Large Scale Seismicity Related to Wastewater Injection near Trinidad, Colorado, USA

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Summary

The sudden swarm of very small earthquakes (M1-M3) near wastewater injection wells in previously quiet seismic regions has been broadly reported throughout the US. The strong correlation between the timing and location of the seismicity and the water injection indicates there may be a direct cause and effect. However the same does not necessarily apply to more recent moderate events (M4-M5), which are being recorded a few kilometers away from the injection wells raising the question as to whether these are “natural” tectonic earthquakes or are being triggered by the wastewater injection. To look into the possible mechanisms that may be causing these larger earthquakes we examine an on-going earthquake sequence near Trinidad Colorado that started in August 2011. Our analysis focuses on improving the detection, location and source characteristics of this sequence of events in order to better discriminate between possible causative mechanisms. We increased our catalogue by visual inspection of the data time series. Refining and establishing a more detailed local velocity model obtained improved absolute locations. Based on our analyses, we identified two distinct fault segments as the causative faults of this sequence and two consecutive periods where slip was sequentially being accommodated in each segment. Based on the strong temporal and spatial correlations observed between the region of injected water and earthquake occurrence, we speculate whether their behavior may be related to hydraulic connectivity between the reactivated structures and the injection wells or that stress transfer between regions is responsible for the observed seismicity. However, based on our analyses, there is insufficient information to discriminate or identify the probable cause itself. In on-going work, we will consider whether it is possible to identify and understand the driving mechanism of the large-scale seismicity occurring near these wastewater injection wells and whether it will be possible to establish mitigating measures to reduce seismic risk in these regions.

Introduction

The sudden swarm of small earthquakes near wastewater injection wells in previously quiet seismic regions has made the public aware of the seismic risks related to waste water injection. This is the case of Oklahoma, for example, which historically reported less than 50 small earthquakes per year and has experienced more than one thousand small earthquakes in 2010 after the start of wastewater injection operations. These earthquakes induced by the injection of fluids in the crust are usually small (M1-M3) and rarely felt by the population. However, the recent occurrence of four large earthquakes near wastewater injection wells in Arkansas (M4.7), Colorado (M5.3), Ohio (M4.6) and Oklahoma (M5.6) has raised the public concern regarding the seismic risk of waste water disposal by deep-well injection.

So far, a direct correlation between these larger events and the disposal of wastewater has not been established. The main question is: are these earthquakes "natural" occurring tectonic earthquakes unrelated to the hydrocarbon exploitation activity, or are they a direct consequence of the injection process itself? The relationship between fluid injection and triggered seismicity is not new and has been extensively reported in the literature (e. g. Bardwell 1970; Martin, 1975; Herrmann et al., 1981; Ake et al, 2005), particularly in geothermal environments where water is used to stimulate steam production (e.g. Eberrhart-Phillips and Openheimer, 1986; Smith *et al.*, 2000). In Colorado, there are several previous documented cases of earthquakes triggered by deep well injection: Rangeley (e.g., Dieterich et al, 1972) and the Rocky Mountain Arsenal (e.g., Hoover and Dietrich, 1969; Hsieh and Bredehoeft, 1981) in the 60's, and Paradox Valley in the 90's (e.g., Ake et al, 2005). In all three Colorado cases the water was injected under pressure and there was a direct correspondence between the local seismicity rates and the injection pressures, with decreasing seismicity for reduced injection pressures and even fluid extraction (Rocky Mountain Arsenal). However, in many sites throughout the US there is no sudden increase in the background seismicity. So one pressing question is what are the differences between these well sites? It appears that wastewater disposal wells located close to faults can trigger or reactivate seismic activity on the fault. In seismically quiet zones, such as Colorado, in which earthquake recurrence rates are long, the 50 year old instrumented seismic record is not long enough to register motion on these faults and most are unknown and unmapped. The faults are only triggered due to the wastewater injection. It seems that the deep injection wells do not have to cross the fault, since there have been reports of triggered seismicity in faults ~ 6 km away from the injection well (Horton and Ausbrooks, 2010).

The coal-bed methane gas production in the Raton Basin located west of Trinidad, CO, generates vast quantities of wastewater, part of which must be disposed by injection into porous rock formations deep in the earth crust, in accordance to state environmental regulations. In this study, we investigate the recent M5.3 and foreshock and aftershock sequence which started in 2011 in the Raton Basin region, and its connection to waste water injection in the region.

Historical and Current Seismicity

Colorado has a seismic record containing some significant (M4s) historical earthquakes, but most of the micro-seismicity recorded in the region is related to oil and gas exploitation activity as can be seen by the correlation between the locations of the micro-seismicity and oil and gas production wells (Figure 1). In the Trinidad region, two earthquakes where felt in 1966 and 1973 (Figure 2) and a swarm like sequence was reported in 2001. The 1966 and 1973 events are likely of tectonic origin since they happened before oil and gas exploration activities started in the region (Meremonte et al., 2002). The 1973 event appear to have occurred in the same area of the 2001 swarm which occurred after deep wastewater injection started in 10 wells in the area. A detailed study of the 2001 swarm by the USGS was inconclusive in finding a direct relationship between the earthquake swarm and the wastewater injection operation (Meremonte et al., 2002) but it was able to identify a 3 km width and 6 km long fault structure trending NE and steeply dipping to the southeast which accommodated the normal faulting motion of the 39 analyzed earthquakes. However, the constrained hypocentral depths of 3 to 6 km deep were not in agreement with the shallower depths at which the methane gas is extracted and the wastewater is injected. Meremonte et al., (2002) analyzed the data from a short period of time (few months) and suggested that a good indication of induced seismicity would be the continuation of the current seismicity for a number of years while injection continues at the current level. If the earthquakes are of tectonic origin, a decrease is seismicity and subsequent arrest is expected in

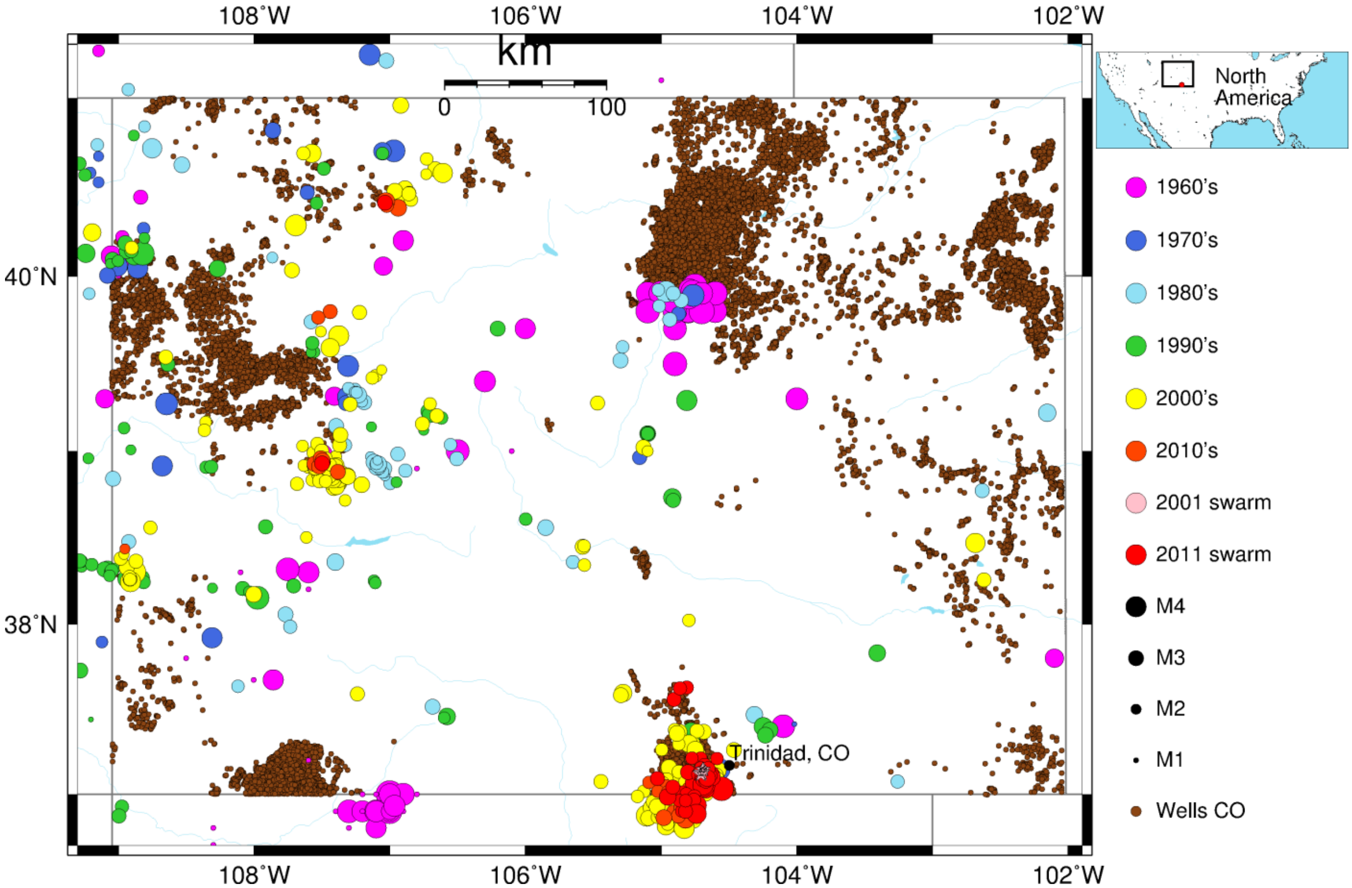

Figure 1. Colorado seismicity from 1961 to 2012 and locations of oil and gas production wells.

a relative short period of time. An analysis of the ANSS (Advanced National Seismic System) earthquake catalog, as in Figure 3, shows that seismicity has not decreased with time, but quite the opposite: it has increased not only in number but also in magnitude. At least one M3.5 or larger earthquake was detected per year from 2001 to 2011 and the magnitude of the largest event evolved from a M4.6 in 2001, to a M5.0 in 2005 and finally to a M5.3 in 2011. The number of wastewater injection wells also duplicated in the area from 10 in 2001 to 21 in 2012. We note that the temporary deployment of the USArray stations in the region in mid 2008 is responsible for the increase in the number of detected small earthquakes in the catalog, as an increased station density allows for a reduction in the magnitude threshold of the catalog. However, the increase in the number of stations does not affect the detection of the larger events, so the observed increase in magnitude is not biased by the different station configurations. We also note that most of the large events (>M4) had foreshocks occurring a few hours to a day before indicating that there is some consistent type of trigger mechanism in the Raton Basin region. An improved location of these events would help clarify what the mechanism is. For example, if the foreshock and mainshock are collocated, it may indicate that the foreshock breaks a strong asperity making the fault weaker and thus more susceptible to rupture a larger extension of it. If both earthquakes have different locations, the trigger mechanism may be the static or dynamic loading of the fault, by changes in the surrounding stress field or yet by fluid motion within the crust. The foreshock perturbs the local stress field, closing and opening fractures and causing fluid motion which will increase the pore pressure near the mainshock fault and thus reducing the effective stress on the fault, causing it to slip.

The Raton Basin earthquakes, which occurred since 2000 for which a moment tensor solution is reported in the Saint Louis University (SLU) Moment Tensor Catalog for North America consistently, show shallow hypocenters varying from 2 km to 5 km deep and a normal faulting mechanism striking N-

S to NE-SW. These hypocentral depths are systematically shallower than the 10 km to 15 km depths of other Colorado earthquakes for which moment tensor solutions were also calculated, and can be an indication of a different type of triggering mechanism possibly connected with wastewater injection.

The Raton Basin has a geothermal anomaly with increasing heat flow values ranging from ~100 mW/m^2 at the rim of the basin to ~200 mW/m^2 approximately NE of the center of the basin. High heat flow values may have different origins. Some possible reasons are the existence of an igneous pluton at depth, an area of relatively thin crust over a warm mantle, remaining heat signature from an old volcanism episode, or the upwelling of deep heated groundwater. The origin of the geothermal anomaly may provide an alternate cause for the shallower seismicity over the basin other than water injection induced, by for example, limiting the seismogenic depth.

The ANSS earthquake catalog reported 38 >M2.4 earthquakes in the Raton Basin region from August 22nd 2011 to January 29th 2012. The M4.6 foreshock occurred on August 22nd, 6 hours before the M5.3 mainshock. The current catalog earthquake locations carry a horizontal uncertainty of at least 10 km and as large as 20 km, and an equally large vertical uncertainty. Despite this large uncertainty in the epicentral locations, the earthquakes of the 2011 sequence seem to align along a NE-SW trend, coincident at the NE end with the fault structure illuminated by the 2001 swarm, and further extending into the SW end, into New Mexico (Figure 2).

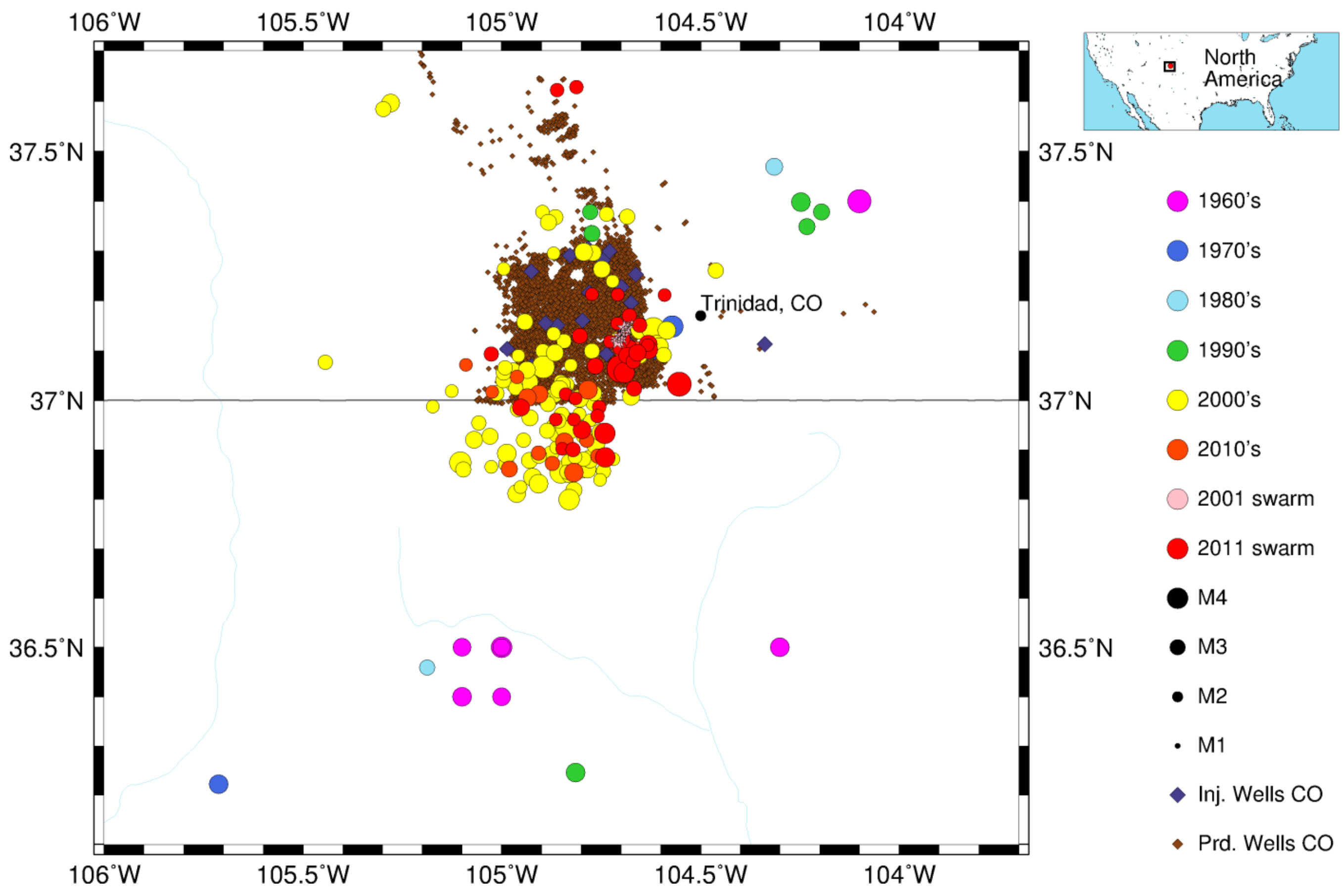

Figure 2. Seismicity in Raton Basin near Trinidad, Colorado from 1961 to 2012. The oil and gas production wells (brown diamonds) and injection wells (blue diamonds) locations are also shown. The 37N horizontal line indicates the Colorado-New Mexico state boundary. Only CO wells are plotted.

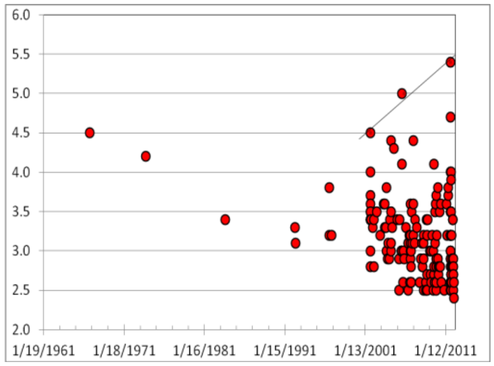

Figure 3. Time/magnitude evolution of the seismicity near Raton Basin, CO from 1961 to 2012. The black line indicates the trend of increasing magnitude events.

Waste-water Injection and Geological Formations

The number of injection wells in the Raton Basin increased from 10 in 2001 to 21 in 2012. The region has over 700 gas production wells. The location of the injection and production wells can be seen in Figure 2. The Raton Basin consists of layered Cretaceous and Tertiary sedimentary rocks such as sandstone, siltstone, and shale. The shallower layers contain coal beds with high concentrations of methane gas, particularly the Vermejo formation. Tertiary volcanic activity resulted in intrusive dykes cross-cutting these sedimentary layers and formed the Spanish Peaks Mountains that bound the basin to the NW (Meremonte et al., 2002). Wastewater is injected into the Dakota and Purgatoire formations (porous sandstone, siltstone and shale) via hydrostatic pressure only in 15 of the 21 wells and in deeper formations via pressure injection at the 6 remaining injection wells. The rock formations have large lateral extent with varying burial depth throughout the basin, with the Dakota formation outcropping to the east of the basin. The geological column obtained from the coring of the water injection well overlying the fault plane identified in the 2001 swarm study locates the Vermejo formation at ~120 m depth and the Dakota formation at ~1200 m. From the geological profiles of the injection wells, the depth of the bottom of the Dakota formation varies from 1160 m to 2160 m and has an average thickness of 40 m (varying from 8 m to 140 m).

Earthquake identification, relocation and source analysis

To better identify and characterize the tectonic structure(s) activated during the 2011 sequence we first revisit the time series looking for smaller local events not identified in the regional catalog. Aftershock sequences are often successfully used to illuminate the mainshock fault. After having identified all the events of the sequence, we relocate them using carefully and consistently picked wave arrival times and a local 1D velocity model to obtain preliminary locations. The preliminary locations will then be improved by using clustering techniques, and the source characteristics of these events will be analyzed. We use time series data recorded at 8 regional broadband stations from the Global Seismic Network, ANSS Backbone and USArray Transportable Array, located within 340 km from the mainshock location (Figure 4), for which most events are well recorded. We double the number of detected events, increasing from an initial number of 38 events listed in the catalog to 77. For an event to be included in the dataset it must be recorded at least at 3 stations. This constraint eliminated 25 smaller earthquakes which were only recorded at the two stations located less than 200 km away from the epicentral region (23 km and 100 km).

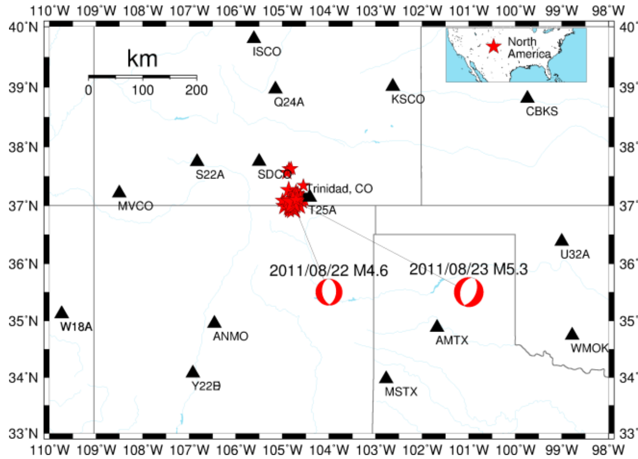

Figure 4: Regional map showing seismic stations and 2011 earthquakes locations. The focal mechanism of the 2 larger events of the 2011 sequence is also shown.

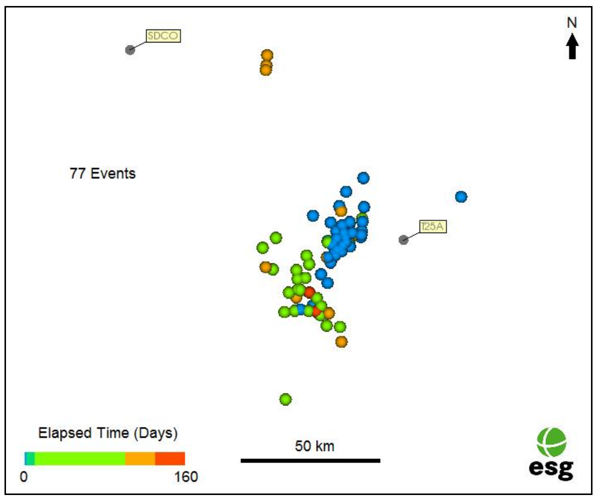

Figure 5. Preliminary locations of the 77 detected earthquakes. The events are color coded by elapsed time. Based on the spatial and temporal distribution three distinct clusters of seismicity are observable.

Figure 5 shows the preliminary locations of the 77 events of our catalog. Three distinct clusters can be seen when analyzing the spatial and temporal distribution of the epicenters. The earthquakes that occurred in the first two days (August 22nd and 23rd, 2011) and are plotted in blue delineate a NE-SW linear structure. This structure is approximately 45 km long 15 km wide and its location coincides with the location of the 6 km long fault structure identified in the 2001 swarm, at its NE end. Both M4.6 foreshock and M5.3 mainshock occurred in this fault segment, indicating that the foreshock weakened the fault pushing it closer to failure in a larger extent. A M2.9 earthquake in the same fault segment indicating a swarm like behavior preceded the foreshock. The earthquakes, which occurred in the following period (August 24th to September 13th, 2011), are plotted in green and delineate a second structure also approximately 45 km long and oriented NW-SE, perpendicular to the first structure and located at its southernmost end. This swarm-like behavior is also observed in this second fault segment with several small earthquakes occurring before a M4.0, the largest event in this fault segment, which occurred on September 13. Such earthquake swarm-like behavior is characteristic of volcanic and geothermal areas in which fluids are usually present. The temporal evolution of the seismicity clearly indicates that the motion of the first fault segment triggered slip on the second fault segment. The second segment is located in New Mexico, for which we do not yet have information on deep well injection. By analyzing the local seismicity in this area (Figure 2) we see that there is ongoing seismic activity, probably in this segment, but the location uncertainties are too large to be able to resolve a structure. Both fault segments reactivated in this sequence were pre-existing and had accommodated slip in the last 10 years. A third cluster of events is observed North of the epicentral region (orange symbols), closer to station SDCO. This cluster contains three M2+ earthquakes that occurred at the end of December. There are several production wells in this region but no reported water injection wells, thus we consider that this events are potentially related with the production activity.

Conclusions

We investigate the relationship between small to moderate seismicity with wastewater injection in the Raton Basin region in Colorado by studying an on-going earthquake sequence, which started in August 2011. We increased the number of detected events by visually inspecting the data time series, and obtained improved absolute locations by developing and using a refined local velocity model. We identified two distinct fault segments as the causative faults of this sequence, and we observe two consecutive periods where slip is sequentially being accommodated in each segment. Based on the strong temporal and spatial observations between the region of injected water and earthquake locations, we can speculate that there may be hydraulic connectivity between the reactivated structures and the injection wells, or that the transfer of stress between regions may be probable causes of the observed seismicity. However, at this time there is insufficient information to discriminate or identify the probable cause itself.

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