In the 1970s, a number of seismologists looked at the mechanics of the earthquake source and used elastic dislocation theory to improve understanding of the energy released by fault slip during an earthquake. This theory proposed that the energy release from a quake is proportional to the surface area of the fault, the average distance that the fault is displaced, and the strength of the fault as measured by the rigidity of the rock mass, giving rise to calculation of *seismic moment* and *moment magnitude*.

M_W Moment Magnitude

Unlike the magnitudes on the previous page, moment magnitude is based on the physical dimensions and properties of the earthquake fault. Seismic moment is defined as the product of the fault area, fault slip and the shear modulus of the rocks in the area.

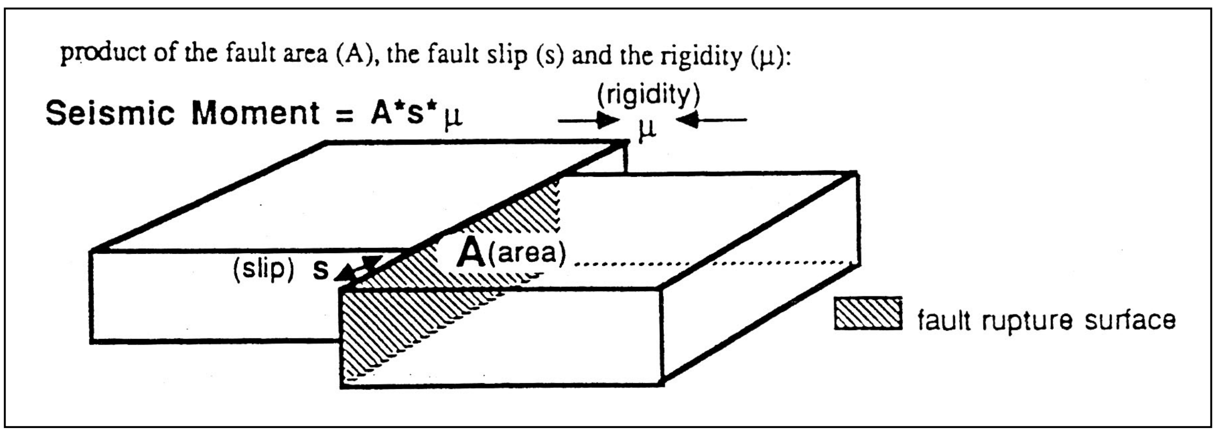

Figure 6. Seismic Moment is directly related to physical properties of the earthquake source. It is the product of the area A of the fault rupture surface, the amount of slip (s) or offset, and how tightly the two sides of the fault are held together – the rigidity (μ).

It is not usually possible to measure the area and slip of a fault directly. Fortunately seismic waves are very sensitive to the fault characteristics and seismologists can analyze the seismograms from a broadband instrument and invert the data to determine the seismic moment. A mathematical relationship allows conversion of the moment value into a magnitude number that on average agrees with the other magnitude determination methods.

Moment magnitude has now become the standard magnitude for all earthquakes of magnitude 5 or larger, and in the United States, is routinely used for West Coast earthquakes in the magnitude 4 range as well. It is particularly useful for determining the magnitudes of very large earthquakes (magnitude 7.5 or larger) where the other magnitude scales break down. In our comparison of the 1906, 1960 and 1964 earthquakes, it was clear that M_s did a poor job of differentiating the size of these events. Calculating the seismic moments of these earthquakes and determining the Moment Magnitude M_w gives these three events sizes that are a much better match for their true scale (Table 1).

TABLE 1: Magnitudes and fault dimensions

Earthquake	area of fault rupture	duration	Ms	Mw
1906 San Francisco	5,000 square km	40 seconds	8.3	7.8
1960 Chile	100,000 square km	7 minutes	8.5	9.5
1964 Alaska	50,000 square km	5 minutes	8.4	9.2

An additional complication in magnitudes is that earthquakes have complex sources and don't send out seismic waves in a completely uniform pattern. The orientation and nature of faulting can cause waves to be directed and amplified in certain directions relative to others. Each seismic network uses a particular set of instruments to locate earthquakes and estimate magnitude. The Berkeley Seismographic Station uses a network of instruments located in northern California. The National Earthquake Information Center uses a network of globally distributed stations. Because the instruments are located in different geographic regions, the calculated magnitudes may vary slightly among scientific agencies.

An earthquake near Seattle in the 90s illustrates how many of these different magnitudes come into play. The May 2, 1996 earthquake (called the Duvall earthquake because of its proximity to the small town of Duvall on the Snoqualmie River) was located about 25 miles northeast of Seattle or 6 miles east-northeast of Duvall. Here is a time sequence of magnitude estimates:

- The Pacific Northwest Seismic Network run jointly by the University of Washington and the USGS released an initial coda length magnitude ($M_{\mathbf{coda}}$) estimate of 4.8 about ten minutes after the earthquake based on automatic processing and duration of shaking as recorded on regional seismographs.
- The U.S. Geological Survey issued a body wave magnitude (m_b) estimate of 5.4 about an hour after the earthquake using the P-wave amplitude as recorded in Golden Colorado.
- The U.S. Geological Survey revised their magnitude to 5.2 after analyzing seismograms from other U.S. seismic stations that recorded the earthquake.
- The Pacific Northwest Seismic Network revised their initial estimate about two hours after the earthquake based on manual review of seismograms from a network of seismographs in the Seattle and Puget Sound area operated by the University of Washington gave a local magnitude (M_L) of 5.3.
- The Pacific Geoscience Center in Victoria, British Columbia estimates a Local Magnitude (M_L) of 5.5 using a Canadian network of instruments.
- A few hours later, Oregon State University estimated a moment magnitude (M_W) of 5.2 by analyzing the complete wave forms of the earthquake as recorded by broadband seismographs in Oregon.
- The next day, the University of Washington estimated a moment magnitude (M_W) using a subset of the Oregon data to get a value of 5.1.
- The final USGS Moment Magnitude estimate is 5.2.

None of these different magnitudes were exactly the same and, although the media stories reported them as a “Richter Magnitude”, none were determined in the way Richter originally defined magnitude. But all of the magnitude scales are calibrated to roughly agree with Richter's scale so that a magnitude 5 earthquake, regardless of scale, is a moderately strong earthquake capable of doing minor damage in the immediate epicentral area.

It is particularly difficult to get a quick accurate magnitude estimate of very large earthquakes because the size of the reflected and refracted phases (such as PcP, PP etc.) obscure the direct waves and the surface waves continue to arrive for many hours. The initial magnitude estimate of the 2004 Indonesia earthquake was an 8.0 and it took many hours before it became clear that the earthquake was in the 9 range. A similar process occurred on March 11, 2011 when the initial estimates of the Tohoku, Japan earthquake were 7.8 – 7.9 and it took about an hour before a magnitude of 9 was confirmed. This is not purely an academic exercise. Likelihood of a tsunami depends on earthquake size and the initial tsunami warning issued by the Japan Meteorological Agency based on the 7.9 magnitude, significantly underestimated the size of the tsunami.

Terminology: *body wave magnitude, coda-length magnitude, duration magnitude, felt-area magnitude, local magnitude, moment magnitude, Richter magnitude, Richter Scale, seismic moment, surface wave magnitude*

Review questions:

1. Epicenter location and **magnitude** are usually the first reported information about an earthquake. Which of the following is a property of magnitude?
   a) depends on the type of geology underlying a site
   b) may be measured by public responses to the "Did You Feel It?" web site
   c) theoretically a single value for each felt earthquake
   d) is related to the depth of the earthquake
   e) distant stations will measure smaller magnitudes than close stations

2. Why is surface wave magnitude (M_s) a poor way to determine the size of a deep earthquake?

3. Give two reasons why magnitude estimates in the first few hours after an earthquake are likely to vary?