Name:____________________________ Date:_________________

Induced Seismicity – Student Worksheet
Version – 5.0; Last updated – July 2015

The process of removing hydrocarbons from Earth's crust has become an essential activity for humankind. However, major challenges arise during oil and gas production that have the potential to affect the natural and built environments in a variety of ways.

One particularly challenging approach is known as the production of ***unconventional gas resources***, through a process known as hydraulic fracturing ("***hydrofracking***"). Hydrofracking involves injecting large volumes of water, sand and chemicals into the rock under high pressure to create cracks through which the gas may escape the rock formation and then be collected. Hydrofracking most commonly takes place in gas fields found in shales.

In addition, water is also trapped in the same pore space as oil and natural gas and is recovered during conventional oil and gas production. The disposal of naturally produced water and/or hydraulic fracture fluid presents major challenges, since the wastewater is frequently injected back into Earth's crust. Some states, such as Oklahoma and Ohio, allow hydrofracking and wastewater injection, while other states such as Pennsylvania, allow hydrofracking but require wastewater to be transported out of state for disposal. In Oklahoma, hydrofrac fluid represents only 10% or less of the fluids disposed of in wastewater injection wells [*Murray*, 2013; *Rubinstein and Mahani*, 2015].

In some cases, the stress generated from hydrofracking and wastewater disposal can cause increased levels of earthquake activity ("***induced seismicity***"). By its very nature, hydraulic fracturing causes very small earthquakes, which are normally not felt. However, the causal relationship between fluid injection and induced seismicity is an active topic of scientific research and debate, as the largest earthquake ever thought correlated with injection is a M5.7 earthquake in Oklahoma that occurred in November 2011 [*Keranen et al.,* 2013; *Sumy et al.*, 2014]. In addition, the complexity of unknown subsurface geologic structures can make drawing direct correlations between hydrofracking or wastewater injection with nearby earthquakes difficult.

The purpose of this activity is to explore the processes involved in unconventional oil and gas resource production (hydraulic fracturing), how we monitor seismic activity and draw correlations (or lack thereof) between fluid injection (related to hydrofracking or from wastewater disposal) and earthquake activity, and ways that we might establish a better understanding of correlations between the two. Lastly, we also investigate geothermal activity at the Geysers in California, to illustrate the difficulty in assessing natural versus induced seismicity in such a geologically complex region.

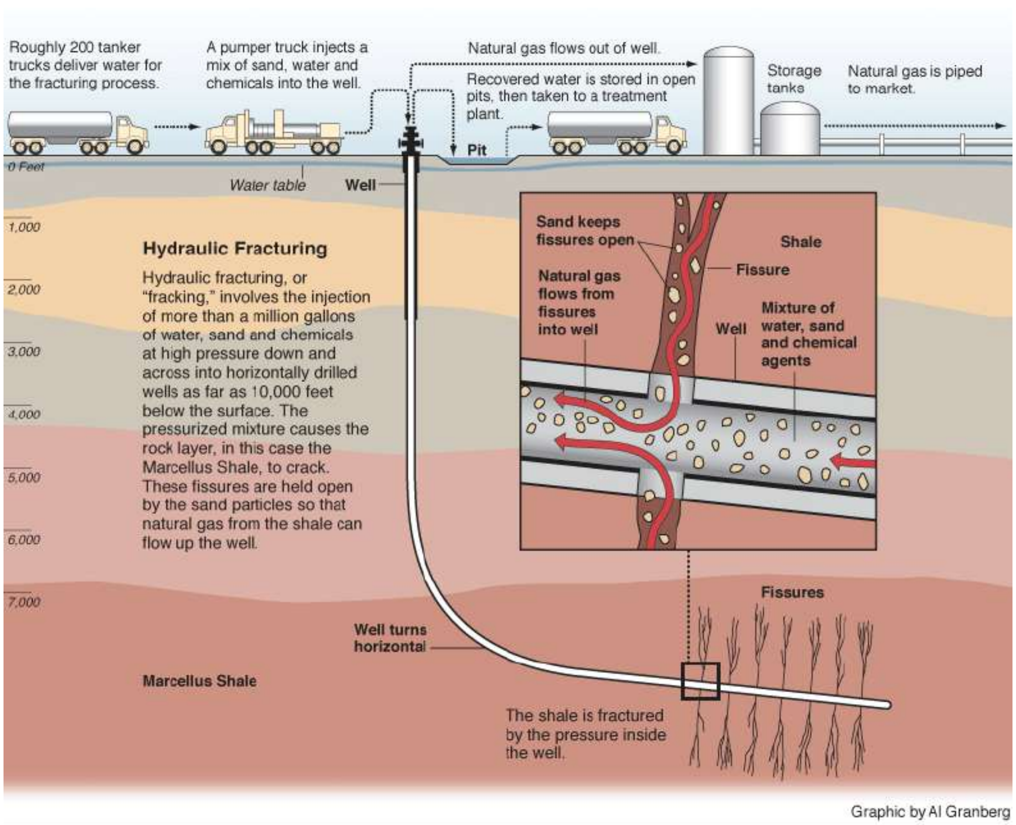
Part I: Unconventional resource exploration: Process and effects

Let's first start with understanding a bit about the hydrofracking process. Start by viewing a video produced by Marathon Oil: https://www.youtube.com/watch?v=VY34PQUiwOQ

Now, let's consider the stresses experienced by the rock during the hydrofracking process.

1) *What kinds of stresses would be generated when fluids are injected into shales during hydrofracking? Sketch the stress directions you think the hydrofracking process would create.*

Answers will vary. The general idea is that the injection of fluids during hydrofracking will generate tensional stresses in the pore spaces of the shale. The tensional stress can be well represented with arrows pushing out from the pore space within the shale.



Graphic by Al Granberg

2) *Sketch a fault in the area of wastewater disposal, and how you think that changes in stresses generated by fluid injection might cause changes in fault stresses.*

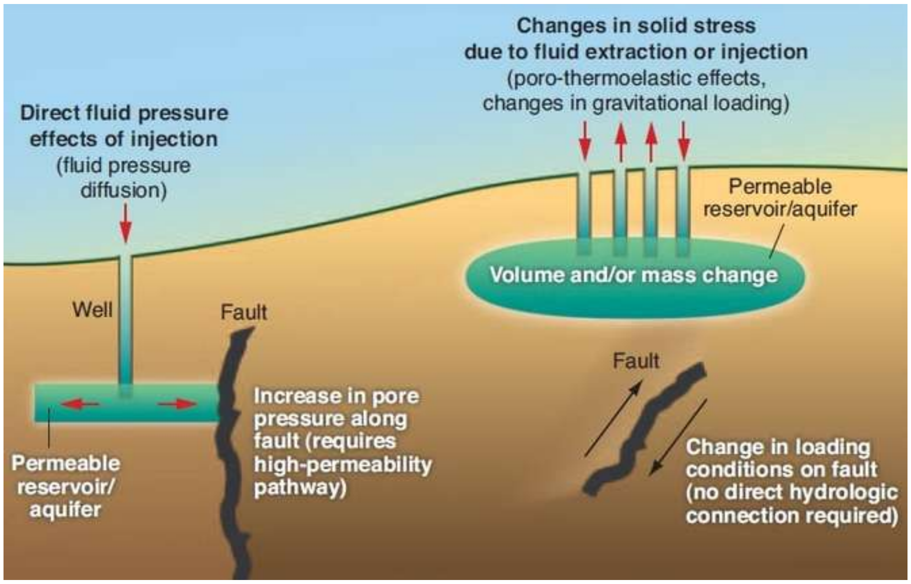


Figure from Ellsworth, Science, 2013.

Answers will vary. The general idea is to get students to consider the impact of stress changes in areas of fluid injection when faults are present. There could be a hydraulic connection with the fault, but there does not have to be. Changes in the loading conditions on the fault could cause it to slip. Otherwise, pore pressure increase along the fault could also cause the fault to slip, and result in an earthquake.

The left side of the figure shows the effects of pore pressure increase on the fault as you dispose of wastewater. The right side of the figure shows that by changes due to fluid extraction or injection on a fault, the volume and/or mass change can change loading conditions and allow the fault to slip.

Part II: Hydrofracking, wastewater injection, and seismic activity - general

Let's start our examination of regions with active fluid injection operations, and how the injection may or may not relate to regional seismic activity.

Let's begin by exploring areas in the United States with significant hydrofracking and/or wastewater injection activity. Go to http://www.fractracker.org/map/national/us-oil-gas/. Click on the map that you see, which will bring up a much larger map with layers that you can overlay or remove. You can simplify the map by pressing the Layers tab at the top of the screen, and deselecting all the layers except the layer on "Oil and Gas Wells (generalized)".

3) List two (2) areas/regions where you expected oil and gas wells to exist. Why?

Answers will vary, but the goal is for students to connect regions of active oil and gas wells to areas traditionally known for hydrocarbon extraction.

4) *List two (2) areas/regions that you were surprised that oil and gas wells exist. Why?*

Answers will vary, but may include regions just west of the Appalachian Mountains.

5) *Do you think that regions of oil and gas drilling end abruptly at state boundaries, such as Texas? Why or why not?*

Answers will vary. Students should also recognize that various states may or may not require reporting of oil and gas wells, and thus the accuracy of data across the country may not be uniform.

6) *Explore the "Shale Plays" and "Shale Basins" layers to examine the relationship between where the wells occur and the geologic formations. Does this change your answer to the above questions?*

After this question, students should recognize that much of the current drilling occurs in shale formations.

Now let's explore more specific information related to fluid injection activity. Injection wells related to oil and gas activities are Underground Injection Control (UIC) Class II wells, and are regulated by the EPA (http://water.epa.gov/type/groundwater/uic/). The Class II wells related to our purposes include ***enhanced recovery wells***, which include wells used in the hydrofracking process, and ***disposal wells***, which are used to dispose of fluids used in the production of oil and natural gas (http://water.epa.gov/type/groundwater/uic/class2/index.cfm).

Go to http://www.fractracker.org/map/us/ and explore a few states that have horizontal wells. The Layers tab can be used again to examine where the horizontal wells are located, and in which counties the wells are situated. Furthermore, you can take a look at the shale plays and basins and learn about their names.

When you click on a horizontal well, information about the well permit and the well type may be included.

7) *What information can you obtain relatively quickly and efficiently regarding details of well permits?*

Answers will vary, but possibilities include well completion date, location, activity, etc. For most/all cases, there will not be information regarding activity dates once the well is completed and in use.

Now let's examine seismicity in the United States using the IRIS earthquake browser (www.iris.edu/ieb). Zoom in on the United States (see icons on the left of the screen, and 'Zoom to Region' button), and choose a time range from 2008 to present (options on right). For best results, after zooming in, select a "Max Quakes" value of 5,000 (if this slows your browser down, reduce Max quakes to 2500). Besides looking at the seismicity in map view, you can also view a table of earthquakes using the "Open as:" feature in the bottom right of the IEB.

8) *Compare and contrast the earthquake activity in California with the rest of the continental United States. California has many active faults, like the San Andreas Fault. Are there other states that have earthquake activity? If so, which ones stand out to you?*

Answers will vary. Students should find that California has many earthquakes along the entire length extent of the state. Students should also observe that states like Washington, Oregon, Idaho, and Utah have earthquakes, among others. Missouri and Tennessee may also stick out as states with earthquakes. All in all, Oklahoma should stick out in the center of the country as a very seismically active state.

9) *Now shift the map to exclude California, and select a "Max Quakes" value of 5,000 (again, if this slows your browser down, reduce Max quakes to 2500). Compare the well maps you examined earlier to the seismicity maps, and describe at least two (2) regions that appear to contain both wells and significant concentrations of seismic activity. Describe the type of geology in the region, the extent of well activity, and the time and magnitude range of seismic activity.*

Answers will vary, but most students will select Oklahoma given the significant seismicity in the region and the likelihood that they have heard about this area in the news. Other possible regions include Texas, central Arkansas, southern Colorado, and central Tennessee west of the Appalachians.

Select one of the regions with spatial clusters of seismic activity. Investigate whether this region also exhibits characteristics consistent with seismic swarms; that is, that the seismic events are clustered in time and space, and usually have similar magnitudes or size. Once you have zoomed in on a region using the IEB, obtain the table of earthquakes using the "Open as: Table" feature in the bottom right of the IEB. Select the data in the popup window and copy to a blank Microsoft Excel sheet (note: the "Download as Excel" button does not work reliably in many cases, but if you do try this button, make sure that Microsoft Excel is already open). Create a seismicity timeline scatterplot to plot date vs. magnitude to assess whether the region you've chosen has experienced swarm type behavior. Use the "Timestamp" column to simplify the generation of this plot.

10) Are there obvious changes in seismicity rates for areas showing clusters of activity? Why or why not?

Answers will vary by region, but the scatterplot should make it easy to interpret (see example Excel spreadsheet entitled Example_IEB_output.xlsx which includes sample data and a plot on separate sheets). The generation of the scatterplot will likely take a bit of time to get the formatting done correctly, particularly handling the date column. Time ranges with many events of different magnitudes over a course of a few days are probably tectonic events and normal aftershock behavior. Look for clusters of many events with similar magnitudes (especially M<3.0) over short time spans.

11) Can you determine whether the observed seismicity is related to fluid injection in space and time? What additional information would help you answer this question?

Answers will vary, but the goal is to get students to recognize that they do not have any information related to the timing of well drilling or injection, and that without it, it's not possible to determine whether there is a correlation between seismicity and fluid injection activity.

Part III: Hydrofracking, wastewater injection, and seismic activity – Oklahoma case study

Here we will investigate potential connections between fluid injection and seismicity to test the hypothesis that wastewater fluid injection causes earthquakes.

As alluded to in the previous portions of this exercise, there is no comprehensive publicly available dataset that documents injection well activities. In lieu of actual well activity data, we will utilize a dataset of well completion dates, combined with a high-resolution catalog of seismicity for the state of Oklahoma.

For this activity, you'll need the Google Earth KMZ file **OK_Earthquakes_Wells_2010-2012.kmz**. Detailed information for each of the datasets is included in the "Places" tab to the left under "Temporary Places."

- Yellow circles: Earthquakes located by the Oklahoma Geological Survey
- White circles: Hydrofracking wells completed between 2010 and mid-2012
- Red circles: UIC Class II injection wells active as of January 2013

A time slider should appear once the data file is loaded in Google Earth. The injection wells are set to display for the entire time period and may or may not have operated during the entire time frame. The length of time for the time window in view can be adjusted using either the wrench on the time slider popup, or adjusting the time slider manually.

First, take some time to familiarize yourself with the operation of Google Earth and the time slider bar. For instance, make sure that the 'Borders and Labels' layer is selected (can be found under 'Layers' tab) and that the 'Scale Legend' is on under the 'View' tab to answer the following questions. Next, visually inspect the dataset over time to probe for earthquake swarms.

12) *Where did you find earthquake swarm activity? Remember from above that swarms are earthquakes that are clustered in time and space, and usually have similar magnitudes or size. To answer this question, you may need to zoom in and out on different regions in Oklahoma. Include the following in your answer:*
    a. *Town nearest the swarm*
    b. *Central latitude and longitude of the swarm*
    c. *Time window in which you observe swarm activity*
    d. *Approximate radius (in mi) that the swarm spans from the answer to (b)*
    e. *Approximate total number of earthquakes in the swarm (i.e. tens or hundreds)*

In 2010, two major swarms begin near: 1) Jones, Oklahoma (35º 33' 46"N, 97º 17' 35"W) that spans ~4-5 mi radius and includes hundreds of earthquakes, and 2) Centrahoma, Oklahoma (34º 39' 07"N, 96º 22' 43"W) that spans an ~7.5 mi radius and includes tens of earthquakes. A few smaller swarms also occur, and a possibility for inclusion would be a swarm near Bradley, Oklahoma in June 2011 (34º 52' 38"N, 97º 42' 24"W) with only about a dozen earthquakes and a ~2 mi radius. Note that the dataset also includes mainshock/aftershock sequences for a couple of regions (like the M5.7 Prague, Oklahoma earthquake that occurred in November 2011), which are difficult to visualize since the KMZ does not have scaled circles to denote event magnitudes.

13) *Does the observed swarm activity correlate with the location of nearby wastewater injection wells, the time of completion of nearby hydrofracking wells, neither, or both?*

From the answer to question 12 above, the 1) Jones swarm occurs near wastewater injection wells (see *Keranen et al.,* 2014 for more information about Jones, Oklahoma), and 2) the Centrahoma swarm occurs in close proximity to both hydrofracking wells and wastewater disposal, however, the earthquakes most closely correlate with the wastewater disposal wells. With respect to the Bradley swarm, both hydrofracking and disposal occur in the area, but the earthquakes most closely correlate with hydrofracking wells. Many regions will exhibit swarms near one or the other type of well, but some that the students pick out may not.

Most induced seismicity occurs within a few kilometers of an active injection well, but due to diffusion of stresses in rock, induced seismicity has been observed to occur up to ~35 km away from injection.

14) *What is the smallest distance you can find between an active wastewater injection welland an earthquake?*

Many regions have events <1 km from the nearest well. However, swarms like the Jones swarm can be up to 35 km away from the closest injection well.

15) *Based on your data and analysis, is there a causal link between wastewater disposal and increased seismicity? That is, do you have evidence to support the hypothesis that fluid injection induces seismicity in your study area?*

There does appear to be a causal link between wastewater disposal and increased seismicity within Oklahoma. Earthquakes occur in regions of active wastewater disposal, and appear to occur more frequently near disposal wells as compared to other parts of Oklahoma. A spatial comparison of earthquakes with hydrofracking wells versus wastewater disposal shows that earthquakes more often occur in regions of active wastewater disposal, and not in regions where just hydrofracking is occurring.

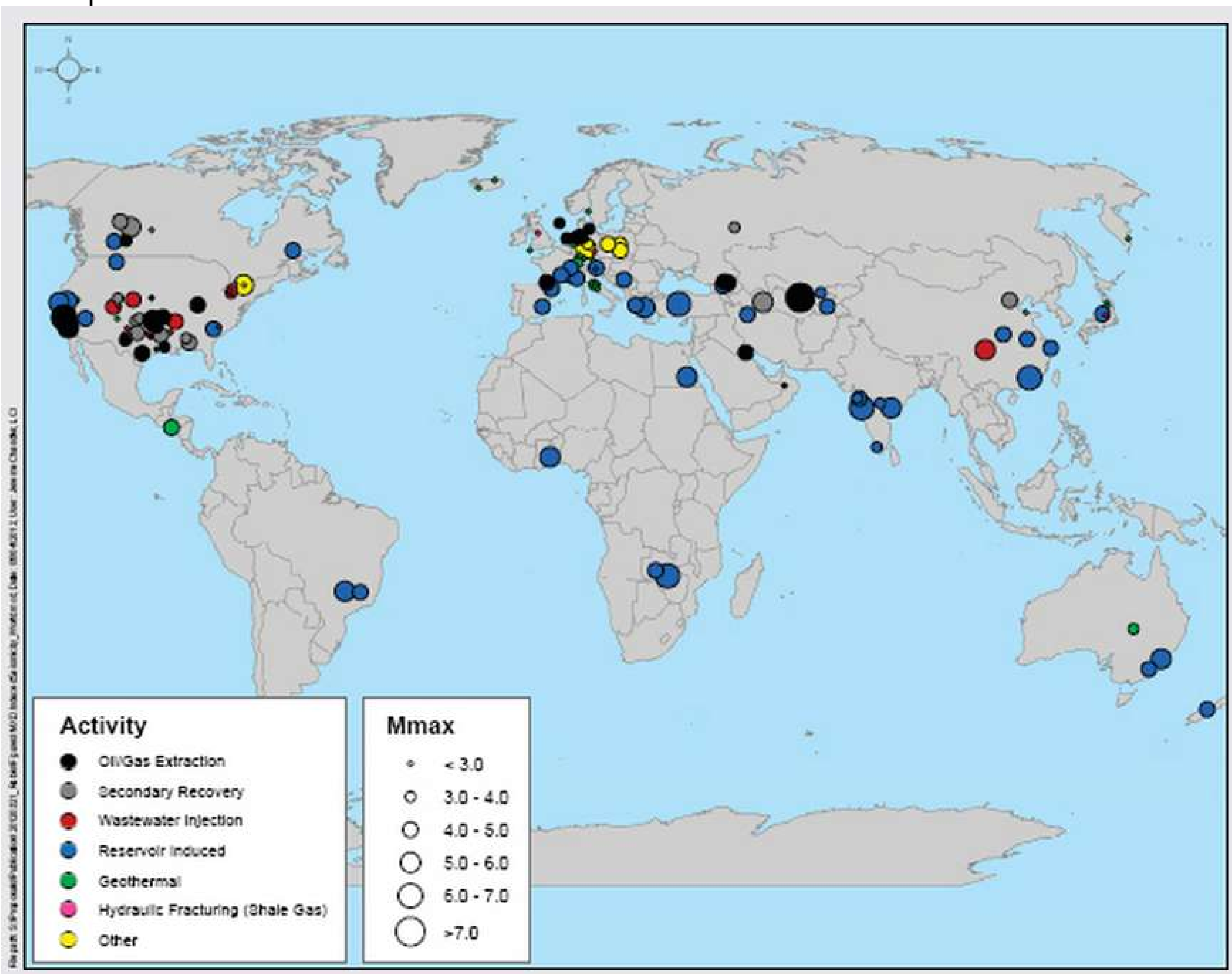
16) *What additional evidence would help you support your claim?*

As above, data showing the actual dates and times of well activity would help establish a more direct correlation.

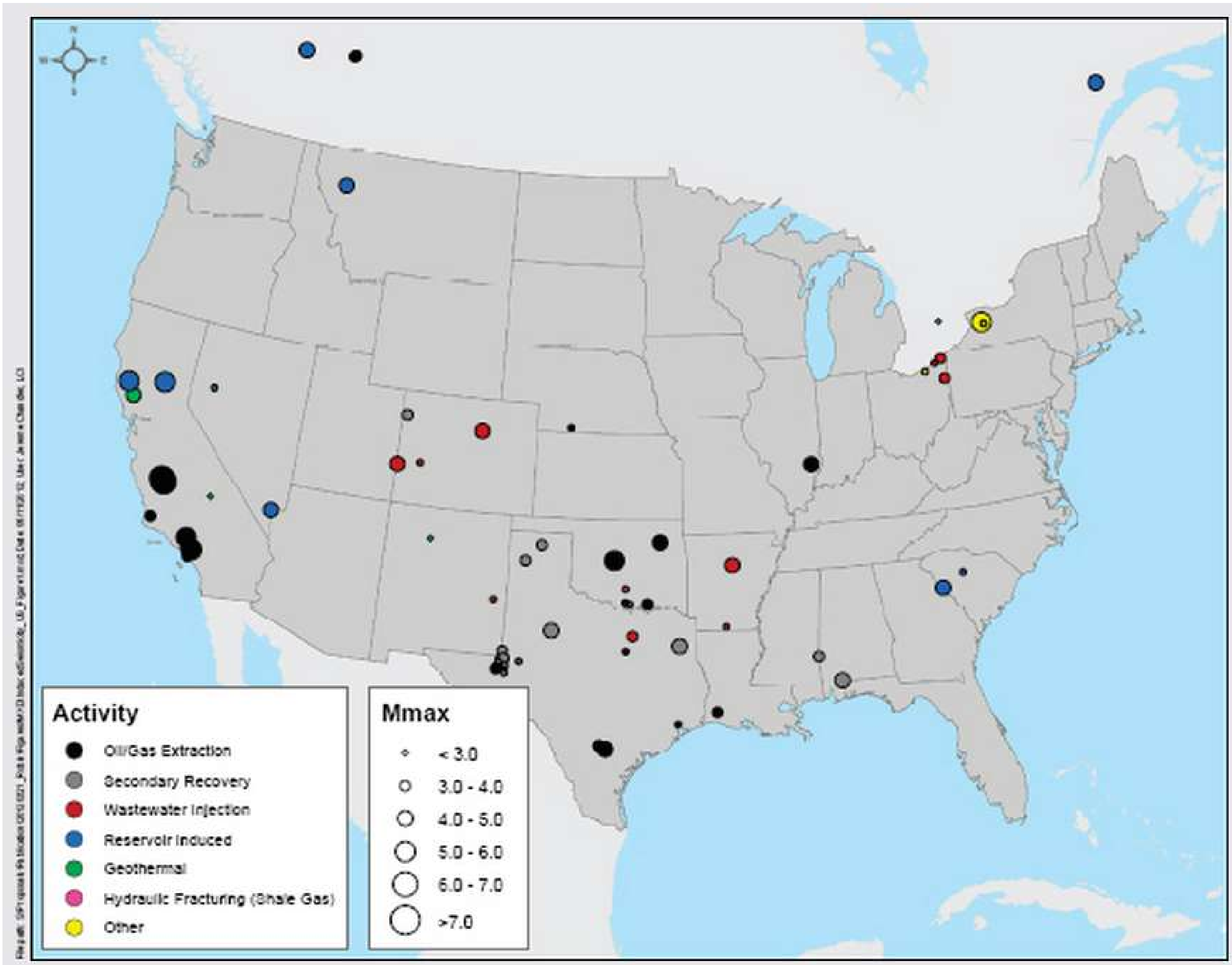
<u>Optional: Part IV: Geothermal energy development and induced seismicity</u>

While there have been isolated confirmed cases in the past, starting in 2011, scientists have observed with increasing confidence that earthquakes in Oklahoma, Texas, Ohio, Arkansas, and Colorado are likely to have been induced by the disposal of wastewater from oil and gas production activities. The National Academy of Sciences responded with a report entitled 'Induced Seismicity Potential in Energy Technologies' (National Research Council, 2013) that documented earthquakes related not only to hydraulic fracturing and wastewater injection, but also to geothermal energy development in the United States and worldwide. In this section of the activity, we will focus on a potential relationship between geothermal energy development and induced seismicity.

The figures below are taken from the 2012 National Academies of Science report on 'Induced Seismicity Potential in Energy Technologies.' The figures show earthquakes caused by or likely related to human activities worldwide and in the United States, respectively. The green circles mark earthquakes related to geothermal energy development.



(Map above) Worldwide locations of seismicity reported in the technical literature caused by or likely related to human activities, with the maximum magnitude reported as induced at each site. Figure and caption from the National Academies of Science.



(Map above) Locations of seismic events caused by or likely related to human activities within the coterminous United States and portions of Canada as documented in the technical literature. Figure and caption from the National Academies of Science.

1) *Based on the above maps, identify areas where earthquakes likely induced by geothermal energy development have occurred, both in the United States and worldwide.*

Answers will vary, but global regions may include Costa Rica, Italy, Iceland, Switzerland, and Australia. In the United States, earthquakes likely induced by geothermal energy development activity have occurred in California, Nevada, and New Mexico.

In 2008, an induced earthquake large enough to be felt occurred in the Geysers geothermal field in northern California, United States. The Geysers region is complex, in that earthquakes here occur due to naturally occurring faults as well as geothermal activity. Thus, it can be hard to differentiate between natural and induced earthquakes in the Geysers region. Here we will examine some of the details of this field as we explore the relationship between energy extraction and potentially related seismicity.

From the National Academies report, '*Geothermal energy production captures the natural heat of the Earth to generate steam that can drive a turbine to produce electricity. Geothermal systems fall into one of three different categories: (1) vapor-dominated systems, (2) liquid-dominated systems, and (3) enhanced geothermal systems (EGS). Vapor-dominated systems are relatively rare. A major example is The Geysers geothermal field in Northern California. Liquid-dominated systems are used for geothermal energy in Alaska, California, Hawaii, Idaho, Nevada, and Utah. In both of these types of hydrothermal resource systems, either steam or hot water is extracted from naturally occurring fractures within the rock in the subsurface and cold fluid is injected into the ground to replenish the fluid supply. EGS are a potentially new source of geothermal power in which the subsurface rocks are naturally hot and fairly impermeable, and contain relatively little fluid. Wells are used to pump cold fluid into the hot rock to gather heat, which is then extracted by pumping the fluid to the surface. In some cases a potential EGS reservoir may lack sufficient connectivity via fractures to allow fluid movement through rock. In this case the reservoir may be fractured using high-pressure fluid injection in order to increase permeability. Permeability is a measure of the ease with which a fluid flows through a rock formation. In each of these geothermal systems, the injection or extraction of fluid has the potential to induce seismic activity.*' (Chapter 1, Page 32)

2) *Which type of geothermal system is the Geysers geothermal field? Is this type of geothermal field common or uncommon?*

The Geysers geothermal field is vapor-dominated (type 1 from above). This type is uncommon (relatively rare).

Both vapor-dominated and liquid-dominated systems work by either steam or hot water extraction from naturally occurring fractures within the subsurface rock, and cold fluid is then injected back into the ground to replenish the fluid supply. Therefore, in contrast with hydrofracking, the fractures in these types of energy extraction settings occur naturally.

The Calpine Corporation owns and operates the Geysers geothermal field. You can find more information about their operations at www.geysers.com. Click on the tab labeled 'Geothermal Energy'.

3) *How large is the Geysers geothermal field? How many power plants does Calpine operate at the Geysers? What is the generating capacity of the geothermal field? How many homes can this power?*

The geothermal field comprises 45 square miles. Calpine operates 14 power plants at the Geysers. The Geysers can generate 725 MW of electricity, enough for 725,000 homes (or a city nearly the size of San Francisco).

Using the IRIS Earthquake Browser, zoom into the Geysers geothermal area. If necessary, use Google Maps, Wikipedia, or other web tools to help you locate the Geysers geothermal region. Once you have zoomed into the Geysers geothermal area, increase the Max quakes to 2500.

4) *Approximately how many earthquakes have been recorded within the Geysers region?*

Answers will vary depending on the region zoomed into, but should be on the order of one thousand plus.

Now let's investigate a more detailed view of seismicity in the Geysers geothermal area using data collected from the Lawrence Berkeley National Laboratory, which is part of the U.S. Department of Energy. To examine the history of seismicity in the region, start here: http://esd.lbl.gov/research/projects/induced_seismicity/egs/geysers.html. Examine the map on the website, and look at the legend (dropdown box in the upper right hand corner of the map) to see what the symbols represent. Each of the 'wifi' looking symbols represents a permanent seismic station, while the pencil icon represents a temporary seismic station. The little buildings show power stations.

5) *Examine the proximity of the seismic stations (permanent and temporary) compared with the power stations. Are they located spatially close together? Why or why not?*

While not immediately next to each other, they are in the same general vicinity, so that the seismic stations can monitor earthquakes potentially related to the geothermal field activity.

On the map, click 'Plot Injection Wells' to observe where the injection wells are compared to the earthquakes (red dots on the map represent earthquakes that occurred during the last 24 hours). Note that the size of the dot represents the magnitude of the earthquake. In addition, change in the drop down box from 'Last 24 hours' to 'Last 30 days'.

6) *Have there been any earthquakes during the past 24 hours (red dots), past week (yellow dots), and past month (blue dots)? Approximately how large was the largest earthquake in each time period (use either the dot size or adjust the plotting filter)?*

Answers will vary based on the day, week, and month time frame examined, but there are earthquakes every day. Magnitude 2 earthquakes are common in a week and there are 20-30 magnitude 3 earthquakes per year.

7) *Does seismicity tend to cluster near sites of injection wells? Why or why not? Provide details explaining your answer.*

The student should recognize that seismicity tends to cluster near injection wells, but not always. This has to do with the fact that the fractures here in Geysers are natural, and that this geological setting is more complicated than the general cases of hydrofracking and wastewater injection.

Beneath the map, you'll find a list below 'About the Geysers'. Click on 'Why is water injection necessary at The Geysers?'

8) Why is injection into the Geysers necessary? What materials are injected into the subsurface near the Geysers? What is the main source of water injected into the Geysers? Is this clean water or wastewater?

Operators inject steam condensate, local rain and stream waters, and most recently treated wastewater into the Geysers to maintain pressure within the geothermal system. Two main sources of water include the Santa Rosa and Lake County wastewater pipelines, which pumps treated wastewater into the subsurface, much like wastewater injection after hydrofracking.

Now return to the map page. Underneath "About the Geysers", click on 'What is the history of seismicity at the Geysers?'

8) *What is the range of earthquake magnitudes in the Geysers geothermal field? Has the rate of M3 earthquakes increased, decreased, or stayed constant since the mid 1980s? What is the largest earthquake thought possible in the Geysers?*

The range of earthquake magnitudes is typically M0.5 to 3.0. The number of M3 earthquakes has been relatively constant since the mid 1980s. The largest earthquake thought possible at the Geysers is a M5 earthquake.

Lastly, return to the map page, and click on the last link, 'What is the risk of a large damaging earthquake at The Geysers?'

9) *What is one of the main causes of seismicity at the Geysers? Is the seismogenic zone (the depth at which earthquakes can occur) at Geysers shallow or deep? What controls the depth at which the earthquakes can occur?*

The main cause of seismicity at Geysers is the injection of water to maintain pressures in the geothermal system at economic levels. The seismogenic zone is shallow, and earthquakes can occur up to depths of 5-6 km. The high temperature in Geysers controls the depth of an earthquake, which makes the rock less brittle at relatively shallow depths. Since there is a limited depth range where earthquakes can occur, this places an upper limit on the size of an earthquake within Geysers.

10) *How does what you learned about the Geysers compare with what you learned about hydrofracking and wastewater injection? What are some similarities and differences?*

The student should be able to conclude that there are many similarities between hydrofracking, wastewater injection, and geothermal systems. All three inject water into the subsurface, whether to generate geothermal power or to stimulate the production of oil and natural gas or to dispose of produced water or hydrofrac fluid. All three also result in the shallow depths of earthquakes, consistent with the depths where injection is occurring. However, geothermal systems have natural fractures, while hydraulic fracturing creates fractures. Earthquakes that occur near wastewater disposal also often occur in regions of high-density fractures or faults, similar to that of geothermal activity, but different from hydraulic fracturing.

Acknowledgements

The data and original idea for comparing Oklahoma seismicity and well information was provided by Austin Holland.

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