A Closer Look At Body Wave Magnitude & Introduction To Moment Magnitude

Previously we have learned the mechanics of calculating earthquake magnitudes with several magnitude scales: Duration Magnitude, Richter (or Local) Magnitude, Body Wave Magnitude, and (very briefly) Surface Wave Magnitude.

In this activity we will focus on a closer look at the Body Wave Magnitude, m_b, as a prelude to a new magnitude scale called Moment Magnitude. We would like to think more deeply about what m_b does and does not tell us about an earthquake. To illustrate the Moment Magnitude scale we will use the 2004 Parkfield earthquake as our dataset.

You can check out a video of the ground shaking during this earthquake here:

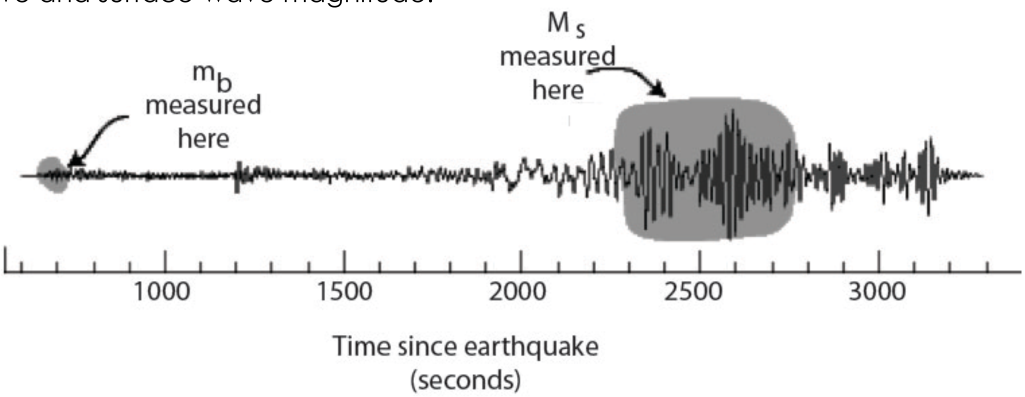
http://earthquake.usgs.gov/research/parkfield/2004.php

as well as other information about this earthquake here:

http://earthquake.usgs.gov/research/parkfield/index.php

Figure 1 below displays what information is taken from the seismogram for the body wave magnitude, m_b. For comparison the portion of the seismogram used for surface wave magnitude, M_s, is also highlighted. A take-home point is that both of these magnitudes select just a portion of the seismogram, discarding the rest of the information it contains.

Figure 1. Locations of seismic wave arrivals in a seismogram used to determine body-wave and surface-wave magnitude.



To jog your memory, the body-wave magnitude formula is listed here:

$$m_b = \log A - \log T + 0.01\Delta + 5.9$$

Body-Wave Magnitude Review

Question 1. Think about two earthquakes recorded here is San Luis Obispo. Suppose the first earthquake was located in San Francisco and the second earthquake was located in *San Jose* (as in the capital city of Costa Rica!) - see Figure 2 below. Assume the earthquakes are otherwise “equal.” Recall that the body wave magnitude requires us to measure the amplitude of the P-waves. Which earthquake would you predict to have the larger P-wave amplitude here in San Luis Obispo?

Answer:____

Figure 2. Map of North & Central America.

Question 2. What is the role, then, of the term 0.01Δ in the formula for body-wave magnitude? In other words, what does it “correct?”

Question 3. In Figure 3, two seismograms recorded at the same seismic station are shown, displaying the seismograms from different earthquakes with nearly the same hypocenter. Are you willing to agree with someone that said the earthquake recorded in the bottom seismogram was significantly larger than the earthquake recorded in the top seismogram? List reasons for why you agree or disagree.

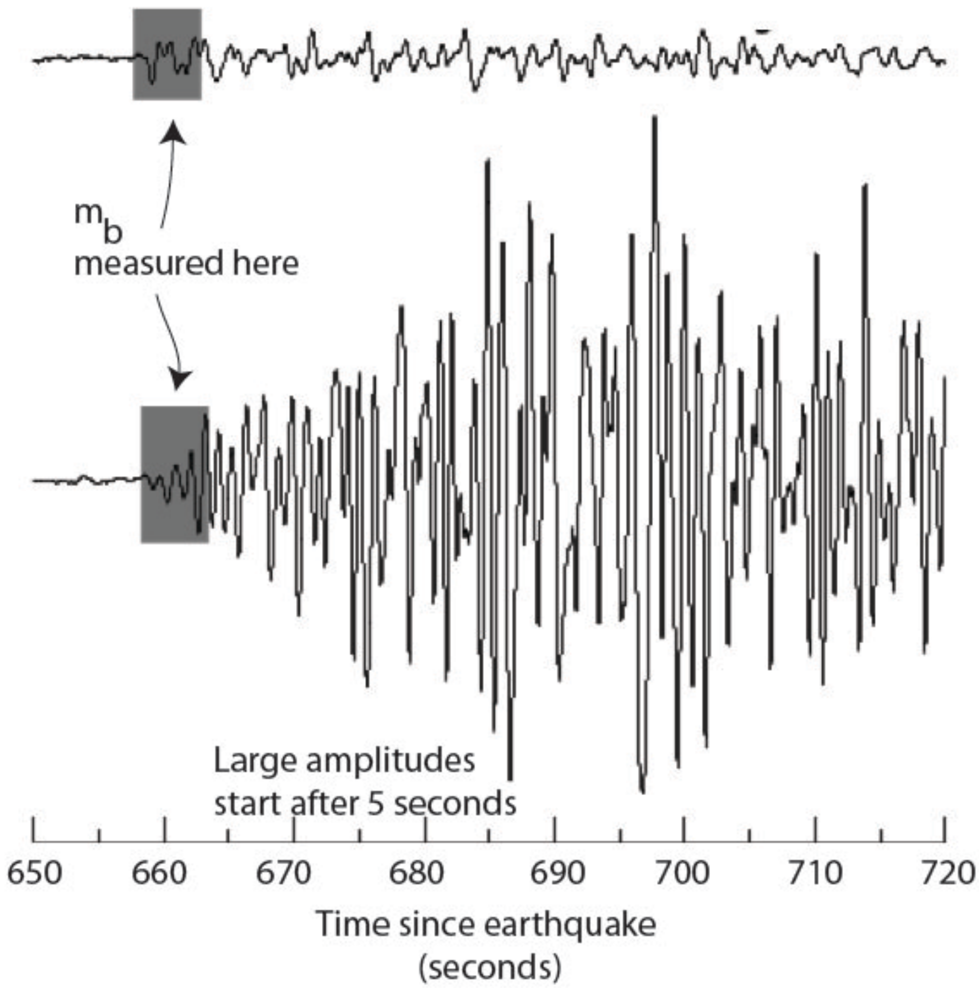


Figure 3. P-waves generated by two earthquakes in Kamchatka and recorded at a seismic station in Cathedral Caves, MO. Time is referenced to the onset of the earthquake rupture for each earthquake.

Question 4. Let's think about applying the body-wave magnitude formula to the above two seismograms.

- Which body wave is used in the body-wave magnitude? ____________
- What two pieces of information do we need to measure from this body-wave?

1. ______________

2. ______________

Without doing the actual body-wave magnitude calculation, do you think that the body-wave magnitude for each of these earthquakes would be very similar, ***or*** very different? List two specific reasons that informed your choice.

1.

2.

Question 5. Body-wave magnitude uses only seismograms to make a magnitude estimate – but nothing about the fault on which the earthquake nucleated. Thinking about the movement on the fault that generated the earthquakes in Figure 3, during which earthquake would you predict that the fault slipped over a larger area – the "top" earthquake or the "bottom" earthquake? State specific reasons why you think so.

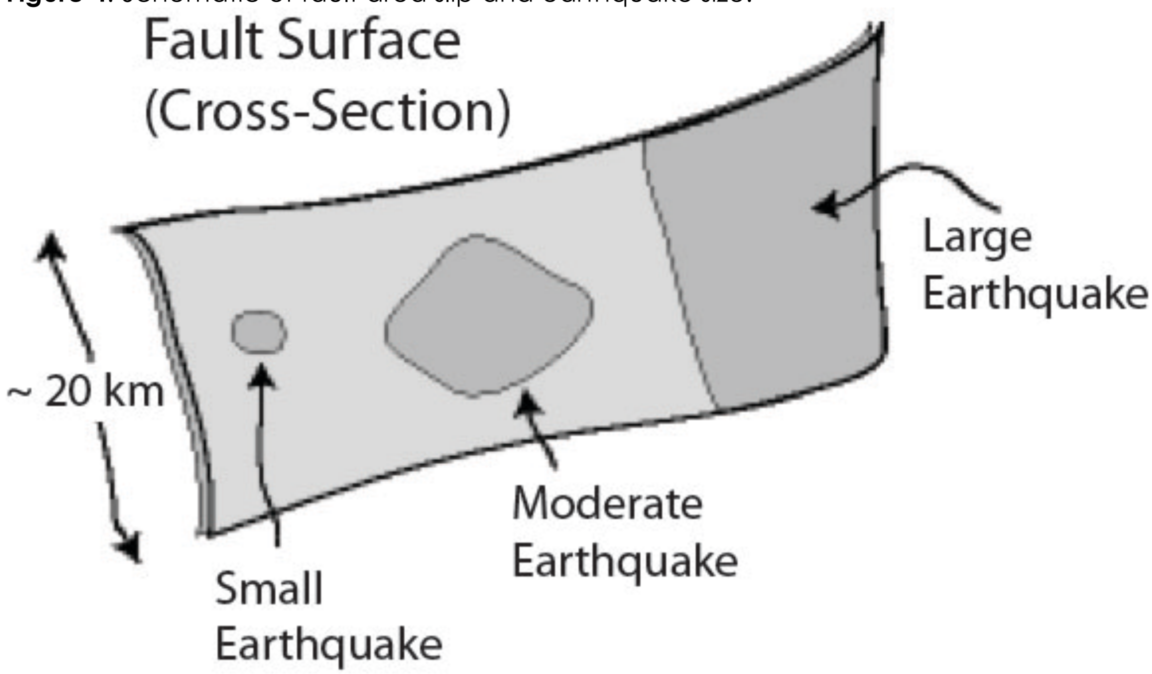
Question 6. Thinking "loosely" about energy release in an earthquake, which earthquake above in Figure 3 do you think released more energy as the fault slipped? Why?

Question 7. Moral of the Story: What is a "limitation" in the body-wave magnitude illustrated by these two earthquakes?

Earthquake Dimensions - Rupture Size and Offset.

Another measure of earthquake size is the area of the fault that slipped during the earthquake. During large earthquakes the part of the fault that ruptures may be hundreds of kilometers long and 10s of kilometers deep. Smaller earthquakes rupture smaller portions of the fault. Thus the area of the rupture is an indicator of the earthquake size.

Figure 4. Schematic of fault area slip and earthquake size.



The **area** that slips during an earthquake increases with earthquake size. The shaded regions in the figure above on the fault surface are the areas that rupture during different size events. The largest earthquakes generally rupture the entire depth of the fault, which is controlled by temperature. The temperature increases with depth to a point where the rocks become plastic and no longer store the elastic strain energy necessary to fail suddenly.

A second aspect of earthquake size is the length of the **offset** produced during an earthquake - that is, how far did the two sides move relative to one another? Small earthquakes have slips that are less than a centimeter; large earthquakes move the rocks 10-20 meters! Stop and think about that for a minute…if you aren't impressed, think some more…

IMPORTANT: Note the difference between the area of a fault that slipped, and the offset or distance that it slipped.

Estimating the *Area* of Slip

The area of the fault rupture might be estimated if a large number of aftershocks can be located. Why is the spatial location of aftershocks a reasonable way to roughly estimate the area of slip?

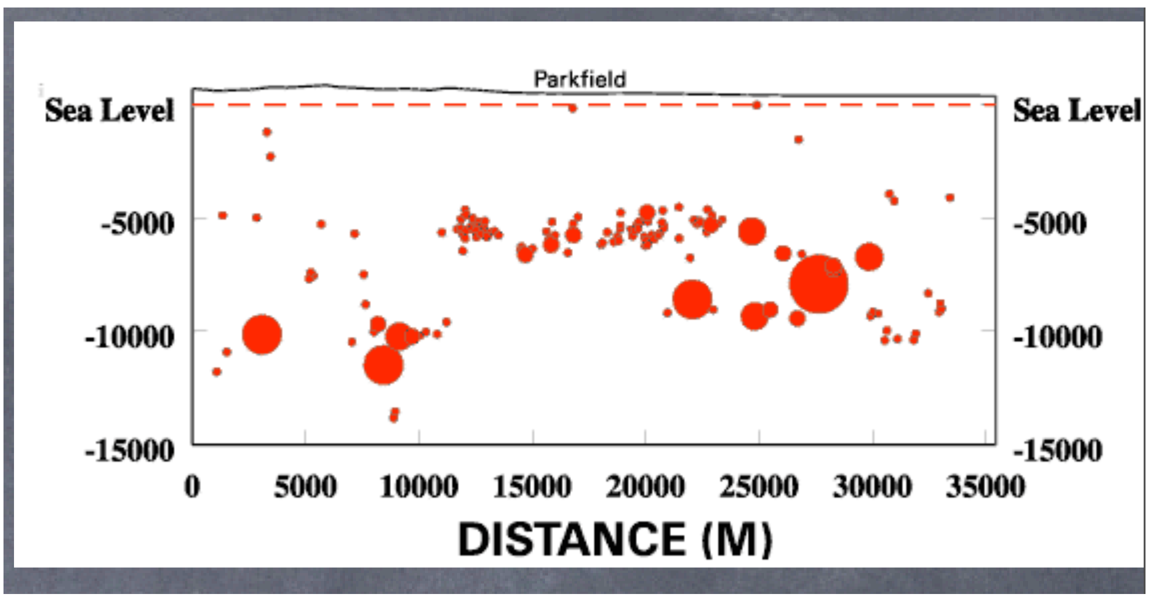


Figure 5. Aftershock distribution of the 2004 Parkfield earthquake (San Andreas Fault).

Question 8. Examining Figure 5, estimate the **area** of the San Andreas Fault that moved during the 2004 Parkfield Earthquake. Use the simplest and most obvious geometric shape to estimate the area. Make sure you attach appropriate units to your answer!

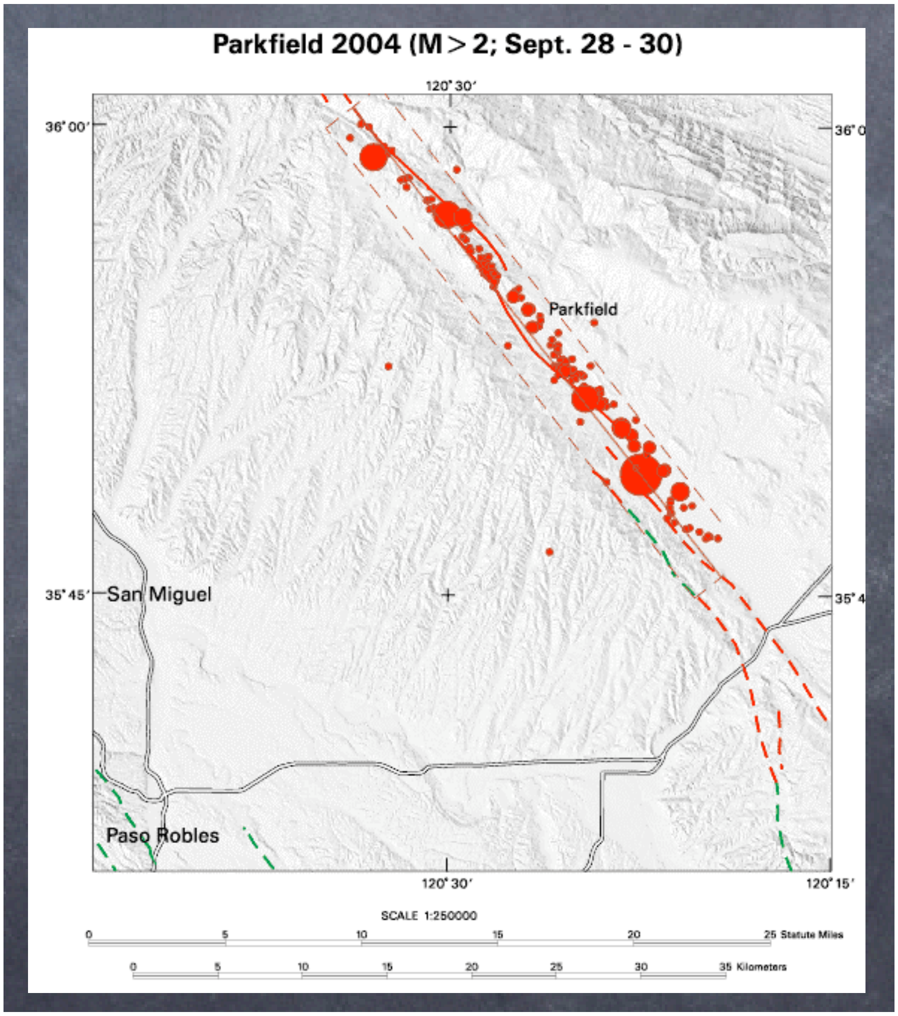


Figure 6. Surface projection of the aftershocks from the 2004 Parkfield earthquake.

A different point of view to ponder:

Figure 6 above shows the surface projection (map-view) of the hypocenters in the cross-section shown in Figure 5. It displays the hypocenter data of Figure 5 in only one dimension. In other words the hypocenters are now shown as epicenters.

Let's now move on to the definition of Moment Magnitude…

Seismic Moment (M_0) and Moment Magnitude (M_w)

The moment magnitude will re-connect earthquake size, or magnitude, with the actual process of fault slip. In addition, it will be an improvement over previous magnitude scales because it will measure energy release by the earthquake.

Seismic moment (denoted as $\mathbf{M_0}$) is a quantity that combines the area of the rupture, the amount of fault offset, and a measure of the strength of the rocks: rock rigidity, μ. The units of rock rigidity are $\frac{N}{m^2}$, where N is the unit of force, Newtons, from "F = ma."

M_0 = Seismic Moment = μ x (Rupture **A**rea) x (Fault Offset-**D**istance)

In compact form, the above formula reads:

$$M_0 = \mu A d$$

Let's check out the units that are produced by the right-hand side of this formula:

$$\frac{N}{m^2} \cdot m^2 \cdot m = N \cdot m = J\,(Joules)$$

IMPORTANT: The physical units of seismic moment are Joules, *J*, which are units of energy:

(Newtons) *times* (meters) = Joules (units of energy).

This is a measure of **energy** released by the earthquake, and thus an improvement over previous magnitude scales because it measures a physical aspect of the earthquake without referring to the seismogram – ENERGY RELEASE.

Seismic Moment is a large number and so it is difficult to easily internalize. To compare seismic moment M_0 with previous magnitude scales, we can use the following empirical formula:

$$M_w = (2 / 3)*\log(M_0) - 6.$$

This number, $\mathbf{M_w}$, is dimensionless like our previous magnitude scales and is called the ***Moment Magnitude***.

Let's now move on to estimating the **fault offset**, denoted by **d**.

Keep in mind the differences between:

(1) The **length** along the surface (map-view) that the fault ruptured/slipped.
(2) The **area** of the fault (cross-section) that ruptured/slipped.
(3) The relative **offset** of the fault due to the earthquake.

It is difficult to estimate one number for the offset of a fault during an earthquake. For very large earthquakes, such as the 1906 San Francisco earthquake, there can be obvious offset markers such as fences offset by several meters. In the case of a moderate earthquake like the 2004 Parkfield event, the surface may not contain any obvious and reliable offsets to use.

However, using results from a study of this earthquake [Johanson, 2006], which estimated both "co-seismic" and "post-seismic" slip, we will use an **offset of 300 mm** for our discussion here.

Question 9. Let's now calculate the moment magnitude, M_0, of the 2004 Parkfield Earthquake. Fill in the blanks below to collect all your information from above into one place (remember to also label your values with appropriate units)

- Area of fault rupture (previously calculated): ________________

- Offset of fault (given above): _____________________

- Rock Rigidity μ: $3\times10^{10}\frac{N}{m^2}$ (This is a typical value).

- Calculate the Seismic Moment M_0 using the formula stated on the previous pages: $M_0 = \mu A d$. Show your calculation in detail writing the units along with each number – we want to see how the units cancel out and combine. What is the final value and unit?

- Now calculate Moment Magnitude, M_w, using the formula stated above: $M_w = (2 / 3)*\log(M_0) - 6$.

- The 2004 Parkfield earthquake is listed as a magnitude 6 event by the USGS – see a summary poster at the following website: http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2004/20040928.php

  How well does your estimate compare?