Earthquake Swarms – A Reflection in Space and Time

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Summer 2017 Yellowstone National Park is filled with visitors when hundreds of small earthquakes shake the Park's northern boundary. Park officials do nothing to inform the visitors, while dubious internet sources announce that magma is on the move and the Yellowstone supervolcano will soon erupt. Visitors remain blithely unaware of the purported impending disaster because most of the quakes are perceptible only to finely-tuned instruments. Then the news leaks out . . . will panic or science prevail?

Plotted on a map (Figure 1) the thousands of small Yellowstone earthquakes (from Summer 2017) appear to cluster like a swarm of mosquitoes and are aptly named an "earthquake swarm." Besides observable spatial and temporal clustering, the other distinguishing characteristic of an earthquake swarm is a lack of a single large event. In other words, earthquake swarms are not aftershocks or foreshocks of a major earthquake; rather, they occur in response to less perceptible yet significant changes in local crustal stress.

The occurrence of an earthquake swarm prompts several questions. Media personnel ask whether the swarm is a rare or common event for the region or if it might be the purveyor of a catastrophic earthquake or volcanic eruption. Scientists and the curious public wonder why the swarm is occurring and what it might tell us about Earth's dynamic processes. These types of questions help validate the mantra I use as my email tagline "Geology … it's more than rocks!".

I am a geologist who uses data with spatial and temporal components to study Earth processes. I teach spatial analysis to students across campus including those who major in geology, civil engineering, natural resources, agriculture, environmental science, and the very employable geospatial computing. Spatial analysis using a Geographic Information System (GIS) is an essential skill

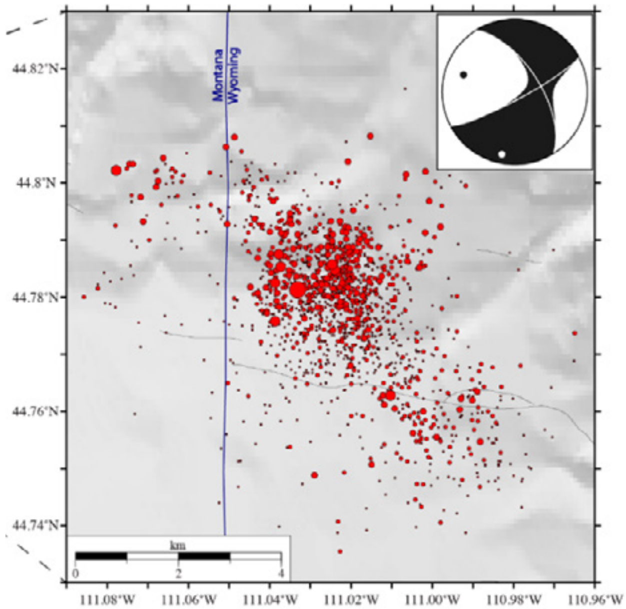

Figure 1 (Farrell, 2017). The locations of over 2000 small earthquakes that occurred the summer of 2017 in the northwestern corner of Yellowstone. The size of dot indicates relative earthquake magnitude; the moment tensor diagram in the upper right corner indicates lateral motion of the largest event (Mw 4.4)

for careers in these and many other disciplines because data location impacts both interpretation and decision-making. As examples, spatial analysis is used to site a new business, track pollutants, distribute fertilizers, and plan delivery routes.

BYU-Idaho geology and geospatial computing majors who worked recently with me on their senior research projects studied earthquake swarms near Soda Springs, Challis, and Draney Peak, Idaho. One student used InSAR (Interferometric Synthetic Aperture Radar) to evaluate surface deformation; others evaluated spatial and temporal patterns in the earthquakes to identify faults and model potential explanations for the swarms. I summarize here some background research my students read on three well-studied and well-instrumented Yellowstone earthquake swarms; together, these three swarms are excellent examples of how swarm metrics and swarm patterns, mapped across time and space, provide insights into Earth's sub-surface processes.

Swarm Metrics

A system of 26 seismic stations, 14 permanent GPS stations, and 6 borehole geophysics stations currently gather data about Yellowstone's earthquake swarms and supervolcano (NPS.gov). Collected data suggest that swarms are common in the region (e.g., 80 in 10 years) (Waite and Smith, 2002). The majority of earthquakes in a swarm are imperceptible to humans; in a recent swarm of 1,562 events only one was large enough to be felt by humans (University of Utah, 2017).

Tiny Earthquakes

Seismologists working in Yellowstone recently developed ground-breaking techniques to detect earthquakes with seismic moment magnitudes[1] as small as -1 (Shelly, 2019). The tiny amount of energy released by a -1 magnitude earthquake is about the same as the kinetic energy released by a large man jumping off a 2-m-high fence. (By comparison, a magnitude 9.6 earthquake—the largest ever recorded —releases about the same energy as 20,000 Hiroshima atomic bombs.) New data processing and cross-correlation algorithms of large seismic data sets enable seismologists to detect the location, timing, and energy released by the tiny magnitude 0 and less earthquakes which in turn has led to more accurate models and better interpretations of earthquake swarms.

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From Data to Information

Earthquake swarms and ground deformation are little more than a curiosity until the events are plotted, numerically modeled, correlated and analyzed to help understand why they occur and whether they may be precursors to a major volcanic eruption or other geologic hazard. Figures 2, 3, and 4 summarize a few details from three Yellowstone swarms: 1985, 2008-2009, and 2017. Each swarm has a different temporal and spatial signature and was produced by different Earth processes. 1985—Uplift reversed!

[1] Seismic moment is a measure of energy released during an earthquake. The moment magnitude (Mw) scale, is based on energy release while the media-popular Richter scale is based on seismic wave amplitude. The more quantitative moment magnitude is the current preferred scale. An increase of 1 on the moment magnitude scale correlates with a nearly 31.6 times increase in energy release. Due to the logarithmic nature of the Mw scale, a Mw 8 earthquake releases 31.6 times more energy than a Mw 7 quake, 999 times more than a Mw 6, and 31,554 times more than a Mw 5

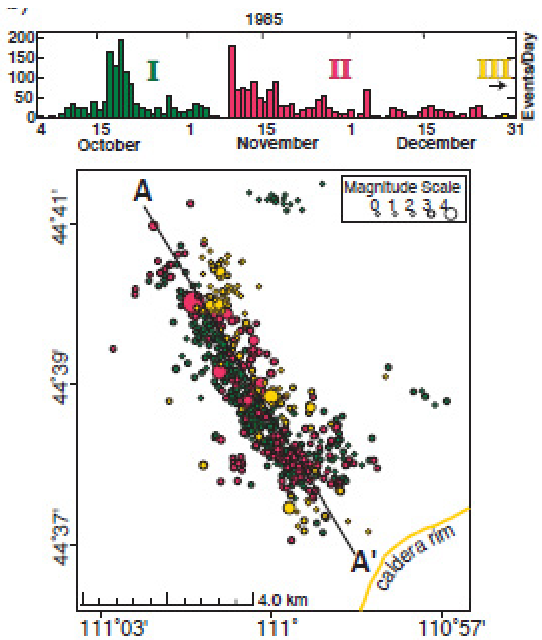

Figure 2 (Waite and Smith, 2002). The 1985 swarm is the largest and longest on record in Yellowstone (87 days, 3156 recorded earthquakes) (Waite and Smith, 2002). The earthquakes started deep and migrated along a planar feature upward and outward from the Yellowstone caldera. This swarm is particularly interesting because it overlapped a reversal from decades-long, caldera-wide uplift to caldera-wide subsidence.[2] The spatial and temporal overlap suggests the earthquakes and subsidence were caused by the same process--most likely the leakage of previously-sealed hydrothermal fluids out of the caldera system along a preexisting fault zone (Waite and Smith, 2002). (In the figure, the size of dot indicates relative magnitude of the earthquakes; green symbols represent events that occurred during the first month of the swarm and red occurred in the following months.)

[2] One way to think of uplift and subsidence is inflating and then slightly deflating a balloon. Just as an inflated balloon deflates when there is leakage in the volume of air inside it, subsidence of Earth's surface occurs when there is a net loss in the volume of material underneath it—in this case a leakage of fluids.

2008-2009—Magma on the Move

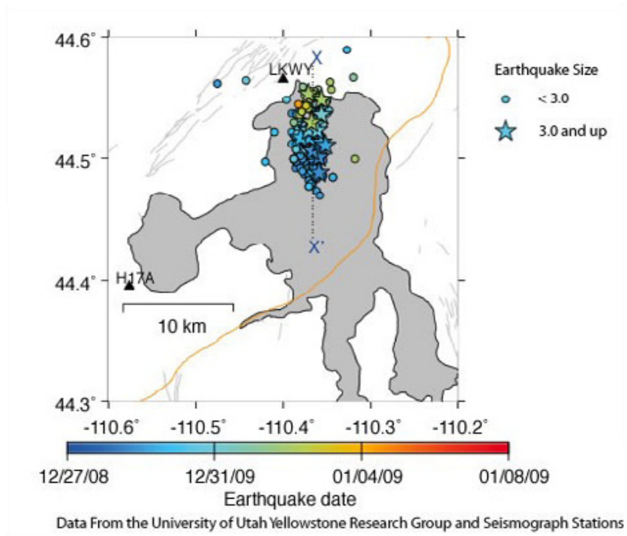

Figure 3 (Yellowstone Volcano Observatory, 2009). The 2008-2009 swarm lasted 11 days and consisted of only 811 earthquakes. It is particularly interesting because it overlapped local uplift of the ground surface and crustal extension perpendicular to the swarm (Farrell et al., 2010). The swarm migrated upward along a N-S planar feature from a depth of 12 to 2 km at the rapid rate of 1 km per day. The uplift and extension, the narrow lateral extent of the swarm, and its consistent upward migration suggest it was induced by movement of magma along a pre-existing fracture. Had this magma continued to the surface, it likely would have created a minor volcanic eruption, but not the supervolcano eruption alarmists predicted. (The figure plots location of the earthquakes. Blue colors symbolize early events; red represent those that occurred later. Stars symbolize M 3.0 and greater earthquakes; circles represent smaller events.)

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2017-Tiny Earthquakes Yield Unprecedented Detail

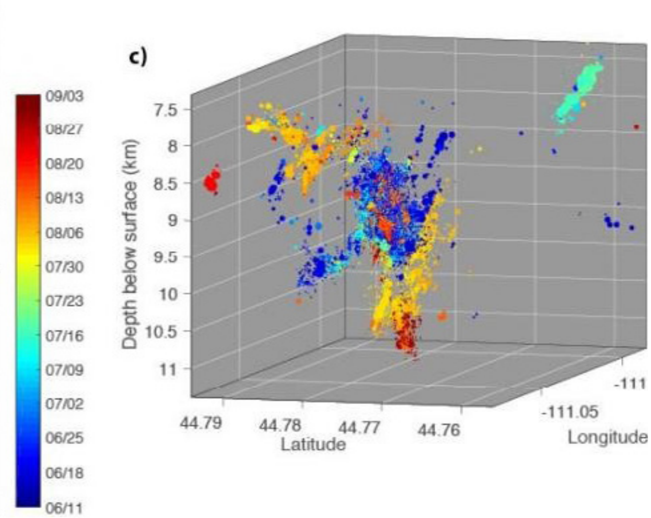

Figure 4 (Shelly, 2018). The 2017 swarm is the second largest and longest lasting on record in Yellowstone (over 80 days, and ~2500 earthquakes detected by routine methods (Shelly, 2018). In a ground-breaking new study using cutting-edge, enhanced-detection methods, Shelly and Hardebeck (2019) precisely located an unprecedented 15,912 earthquakes associated with the 2017 swarm—including hundreds of tiny quakes with a magnitude of 0 or less. The resulting extraordinary detail reveals that the earthquakes gradually propagated outward in all directions both laterally and in depth. (Note the patterns in Figure 4: early earthquakes (blue) cluster near the center and separate the later earthquakes (yellow and red).) The temporal and spatial patterns suggest the swarm occurred within a progressively expanding, complex network of micro-fractures likely associated with the movement of non-magmatic fluids. The principals of rock mechanics (the same principals used to plan mining operations and tunnels), stipulate that the presence of fluids decreases the stress required to fracture rock. So in the 2017 swarm as fluids moved incrementally outward, localized stress decreased which allowed new fractures to form (with associated earthquakes); the new fractures provided paths for the fluids to migrate farther, which decreased local stress and prompted a new set of fractures to form in a self-propagating system. Unlike the 1985 and 2009-10 swarms, in 2017 there was no associated surface deformation. (The three-dimensional figure plots earthquake locations colored by time; cool colors represent earlier events; warm colors represent later events.)

Conclusion and Future Work

Studying earthquake swarm mechanisms helps scientist more accurately assess volcanic and earthquake hazards. But perhaps more importantly, it reveals on-going Earth processes including those associated with the Yellowstone magmatic system, our slumbering neighbor to the north.

For me, the pursuit of knowledge about Earth's dynamic nature is a spiritual undertaking. Reading the scriptures helps me understand why Heavenly Father created the Earth; reading the Earth (using tools from geology, math, and physics) helps me understand how He created it. I look forward to helping future students learn the "how" of God's creative process as we together analyze and compare the moment release, surface deformation and tectonic processes that accompany slow earthquakes (a newly developed interest of mine) with tectonic (rather than magmatic-induced) earthquake swarms.

Do you want to learn more?

If you want a weekly update on Yellowstone earthquakes or geysers (a current "hot" topic due to activity of the Steamboat geyser), use this link to Caldera Chronicles: https://volcanoes.usgs.gov/volcanoes/yellowstone/article_home.html?vaid=130

To learn how to be a Steamboat Geyser watcher, use this link: https://volcanoes.usgs.gov/volcanoes/yellowstone/

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