Earthquakes log and exponential relationships

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Objectives for the day

• Learn to use the frequency-magnitude model to estimate recurrence intervals for earthquakes of specified magnitude and greater.

• Frequency magnitude and microseismic

• Learn how to express exponential functions in logarithmic form (and logarithmic functions in exponential form).
World seismicity – Jan 13 to Jan 20, 2015
http://earthquake.usgs.gov/earthquakes/map/
Larger number of magnitude 2 and 3’s and many fewer M5’s

<table>
<thead>
<tr>
<th>MAG</th>
<th>UTC DATE - TIME</th>
<th>LAT deg</th>
<th>LON deg</th>
<th>DEPTH km</th>
<th>Region</th>
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<td>2013/01/21 22:48:07</td>
<td>5.000</td>
<td>96.039</td>
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Earthquake magnitudes histogram January 13-20, 2015

Tom Wilson, Department of Geology and Geography
Some worldwide data

<table>
<thead>
<tr>
<th>m</th>
<th>N/year</th>
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<tbody>
<tr>
<td>5.25</td>
<td>537.03</td>
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<tr>
<td>5.46</td>
<td>389.04</td>
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<tr>
<td>5.70</td>
<td>218.77</td>
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<td>5.91</td>
<td>134.89</td>
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<td>9.27</td>
<td>0.04</td>
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<td>9.47</td>
<td>0.03</td>
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Observational data for earthquake magnitude (m) and frequency (N, number of earthquakes per year (worldwide) with magnitude m and greater)

What would this plot look like if we plotted the log of N versus m?
Log linear plot – The log transformation on the y axis but not x turns this relationship into a straight line.

Looks almost like a straight line. Recall the formula for a straight line?

On log scale
Here is our formula for a straight line ...

\[ y = mx + b \]

What does \( y \) represent in this case?

\[ y = \log N \]

What is \( b \)?

the intercept
The Gutenberg-Richter Relationship or frequency-magnitude relationship

\[ \log N = -bm + c \]

-\(b\) is the slope and \(c\) is the intercept.
January 12\textsuperscript{th}, 2010 Haitian magnitude 7.0 earthquake
Shake map

Map Version 7 Processed Wed Jan 13, 2010 06:53:11 PM MST – NOT REVIEWED BY HUMAN

<table>
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<th>PERCEIVED SHAKING</th>
<th>Not felt</th>
<th>Weak</th>
<th>Light</th>
<th>Moderate</th>
<th>Strong</th>
<th>Very strong</th>
<th>Severe</th>
<th>Violent</th>
<th>Extreme</th>
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<tr>
<td>POTENTIAL DAMAGE</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>very light</td>
<td>light</td>
<td>moderate/heavy</td>
<td>heavy</td>
<td>very heavy</td>
<td></td>
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<td>&lt;17</td>
<td>1.7-1.4</td>
<td>1.4-3.9</td>
<td>3.9-9.2</td>
<td>9.2-18</td>
<td>18-34</td>
<td>34-65</td>
<td>65-124</td>
<td>&gt;124</td>
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<td>PEAK VEL (cm/s)</td>
<td>&lt;0.1</td>
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<td>1.1-3.4</td>
<td>3.4-8.1</td>
<td>8.1-16</td>
<td>16-31</td>
<td>31-60</td>
<td>60-116</td>
<td>&gt;116</td>
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<tr>
<td>INSTRUMENTAL INTENSITY</td>
<td>I</td>
<td>II-III</td>
<td>IV</td>
<td>V</td>
<td>VI</td>
<td>VII</td>
<td>VIII</td>
<td>IX</td>
<td>X+</td>
</tr>
</tbody>
</table>

USGS NEIC

110 10 00 12 21:53:10 UTC 18.46N 72.53W Depth: 13.0 km, Magnitude: 7.0

Earthquake Location
Notice the plot axis formats

Haiti (1973-2010) Magnitude 2 and higher

\[ \log(N) = -bm + c \]
Magnitude 7 earthquakes are predicted from this relationship to occur about once every 20 years. Let's work through an example using a magnitude of 7.2.
The seismograph network appears to have been upgraded in 1990.
In the last 110 years there have been 9 magnitude 7 and greater earthquakes in the region.
Magnitude 7 earthquakes are predicted from this relationship to occur about once every 20 years. Let’s work through an example using a magnitude of 7.2.
Let's determine $N$ for a magnitude 7.2 quake.

$\log N = -0.935m + 5.21$

$\log N = -0.935(7.2) + 5.21$

$\log N = -1.52$
Hydraulic fracture stimulation

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Magnitude range very low compared to tectonic related earthquakes

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Microseismic applications

Figure 1. Post-treatment microseismic activity along a known fault plane (after Maxwell et al., 2009)

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
“out-of-zone” events

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Stage 7 – extensive out-of-zone activity

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Frac versus post frac b-values

Using b-values to discriminate between stimulation of smaller natural fractures and somewhat larger tectonic faults in the surrounding area.

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Record of pump pressure & microseismicity
Continued microseismic activity
Out-of-zone

~50°

~5° to 10°
Stage 7, b~1 associated with activity along pre-existing fault

Figure 11. Stage 7 frequency-magnitude plot and trend line.

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Stimulation of smaller natural fractures in the reservoir

The difference in the trend of moment-magnitude values is readily apparent when comparing Stage 2 to Stage 7. The b-value is approximately 2 for this data set and is illustrated by the trend line that has been added to the plot.

Downie, R., Kronenberger, Carizo, Maxwell, 2912, SPE 134772
Stage-by-stage and through time

Figure 13. Comparison of frequency-magnitude data for selected stages.

Figure 14. Moving window calculation of b-value during stage 6.
Another application ... See http://www.cspg.org/documents/Conventions/Archives/Annual/2012/313_GC2012_Comparing_Energy_Calculations.pdf

For applications to microseismic events produced during frac’ing. Missing data or – how many events didn’t you hear?

\[
\log_{10} N = a - bM_0
\]

Gutenberg-Richter Magnitude-Recurrence Relationship

Cumulative number of earthquakes (\(N \geq M_0\))

Magnitude (\(M_0\))

Missing data
Rupture area associated with microseismic events is very small.

Earthquake/Fault Scaling Relationships

- Minor: felt but does not cause damage
- Noticeable shaking but damage is unlikely
- Moderate: can cause damage to poorly constructed buildings
- Strong: can be destructive in populated areas
- Major: can cause serious damage over large areas

Zoback, 2014, online geomechanics class
Seismicity induced through increased brine disposal

A Recent Increase in Intraplate Seismicity

About 150,000 Class II EPA Injection Wells Operating in the US

Why the Increase in Seismicity?

Zoback, 2014, online geomechanics class
Back to class example, you know \( b \) from analysis of the data. How do you solve for \( N_{7.2} \)?

\[
\log N = -0.935m + 5.21 \\
\log N_{7.2} = -0.935(7.2) + 5.21 \\
\log N_{7.2} = -1.52
\]

What is \( N_{7.2} \)?

Let’s discuss logarithms for a few minutes and come back to this later.
Any questions about logarithms?

Logarithms are based (initially) on powers of 10.

We know for example that $10^0=1$,
$10^1=10$
$10^2=100$
$10^3=1000$

And negative powers give us
$10^{-1}=0.1$
$10^{-2}=0.01$
$10^{-3}=0.001$, etc.
Remember the general definition of a log

The logarithm of y - i.e. \( \log(y) = x \) solves the equation \( 10^x \) or \( 10^{\log(y)} = y \)

The logarithm of y is the exponent (x) we have to raise 10 to - to get y.

So \( \log 1000 = 3 \) since \( 10^3 = 1000 \) &

\[
\log (10^y) = y \text{ since }
\]
What is \( \log \sqrt{10} \)?

We rewrite this as \( \log (10)^{1/2} \).

Since we have to raise 10 to the power \( 1/2 \) to get \( \sqrt{10} \), the log is just \( 1/2 \).

Some other general rules to keep in mind are that

- \( \log (xy) = \log x + \log y \)
- \( \log (x/y) = \log x - \log y \)
- \( \log x^n = n \log x \)
These rules help guide us in the analysis of exponential or allometric functions. Given any number \( y \), we can express \( y \) as 10 raised to some power \( x \):

\[
y = 10^x
\]

Thus, given \( y = 100 \), we know that \( x \) must be equal to 2.

\[
y = ab^{cx}
\]

and

\[
y = a10^{cx}
\]

where \( b \) and 10 are the bases. These are constants and we can define any other number in terms of these constants raised to a certain power.

\[
i.e. \quad y = 10^x
\]
By definition, we also say that $x$ is the log of $y$, and can write

$$\log y = \log(10^x) = x$$

So the powers of the base are logs. “log” can be thought of as an operator like $\times$ (multiplication) and $\div$ which yields a certain result. Unless otherwise noted, the operator “log” is assumed to represent log base 10. So when asked what is

$$\log y, \text{ where } y = 45$$

We assume that we are asking for $x$ such that

$$10^x = 45$$
Sometimes you will see specific reference to the base and the question is written as

\[ \log_{10} y, \text{ where } y = 45 \]

leaves no room for doubt that we are specifically interested in the log for a base of 10.

One of the confusing things about logarithms is the word itself. What does it mean? You might read \( \log_{10} y \) to say - ”What is the power that 10 must be raised to to get \( y \)?”

How about this operator? -

\[ \text{pow}_{10} \rightarrow y \]
The \textbf{power} of base \textbf{10} that yields (\(\rightarrow\)) \textbf{y}

\[ \text{pow}_{10} \rightarrow 45 = \]

What power do we have to raise the base 10 to, to get 45

\[ \log_{10} y = 1.653 \quad \Rightarrow \quad 10^{1.653} = 45 \]

\[ \text{pow}_{10} \rightarrow 45 = 1.653 \]
We’ve already worked with three bases: 2, 10 and e. Whatever the base, the logging operation is the same.

\[ \log_5 10 \] asks what is the power that 5 must be raised to, to get 10.

\[ \log_5 10 = ? \]

**How do we find these powers?**

\[ \log_5 10 = \frac{\log_{10} 10}{\log_{10} 5} \]

\[ \log_5 10 = \frac{1}{0.699} = 1.431 \]

*thus* \( 5^{1.431} = 10 \)
In general, \[ \log_{\text{base}} (\text{some number}) = \frac{\log_{10}(\text{number})}{\log_{10} \text{base}} \]

or

\[ \log_b a = \frac{\log_{10}(a)}{\log_{10} b} \]

Try the following on your own

\[ \log_3 7 = \frac{\log_{10}(7)}{\log_{10}(3)} = ? \]

\[ \log_8 8 \]

\[ \log_7 21 \]

\[ \log_4 7 \]
Helpful way to remember how to determine the power for an arbitrary base – say \( n \), is that

\[
\log_n(y) = x, \quad \text{where} \quad y = n^x
\]

Take the \( \log_{10} \) of both sides of this equation to get the general rule that

\[
x = \frac{\log_{10}(y)}{\log_{10}(n)}
\]

Otherwise stated as

\[
x = \frac{\log_{10}(\text{the number})}{\log_{10}(\text{base})}
\]
So \( \log_{10} \) is often written as \( \log \), with no subscript.

\( \log_{10} \) is referred to as the common logarithm.

\( \log_e \) is often written as \( \ln \).

Thus

\[
\log_e 8 = \ln 8 = 2.079
\]

\( \log_e \) or \( \ln \) is referred to as the natural logarithm. All other bases are usually specified by a subscript on the log, e.g.

\( \log_5 \) or \( \log_2 \), etc.
Return to the problem developed earlier

\[
\log N = -0.935m + 5.21 \\
\log N = -0.935(7.2) + 5.21 \\
\log N = -1.52
\]

Where \( N \), in this case, is the number of earthquakes of magnitude 7.2 and greater per year that occur in this area.

**What is \( N \)?**

You have the power! 
Call on your base!
Base 10 to the power

Since \( \log N = -1.52 \)

\[ N = 10^{?} \]

-1.53 is the power you have to raise 10 to to get N.

Take another example: given \( b = 1.25 \) and \( c=7 \), how often can a magnitude 8 and greater earthquake be expected? (don’t forget to put the minus sign in front of b!)

\[ \log N = .... \]
Seismic energy-magnitude relationships
more logs

\[ \log_{10}(E_s) = 1.5M + 4.8 \]

What energy is released by a magnitude 4 earthquake?

A magnitude 5?

More logs and exponents!
How would you solve for E?

Where ... \( \log_{10}(E_s) = 1.5M + 4.8 \)

Hint ... \( 10^{\log_{10}(E_s)} = \)
Basic notation reminders

• \( \log(x) \) implies \( \log_{10} \)
• \( \ln(x) \) implies \( \log_{e} \)
• When in doubt – ask.
• Also, when in doubt, specify – \( \log_{10}(x) \)
A question to think about

Where \( \phi = \phi_o e^{-z/\lambda} \)

Solve this equation for \( \lambda \)
Have a look at the basics.xlsx file

Some of the worksheets are interactive allowing you to get answers to specific questions. Plots are automatically adjusted to display the effect of changing variables and constants.

\[ \phi = \phi_0 e^{-z/\lambda} \]

This particular function represents the reduction in porosity that occurs as a function of depth. This decrease is related in a general sense to the increased weight of overburden formations “squeezing” out the open space in the deeper formations.

Just be sure you can do it on your own!
Spend the remainder of the class working on Discussion group problems. The one below is all that will be due today

Some more problems for group discussion [Geology 351 Geomath (Wilson)]
Hand in before leaving

More practice with logarithms & exponentials
The Gutenberg-Richter Frequency Magnitude Relationship (see pb 19)
1. Frequency magnitude (Gutenberg-Richter) analysis of recent seismicity on the Gonave microplate (1973 to present) results in constants of \( b = 0.9346 \) and \( c = 5.213 \). The Gutenberg Richter relationship states that \( \log(N) = -bm + c \) where \( N \) is the number of earthquakes of magnitude \( m \) and greater per year. To estimate the number of years between magnitude 7 earthquakes in this region we solve the following:

\[
\log(N) = -(0.9346)(7) + 5.213
\]

\[
= -1.33
\]

Remember this is the power we raise the base 10 to, to get \( N \).

First – Calculate \( N \) and then estimate the number of years between magnitude 7 and greater earthquakes typical of the seismicity in this region. Show work below.

Exponential (Allometric) decay (or growth) (see formula pbs 15 & 16)
2. In the porosity depth relationship \( \phi = \phi_0 e^{-\frac{z}{\lambda}} \) let \( \lambda = 2 \) and \( \phi_0 = 0.55 \). Estimate the porosity at a depth of 3km.
Show your work below
• **Hand in the group problems (set 2) from last time**

Name: __________________________

Note group members:

Geology 351
Mathematics for Geologists
Group Problems 2

1) In the equation \( \phi = \phi_0 e^{-\frac{x}{d}} \) define all the terms (see section 2.7, pages 31 – 34).

2) Solve the following (see section 2.9) -

\[ \log_4 7 = \; \quad \]

\[ \log_8 10 = \; \quad \]

\[ \log_9 7 = \; \quad \]

\[ \log_5 21 = \; \quad \]
In the next class, we will spend some time working with Excel.

Geology 351 - Geomath
Computer Lab – Introductory Problem (using Excel)

Evaluating Depth/Age Relationships in the North Sea
The following instructions take you step-by-step through the generation and plotting of a data set using Excel. Many of you may already be familiar with Excel, but if you aren’t that’s not a problem. In future exercises you will learn how to fit straight lines and polynomials of higher order to specific data sets. Today, we are going to plot some data and take a conceptual look at some linear relationships we will see within the context of age-depth relationships for sediments deposited in the North Sea. We will learn how to generate xy data plots and format them in various ways.

GETTING INTO EXCEL
Follow along as we bring up Excel. The latest version of Excel (2007) is set up quite differently than prior versions. Access to various controls are arranged around what is referred to in Excel 2007 as the Ribbon. There are several folders across the top that one accesses to perform various tasks. To open a file, go to the office button in the upper left corner and click on it. In the drop down list you will see an open file option. Left click on FILE then browse to your data folder. In most cases this might be on the Desktop under your Favorites list (upper left). A lot of the class files will reside on a network folder. We’ll navigate over to this “common drive” and copy the ExcelData folder over to you G Drive. The G Drive is another network drive that is linked to your account and can be accessed from any computer in the building that is on the network. We’ll spend some time in class reviewing all this (take notes!). For today’s lab, select the data set DepthAge.xls and click the open button. A spreadsheet window containing the depth and age data will appear on the screen.

The data in the spreadsheet were taken from Chapter 2 of Waltham’s text (page 37, problem 2.11). The following data shown in the display below were taken from the Troll 31 well in the Norwegian North Sea.
• Hand in group problems 2 before leaving today
• Look over problems 2.11 through 2.13 for discussion next time
• Continue your reading
• We will examine a comprehensive approach to solving problems 2.11 and 2.13 using Excel next time.