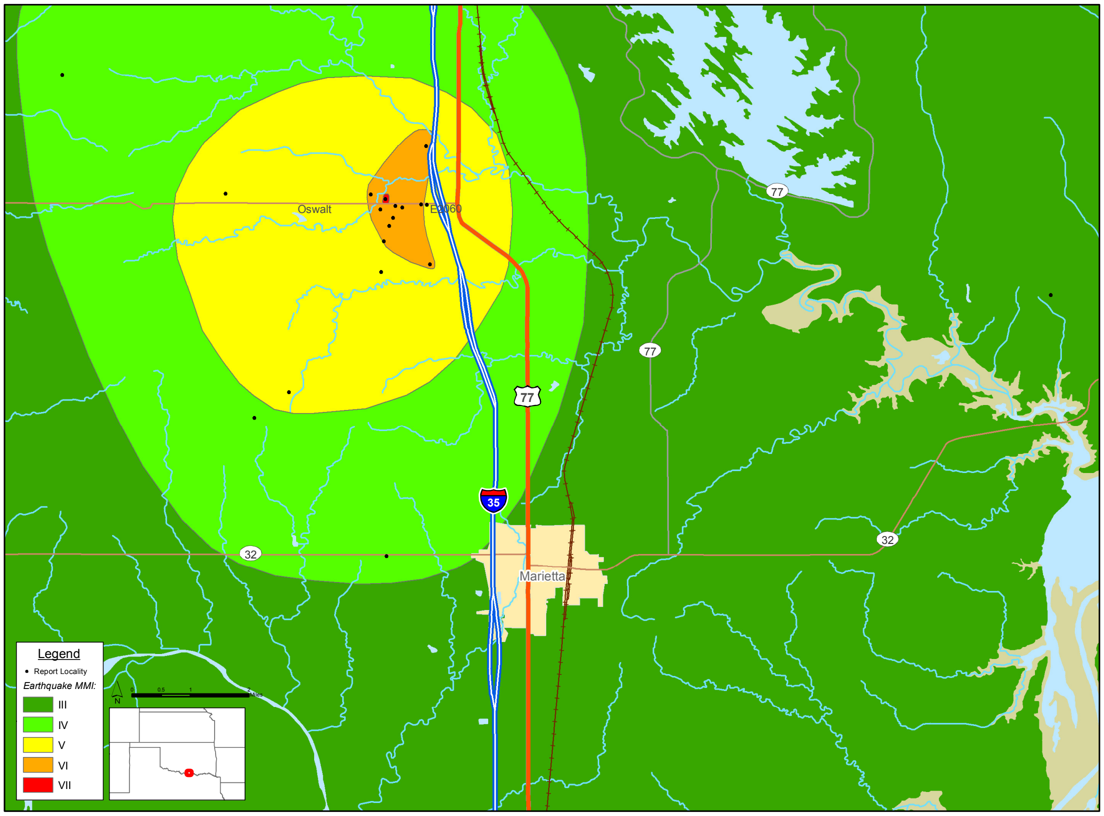
Preliminary Analysis of the 2013 Love County Earthquake Swarm

Austin A. Holland



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Preliminary Analysis of the 2013 Love County Earthquake Swarm

Austin A. Holland
Oklahoma Geological Survey
Sarkeys Energy Center
100 East Boyd St., Rm. N-131
Norman, Oklahoma 73019-0628

September 30, 2013

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OF1-2013 V. 2013.9.3

Introduction

On 17 September 2013 the Oklahoma Geological Survey (OGS) began observing earthquakes in Love County, Oklahoma. The OGS was made aware that many people were feeling these earthquakes and some earthquakes that the OGS was not able to detect using routine processing of the regional network. The OGS was also made aware that there was a new commercial UIC Class II well, LCD #1, located very near where the earthquakes were reportedly being felt. In response the OGS began making preparations to deploy temporary seismic stations to the area.

Prior to the deployment of temporary seismic stations to Love County a magnitude 3.2 and 3.4 earthquake occurred on Monday 23 September 2013. The largest of these caused significant damage to local residents. This damage includes damage to unreinforced masonry including damage to chimneys, columns, and brick façade as well as broken windows and fallen objects from walls and cabinets. This sort of damage from a magnitude 3.4 suggests a shallow focal depth for the earthquake. In addition many local residents were keeping track of felt event times and it is clear that the OGS regional network is not capable of detecting all earthquakes. However, because local residents are feeling earthquakes with magnitudes less than 2 it also suggests a shallow source for these earthquakes. This will be discussed further in following sections.

Not only was the regional network unable to detect all the felt events using routine methods for event identification it also became clear that the earthquake locations are inaccurate. The earthquakes are generally locating further south than the areas in which they were being felt. This observation also reinforced the need for a local monitoring network, which will improve locations of future earthquakes as well as help constrain aspects of past earthquakes. The temporary local monitoring network is discussed in the next section.

It is well recognized that fluid-injection within the subsurface can trigger earthquakes. The question of whether these earthquakes could be caused by injection activities at the LCD #1 will be examined in detail.

Love County Temporary Seismic Network

There currently are four continuously recording seismic stations operating within Love County in response to the earthquake sequence. These stations are located within close proximity to the area of strongest shaking during the magnitude 3.4. The location of these stations can be seen in Figure 1. One of these stations, LOV5, is sending data in real-time to the OGS earthquake data processing system. The temporary seismic stations are powered by solar panel and battery systems, and save data locally to flash storage systems. This data is then downloaded manually by visiting the station and then uploaded to the OGS processing computer.

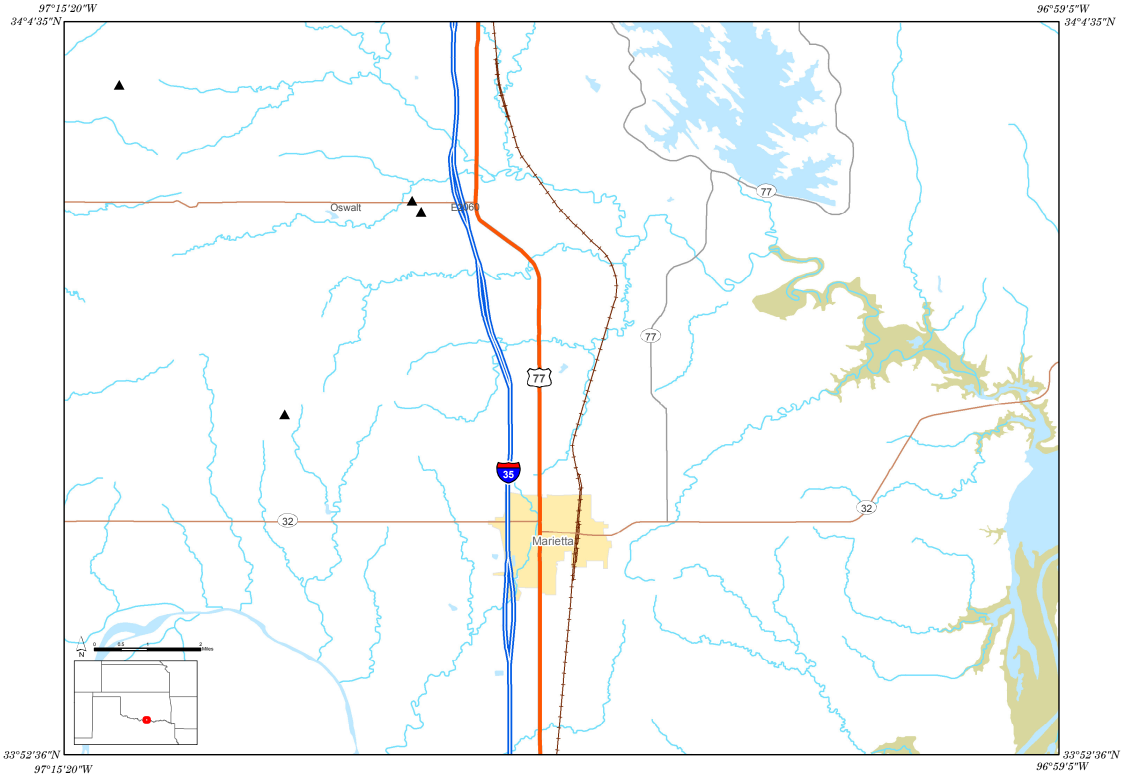

Figure 1 – Temporary seismic stations installed in the study area are shown as black triangles. The study area is the northern area of Love County north of Marietta, Oklahoma.

23 September 2013 Magnitude 3.4 Earthquake

The magnitude 3.4 occurred on 23 September 2013 at 13:56 UTC (8:56 CDT). It was quickly determined that the initial location for this earthquake using the regional network were inaccurate based on accounts of where damage was observed. The current OGS regional network is shown in Figure 2. Locations from the regional network are inaccurate for a variety of reason. All of the regional seismic stations are North of the seismicity, which means that the locations will have greater uncertainty and perhaps have a consistent bias in location. The regional seismic stations are all at significant distances from the earthquakes, which will increase the formal uncertainty of the earthquakes and the resolution of phase arrivals for smaller earthquakes. The complex geology of the Arbuckle mountains, Washita Valley Fault system, and the Ouchita Thrust Belt distort the seismic signals and create significant misfit for phase arrivals using a 1D velocity model which is typically employed for routine earthquake location within Oklahoma. The apparent shallow depths of the earthquakes also make locations more inaccurate as the seismic waves are generated in more complex velocity structures and seismic wave interactions with the free surface distort the waveforms more than for deeper focal depths.

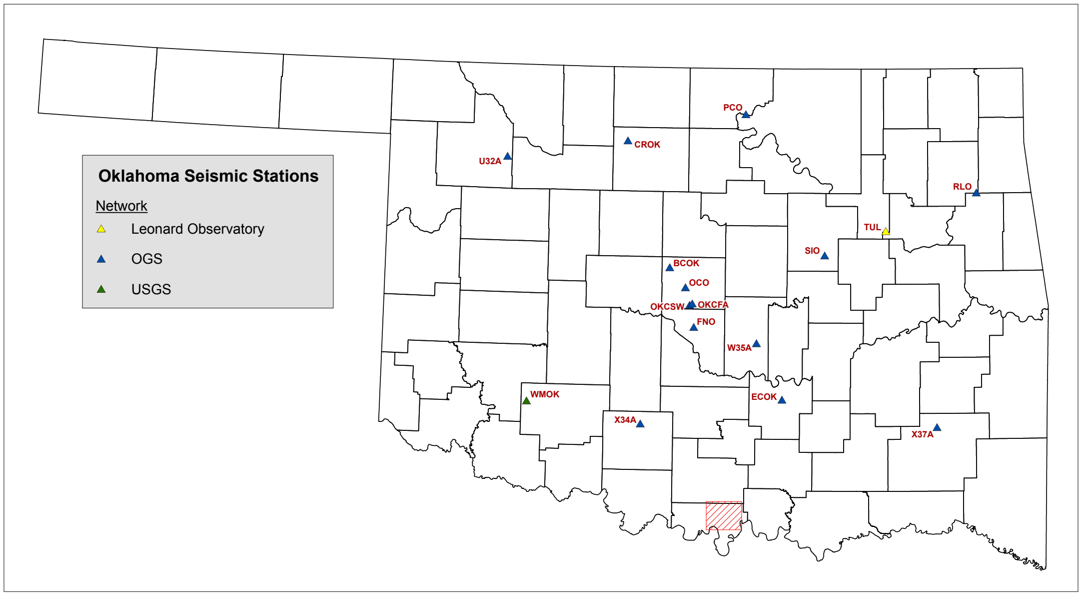

Figure 2 – Seismic stations located within Oklahoma. The OGS monitors seismic stations both within Oklahoma as well as surrounding states. All stations in the OGS regional seismic monitoring network are a significant distance from the Love County study area outlined and indicated in hachured red lines.

One method to constrain the location of the magnitude 3.4 earthquake is by the intensity of shaking observed by residents and structures within the area. Interviews were conducted with local residents and damage was observed to get a sense of the Modified Mercalli Intensity (MMI) at different locations. The location of these reports and the summary intensity map is shown in Figure 3. The intensity map could be improved with more interviews and/or reports from local residents. The process is time consuming, but is being pursued. The MMI contours are relatively well constrained in the epicentral area.

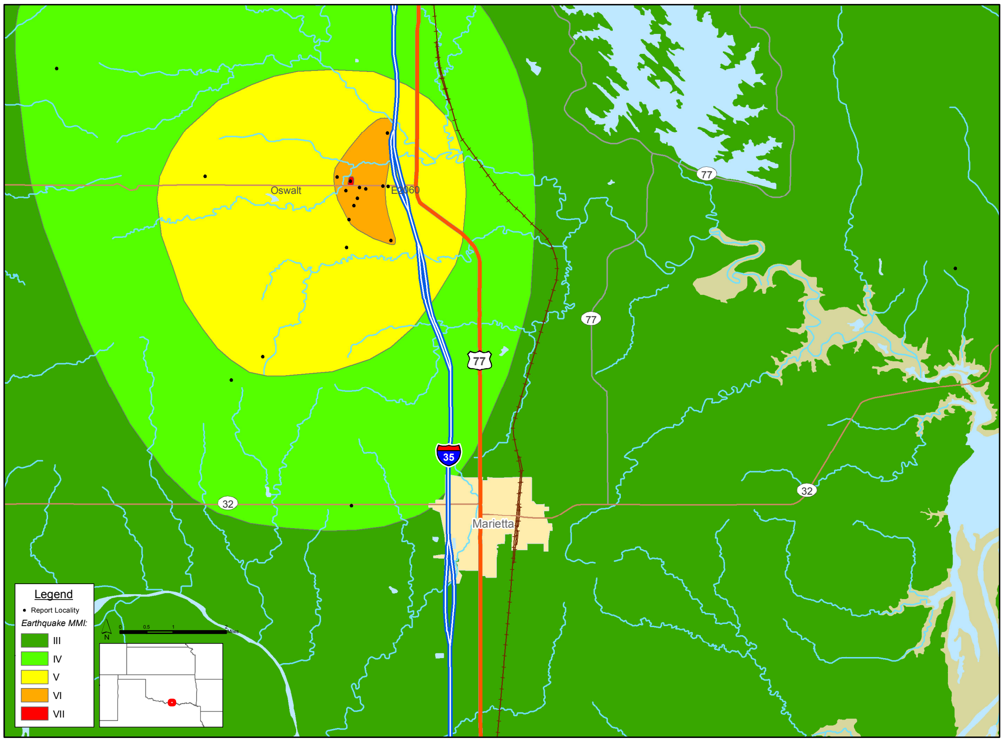

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Figure 3 – Modified Mercalli Intensities for the 13:56 UTC 23 September 2013 magnitude 3.4 earthquake. Locations of intensity reports are shown as black dots.

The maximum intensity observed for this earthquake was an MMI intensity VII, which caused furniture to move and fall as well as chimney collapse. The epicentral location of the earthquake can be assumed to be where the intensity of shaking was greatest, Figure 4. In addition, due to the very strong intensities for a magnitude 3.4 it is clear that the focal depth is considerably shallow. Generally within Oklahoma a magnitude 3.4 has maximum MMI intensities ranging from III to V. The MMI intensities may be most consistent with a focal depth of 2 ± 1 km, although more work needs to be done to address the focal depth of this and the other earthquakes of this sequence before the local seismic network was installed.

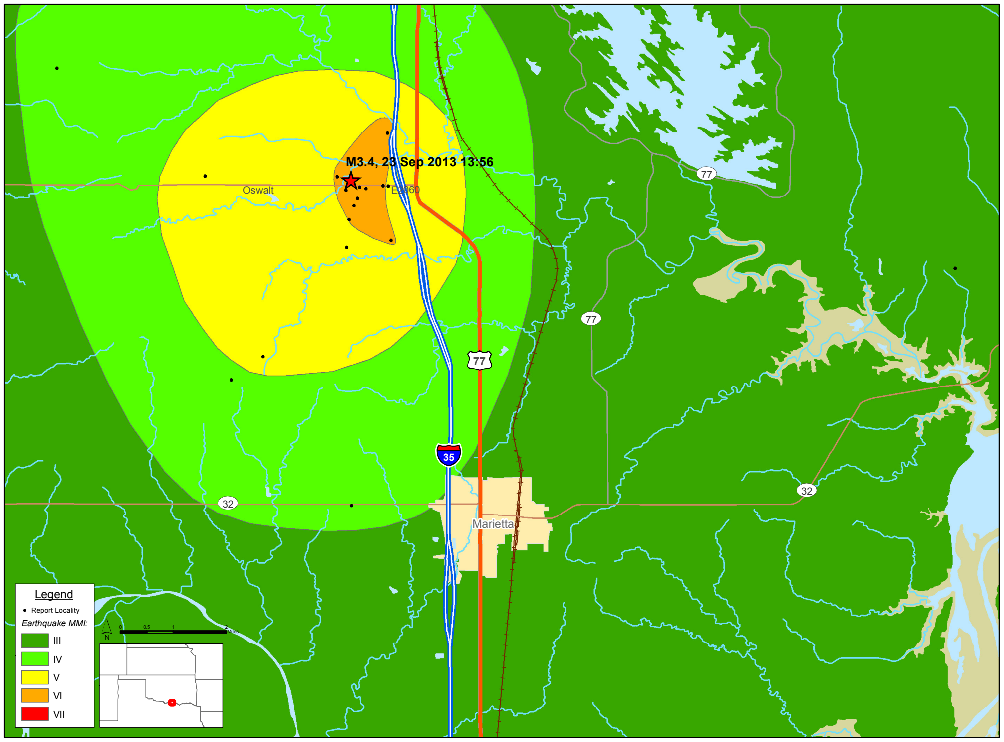

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Figure 4 – Assigned epicentral location for the 13:56 UTC 23 September 2013 magnitude 3.4 earthquake. This location is constrained by where the damage reports were the greatest.

Earthquake and Locations

Earthquake locations from the regional network and routine processing using SEISAN (Havskov and Ottemoller, 1999) are shown in Figure 5. As discussed previously these locations are highly inaccurate and have significant uncertainties. The locations can be improved slightly through the use of HYPODD (Waldhauser and Ellsworth, 2000), which uses similarities in phase observations between different earthquakes to provide better relative locations. Generally improvements in locations are much better than achieved using HYPODD on the data from the regional network for Love County. The relocations do remove some of the scatter in locations and are certainly better than the single event locations Figure 6 and 7.

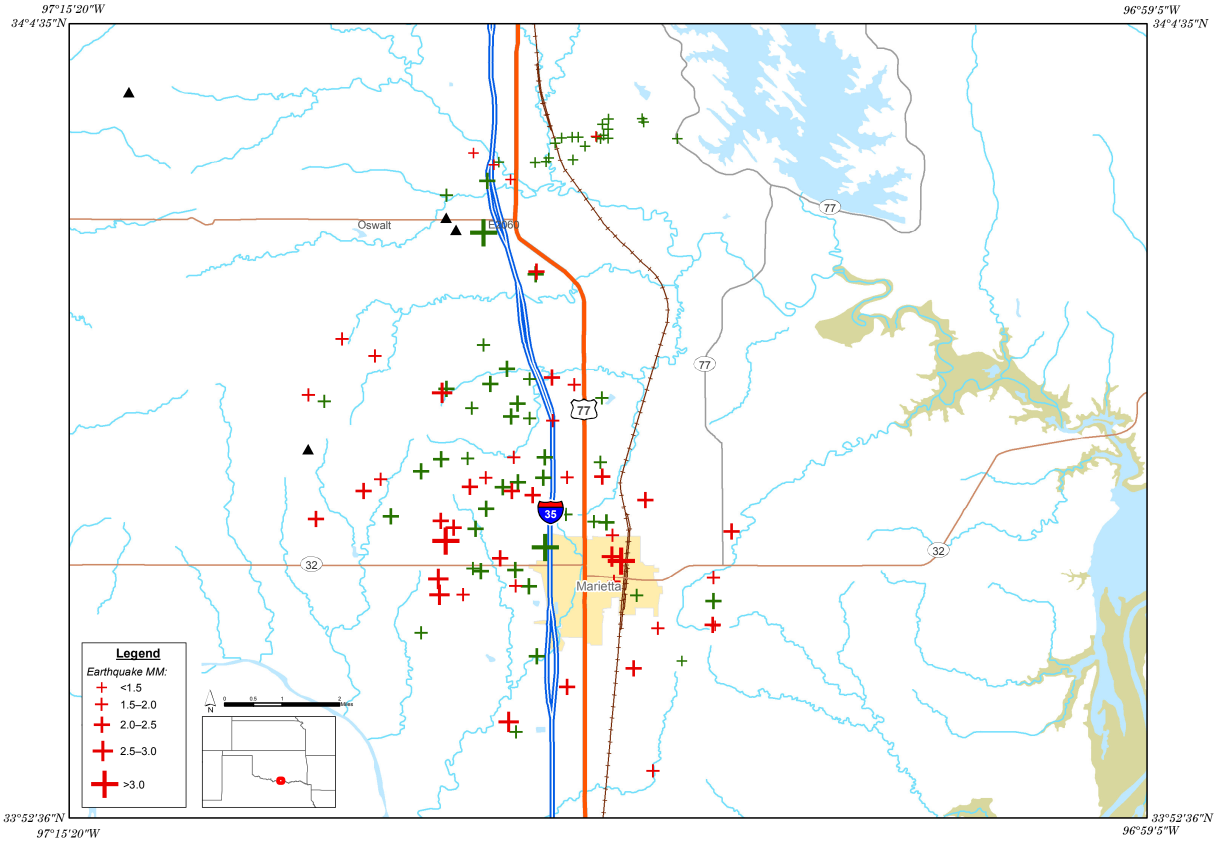

Figure 5 – Earthquake locations for earthquakes in Love County. The red crosses show single event locations from SEISAN. Relative earthquake relocations using HYPODD are shown in green.

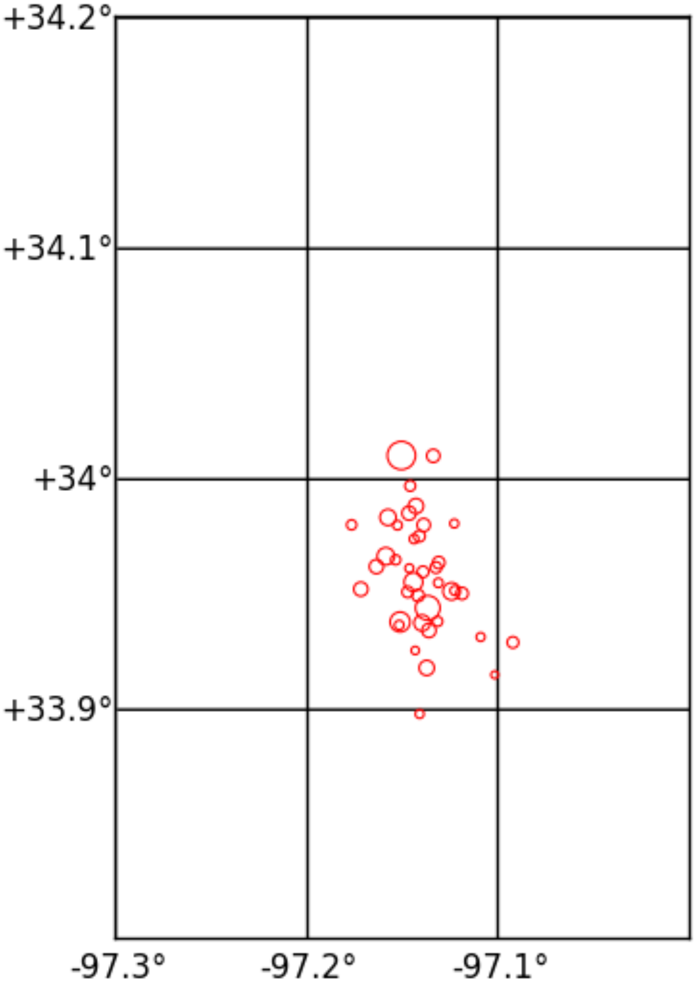

Figure 6 – HYPODD joint hypocenter relocations using regional network phase arrivals.

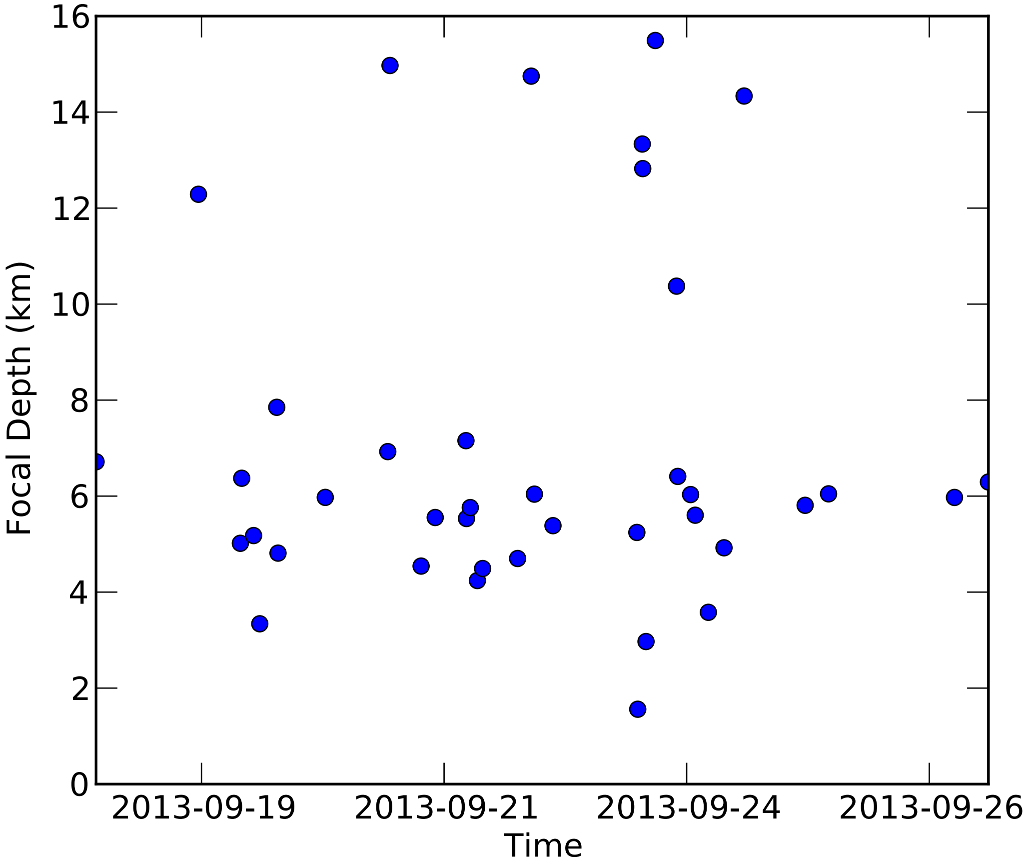

Figure 7 – Focal depths from HYPODD relocations. The depths from regional stations remain unconstrained.

Early results using the first day and a half of data available from the temporary seismic stations has already improved the understanding of where these earthquakes are occurring. The micro-earthquakes recorded by the local network begin to delineate a NE-SW trending zone of seismicity, which corresponds to the area of greatest MMI intensity discussed previously. This fault plane orientation would be consistent with the general stress field and active fault orientations observed within Oklahoma (Holland, 2013b). More earthquakes large enough to be recorded on the regional network and temporary seismic stations will be needed to better constrain the locations of early events within the sequence using relative event location HYPODD. The results of the HYPODD event relocations can be seen in Figure 8. We can also compare how much the HYPODD event locations compare to those in the OGS catalog located individually.

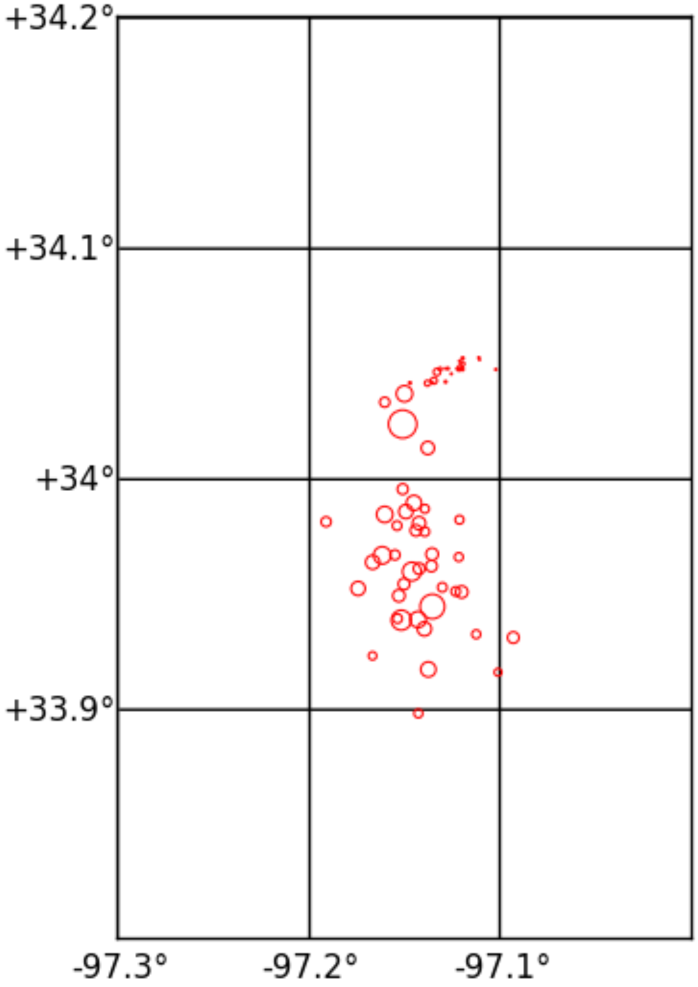

Figure 8 – HYPODD relocations using events recorded by the regional network and the temporary stations. Earthquake symbols are scaled by magnitude and the small micro-earthquakes begin to define a NE to SW trending zone of seismicity.

Local residents report having felt many more earthquakes than have been detected using routine OGS processing methods. In order to address this, we use cross-correlation of template events, usually larger well-constrained events, with continuous recordings for regional seismic stations (Holland, 2011). 13 earthquakes were selected as template events with magnitudes of 2.4 or greater and our template waveform is from the calculated origin-time for the earthquake and is 100 seconds long. The waveforms were bandpass filtered between 1.0 and 5.0 Hz with a 10% cosine taper. Stations X34A, FNO, W35A, and X37A were used to identify events and determine magnitudes of events. Cross-correlations values range from 0 to 1 where 0 is no correlation and 1 is where the waveforms match perfectly. Magnitudes were determined using the local magnitude, M_L, relationship determined for the New Madrid region (Miao and Langston, 2007). Synthetic Wood-

Anderson recordings were simulated by correcting for instrument response and applying the response of a Wood-Anderson seismograph. The distance factor was assumed to be from the fixed location of the magnitude 3.4. Horizontal channels for each identified event were used to calculate the M_L by taking the mean between the two channels for the associated station. This is very computationally intensive and has run for more than 200 CPU hours already and is not complete. The results of this will allow us to assess the temporal characteristics for the rates of earthquakes prior to the temporary seismic stations being installed.

LCD #1 UIC Class II Disposal Well

The Love County Disposal Well #1 (LCD #1) is operated by Love County Disposal LLC. The well is located very close to where the earthquakes are reported felt by residents. The well location is Section 13 Township 6S Range 1E in Love county or 34.02836°N latitude, 97.1445°W longitude and API number 35-085-21171. The well is a vertical well with a total depth of 6,342 ft. (1,933 m) with the perforated interval from 4366 to 6273 ft. (1,331-1,912 m) and indicated to be completed into the Arbuckle Formation. The well was reported completed to the Oklahoma Corporation Commision on 14 August 2013. The well was not hydraulically fractured, but was treated with 10,000 gallons of HCl. An initial injection test was conducted 30 August 2013 with 70 bbls. injected.

The LCD #1 began operating 9 September 2013 with initial injection volumes at a few thousand barrels per day with a peak on 20 September. After the 23 September M 3.4 earthquake, injection volumes were dramatically reduced. Currently the Oklahoma Corporation Commission is limiting injection to 1,000 bbls/day and no more than 375 psi. The relative location of earthquakes to the injection well can be seen in Figure 9, and the injection history for LCD #1 can be seen in Figure 10.

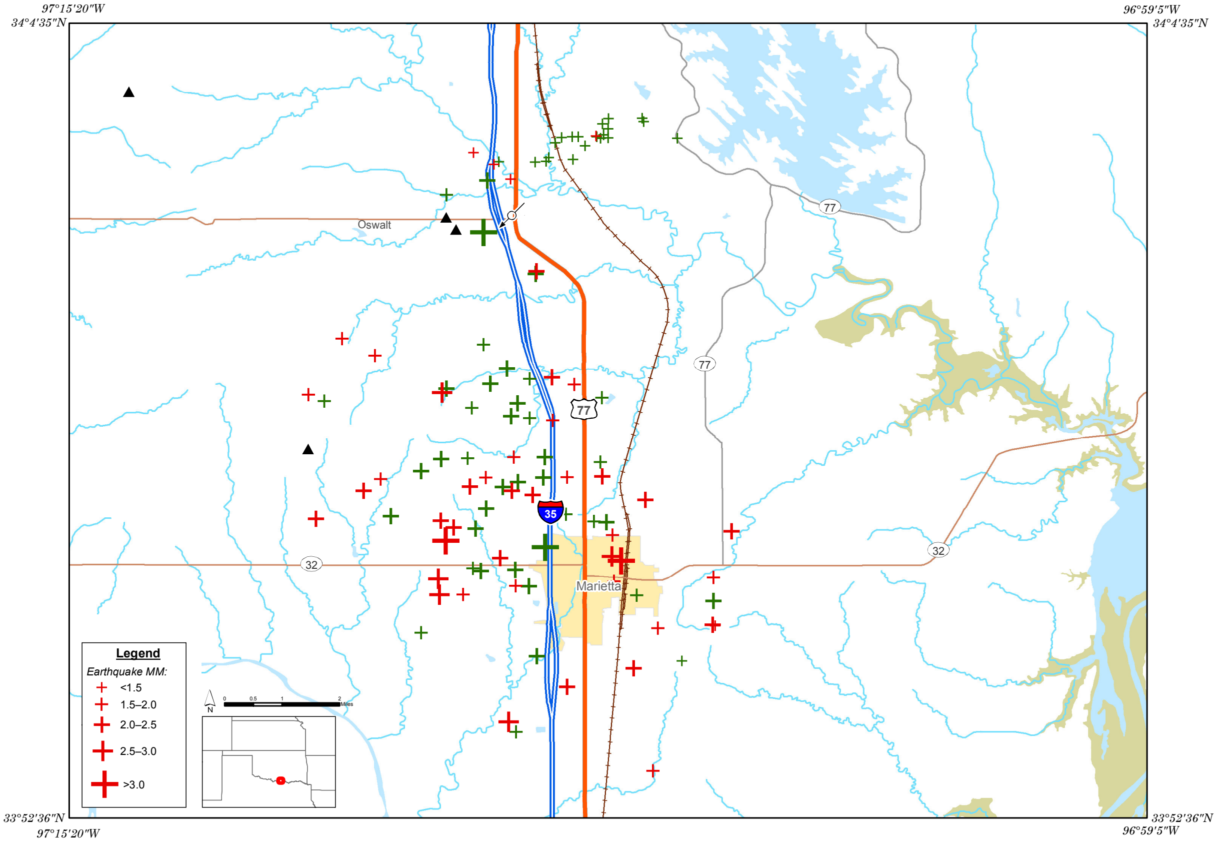

Figure 9 – Location of the LCD #1 disposal well is shown in relation to the earthquakes. The well is located at the intersection of Oswalt Rd. and US Highway 77. The red crosses show single earthquake locations from SEISAN. Relative earthquake relocations using HYPODD are shown in green.

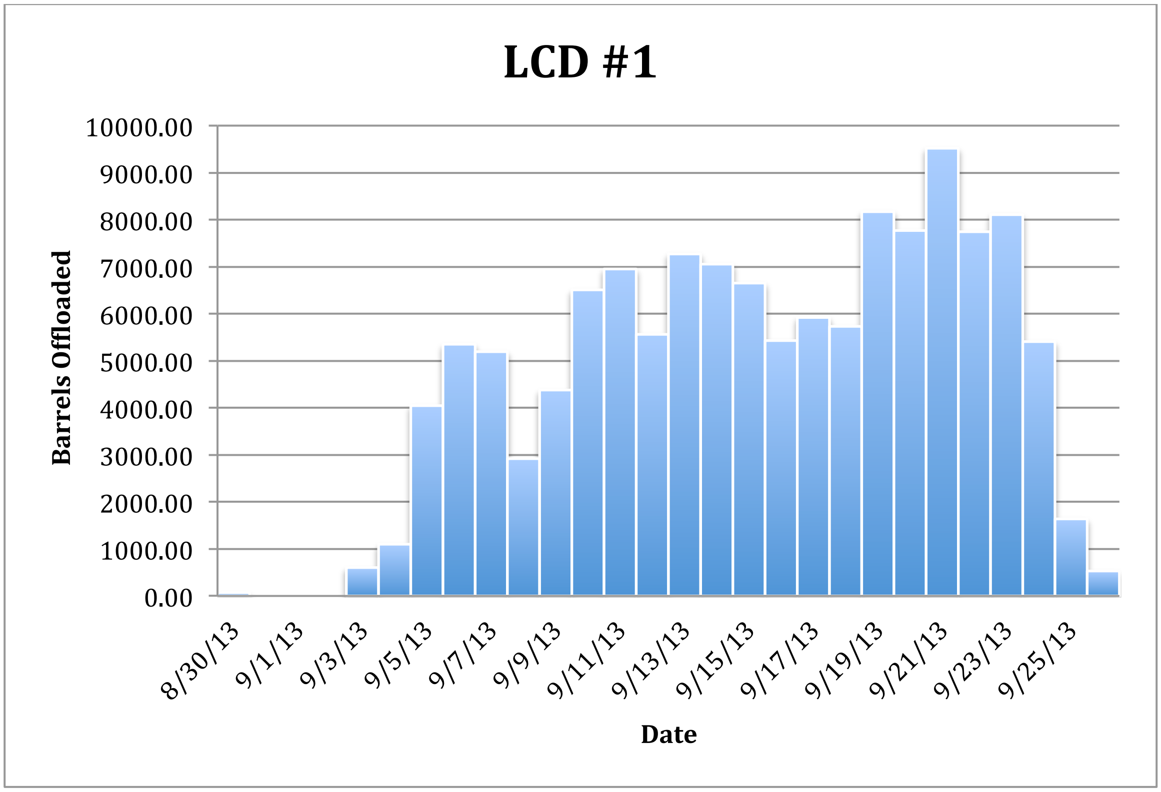

Figure 10 – Barrels reported offloaded corresponds to daily injection volumes, however not completely. Storage tanks at LCD #1 have been allowed to fill to avoid injecting high volumes.

Earthquake Triggering from Fluid Injection

There have been a number of specific cases where the potential of induced seismicity has been suggested in and near Oklahoma over the past few years involving both hydraulic fracturing and disposal well activities (Brown et al., 2013; Frohlich, 2012; Frohlich et al., 2011; Holland, 2013a; Holland et al., 2013; Horton, 2012; Keranen et al., 2013; Rubenstein et al., 2013). These examples include some damaging earthquakes up to a magnitude of 5.7 that have potentially been induced by fluid injection. In addition an earthquake swarm was identified on the Love/Carter county line in the late 1970's. These earthquakes could potentially have been caused by hydraulic fracturing, but no definitive conclusion could be reached with the available data (Nicholson and Wesson, 1990).

Seismicity from oil and gas activities can be induced from either injection of fluids or removal of fluids, and both types of induced seismicity can be difficult to distinguish from naturally occurring seismicity (Suckale, 2009). Changes of stress within a producing field are much more difficult to know and modeling the response of a field to fluid extraction requires a great number of assumptions. Fluid injection should be the easiest to identify because the cause involves a known source location. In addition the diffusion of pore pressure within the Earth has long been recognized to be the triggering mechanism for fluid injection induced earthquakes (Fletcher and Sykes, 1977; Miller et al., 2004; Nicholson and Wesson, 1990; Nur and Booker, 1972; Ohtake, 1974; Rozhko, 2010; Shapiro et al., 1999; Talwani and Acree, 1985). The pore pressure diffusion model allows for the comparison of timing and spatial characteristics of fluid injection and earthquakes to provide an assessment of the likelihood of a given set of earthquakes to be induced by fluid injection. This has often worked well when evaluating the potential of a single well but can prove more difficult when multiple wells may be involved. Generally triggered seismicity is thought to occur on critically or near critically stressed faults, and most faults appear to be near critical stress (Zoback et al., 2002). The primary goal now is to constrain future and past earthquake information enough to examine whether or not the earthquakes within Love County fit our expectations of induced seismicity.

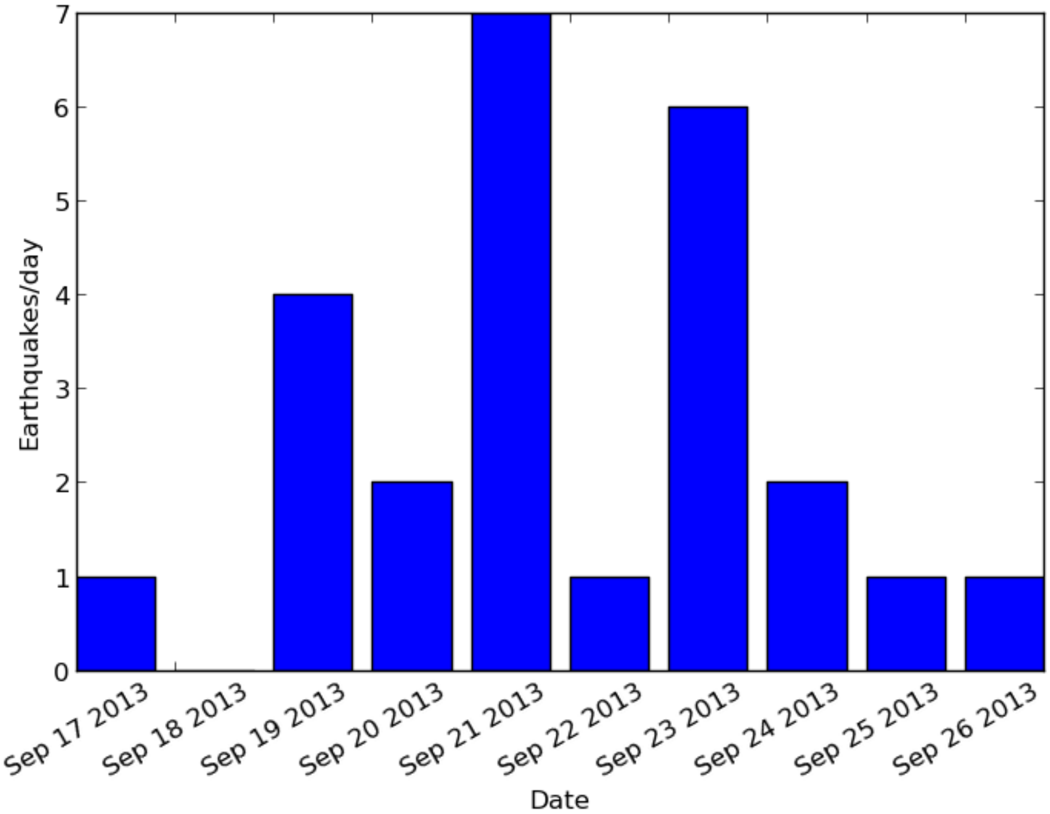

Figure 11 – Number of earthquakes per day of magnitude 2.0 or greater. A magnitude 2.0 is roughly the level of detection for Love County prior to the addition of the local seismic stations.

Conclusions

There is often a correlation between the number of earthquakes and injection parameters in cases of induced seismicity. The number of earthquakes increased as injection peaked and the earthquakes are coincident in time with injection (Figure 11). However, we cannot rule out that this observation could be simply a coincidence. The areas of greatest shaking and the best -constrained earthquakes occur within close proximity to the LCD #1. Given these two observations the current course of action is prudent. Further work will be necessary to constrain the earthquake data further and is underway and will be released in the next version of this document.

Further Work

This is the first issue of this report and there are many more activities occurring to improve and extend this work. We are working on examining and improving the velocity model used to locate the earthquakes. The ability to accurately assign depth to an earthquake is highly dependent on the velocity model. The earthquake identification through cross-correlation is still running, but should provide a more accurate view of the number of earthquakes through time.

Acknowledgements

Most of all, sincere gratitude to Mr. Tom Dunlap for his willingness to work with the Oklahoma Geological Survey to better understand the seismicity within the area. Thanks to the Corporation Commission for their help and input. Thanks to Russell Standbridge, who's help generating maps for this report was essential to getting it out in a timely manner. Thanks to graduate students Chen Chen and Chris Toth for their help in organizing instrumentation and other support of this effort.

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