Intraplate Induced Earthquakes: Investigating Two Potentials Events

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INTRAPLATE INDUCED EARTHQUAKES: INVESTIGATING TWO POTENTIALS EVENTS

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INTRAPLATE INDUCED EARTHQUAKES: INVESTIGATING TWO POTENTIAL EVENTS

by

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THESIS
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Thanks to all my family members and friends
ABSTRACT

In this project we investigate the characteristics of two recent intraplate seismic events to better understand earthquake swarms and induced seismicity. These events include a M=5.3 earthquake potentially induced by mining activities in Duncan, Arizona, and a swarm of earthquakes in Northeastern state of Nuevo Leon, Mexico potentially induced by fluid injection. For each region, we investigate characteristics including b-values, stress drop, events distribution pattern and seismic waves properties. For the case in Arizona, we investigate a potential case of earthquakes induced by mining activities. We examined 594 seismic events that occurred in an area encompassing the Morenci mine and the epicentral location of a M 5.3 earthquake in southeastern Arizona to determine whether mining activity contributed to the M 5.3 earthquake. Based on our observations, we suggest that most of the events, smaller than the M 5.3, correspond to blasting at the mine or were directly induced by nearby mine blasts. We performed a FEM numerical model that suggests the stress change caused by the removal of material from the mine was not large enough to trigger the M 5.3 earthquake. However, the numerical model does indicate the stress change was large enough to potentially overstress nearby faults which is supported by the temporal and spatial distribution of smaller earthquakes in this region. For case in Nuevo Leon, we investigate a potential case of earthquakes induced by fluid injection. We examined 281 earthquakes in Nuevo Leon to determine whether these earthquakes correlate to fluid injection by shale gas wells. Based on our observations, we suggest that earthquakes that surround to shale gas wells Tangram-1, Nerita-1, Batial-1 and Kerner-1 are induced by their fluid injection. Earthquakes that are in the mountain or close to mountain front are tectonic earthquakes. We performed b-value analysis that suggest earthquakes that surround to shale gas wells are induced earthquakes, and earthquakes that close to Mojave-Sonora megashear are tectonic earthquakes. We further
performed temporal and spatial analysis for the distribution of all earthquakes which support the suggestion of $b$-value analysis.
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CHAPTER 1
INTRODUCTION

1.1 Intraplate Earthquakes

In the recent years, there has been a significant increase in the number of intraplate earthquakes observed in the north-central and central U.S. in places previously considered to have very low seismicity (e.g., Ellsworth, 2013) (Fig 1.1). An analysis of earthquake catalogs from Mexico shows that the increased seismicity is not restricted to the U.S. but also extends well into northern Mexico. I investigated two new observations of intraplate earthquake swarms: A case in Morenci, Arizona, and another in Nuevo Leon, Mexico. This project provides new results that can be integrated with recently reported observations of earthquakes swarms in northern and central North America. To investigate these unusual events, I used available earthquake data collected by the U.S. and Mexican research agencies (earthquake catalogs), as well as seismograms recorded at seismic stations in the U.S. and Mexico by The University of Texas at El Paso (UTEP).

Numerical models suggest that near the epicenters, intraplate earthquakes are expected to cause shaking comparable to that from a tectonic boundary (interplate) earthquake about one magnitude unit larger [Stein, 2007] because continental interior transmits seismic energy more efficiently than tectonically active regions. Data and results from this research will be used to assess seismic hazards in regions where the historically low seismic rates have resulted in a lack of earthquake preparedness. As of today, the recent earthquakes in midcontinental North America have caused no fatalities, nevertheless some of these events have reached magnitudes similar to the 1986 San Salvador, El Salvador interplate earthquake (M=5.8) that killed more than 1500 people, injured more than 10,000 and left 100,000 homeless [Ellsworth 2013; Harlow et al, 1993].

1
Although losses of this scale are unlikely in the U.S., the hazard in Mexico could be much higher due to poor construction practices and regulations. The recent swarms in Mexico have caused considerable structural damages in houses and schools in the state of Nuevo Leon (e.g. Martinez, 2014).

In addition to the natural earthquakes, recent studies suggest that an important number of the intraplate earthquakes observed in the central U.S. were induced by human activities, mainly by the injection of waste water in deep wells [e.g., Ellsworth, 2013]. This research focused in two unreported earthquake events potentially induced by human activity.

1.2 Induced Seismicity

According with Ellsworth (2013), the term “induced” may include both:

(1) Earthquakes that primarily release the stress created by anthropogenic activities. For example, earthquakes caused by impoundment and discharge of reservoirs.

(2) And, earthquakes triggered by anthropogenic causes that primary release tectonic stress. For example, when fluids are injected near or in an overstressed preexisting fault, the fluids can elevate the pore pressure, weakening the fault and causing it to fail.

Figure 1.2 schematically presents examples of these two mechanisms of induced seismicity by anthropological activities that modify the stress and/or pore pressure. Induced earthquakes sometimes occur at the source of the stress or pressure perturbation; at other times, these events take place deep below and kilometers away from the source. Induced earthquakes typically release stored tectonic stress on preexisting faults, as do natural earthquakes. Sometimes induced events occur shortly after the anthropologic activity begins, but in other cases they happen long after it has been under way or even ceased. Factors that should enhance the probability of a stress or pore-pressure perturbation inducing earthquakes include the magnitude of the perturbation, its spatial...
extent, ambient stress condition close to the failure condition, and the presence of faults well oriented for failure in the tectonic stress field. Hydraulic connection between the injection zone and faults in the basement may also favor inducing earthquakes (Ellsworth, 2013). All these factors will be investigated for the two study regions.

Ellsworth [2013], and many other studies, suggests that several of the recent largest earthquakes in the U.S. midcontinent may have been induced by wastewater injected into deep wells near preexisting faults, including events M≥5.5 in Oklahoma. In recent years, the application of hydraulic fracturing or “fracking”, to tight shale formations, is enabling the production of oil and gas from previously unproductive formations. However, fracking and the injection in the subsurface of the wastewater resulting from this activity, has also been suggested to be responsible for a significant number of earthquakes in the U.S. In order to extract the hydrocarbons from shale formations, fluids are injected under high pressure through horizontal drill holes extending several kilometers along a shale formation to create tensile fractures that intentionally induce numerous micro-earthquakes to increase the permeability of the rock formation and facilitate the extraction of the hydrocarbons. The vast majority of these micro-earthquakes have magnitudes M<1 and impose a very low risk. However, much of the concern about earthquakes and fracking centers on the observations of larger earthquakes apparently induced by the injection of wastewater composed of flow-back fluids and coproduced formation brines from the fracking in deep wells.

Besides the cases in Oklahoma, reported cases of earthquakes potentially induced by disposal of gas/oil shale wastewater include: the 2011 M=4.7 earthquake in Arkansas [Horton, 2012]; the 2011, M=4.0 earthquake in Youngstown, Ohio [Kin, 2013]; the recent elevated seismicity in the Dallas-Fort Worth, Texas region [Frohlich, et al., 2011]. In this proposal, we show a potential case of fluid-induced seismicity in Mexico that will be investigated in this project.
In Chapter 2, we investigate a potential case of earthquakes induced by mining activities. We examined 594 seismic events that occurred in an area encompassing the Morenci mine and the epicentral location of a M 5.3 earthquake in southeastern Arizona to determine whether mining activity contributed to the M 5.3 earthquake. Based on our observations, we suggest that most of the events, smaller than the M 5.3, correspond to blasting at the mine or were directly induced by nearby mine blasts. We performed a FEM numerical model that suggests the stress change caused by the removal of material from the mine was not large enough to trigger the M 5.3 earthquake. However, the numerical model does indicate the stress change was large enough to potentially overstress nearby faults which is supported by the temporal and spatial distribution of smaller earthquakes in this region.
LIST OF REFERENCES


Figure 1.1 Number of earthquakes with a magnitude of 3.0 or larger in the central and eastern United States, 1970–2016. The long-term rate of approximately 29 earthquakes per year increased sharply starting around 2009 (https://earthquake.usgs.gov/research/induced/images/hockey-stick.png, 2018, USGS)
Figure 1.2 Schematic diagram of mechanisms for inducing earthquakes.

Earthquakes may be induced by increasing the pore pressure acting on a fault (left) or by changing the shear and normal stress acting on the fault (right) [from Ellsworth, 2013].
CHAPTER 2

IS MINING ACTIVITY AT THE MORENCI MINE RELATED TO A MAGNITUDE 5.3 EARTHQUAKE NEAR DUNCAN, ARIZONA?

2.1 Abstract

In this work we investigate a potential case of earthquakes induced by mining activities. We examined 594 seismic events that occurred in an area encompassing the Morenci mine and the epicentral location of a M 5.3 earthquake in southeastern Arizona to determine whether mining activity contributed to the M 5.3 earthquake. Based on our observations, we suggest that most of the events, smaller than the M 5.3, correspond to blasting at the mine or were directly induced by nearby mine blasts. We performed a FEM numerical model that suggests the stress change caused by the removal of material from the mine was not large enough to trigger the M 5.3 earthquake. However, the numerical model does indicate the stress change was large enough to potentially overstress nearby faults which is supported by the temporal and spatial distribution of smaller earthquakes in this region.

2.2 Introduction

It is widely recognized that human activities such as mining and the injection of fluids into the ground can trigger an earthquake. A magnitude ML 5.0 earthquake near the Kalgoorlie mine in Australia, on 20 April 2010 is an example of a large earthquake apparently triggered by mining activity (Gibson and Sandiford, 2013). Gibson and Sandiford (2013) suggest mining activity induces earthquakes primarily as a result of blasting because many earthquakes occur within minutes of a mine blast. We considered, however, the possibility that earthquakes can also be
induced by changes in the stress field due to the long-term removal of material or to other mining activity rather than directly due to blasting explosions.

To better understand how mining affects the local stress field and seismicity, we focused on the Morenci copper mine in Arizona to determine whether there is a correlation between a M 5.3 earthquake in Duncan, Arizona, on 28 June 2014 (Fig 1), and the Morenci mining activity. In this case the earthquake was located approximately 55 km south of the mine and at a depth of about 7 km (Young and Pearthree, 2014). We used the earthquake catalog from IRIS to analyze spatial and temporal variations in the patterns of seismicity to determine whether the earthquakes near Morenci are triggered by blasting or other mining operations or are tectonic in origin. We also developed a 3D Finite Element Model (FEM) to calculate how the principal stress changes due to removal of rock mass to determine whether such a change could trigger an earthquake.

Our research suggests that mining at Morenci likely played a role in the Duncan earthquake. However, it does not appear to be directly related to blasting or removal of material from the mine shortly before the earthquake occurred. Rather, we infer the M 5.3 earthquake occurred more than 10 years after a period of major mining activity activated a trend of seismicity that connected the epicenter to the mine. The triggering mechanism has not yet been determined but it could include long term changes in the stress field.

2.3 Geological and Tectonic Settings

The Morenci porphyry copper-molybdenum open-pit mine is located in Arizona near the Arizona-New Mexico border (Figure 2.1). The Morenci mine is located in the transition between the Basin and Range Province and the Colorado Plateau where tectonic earthquakes are not uncommon (Stegen and Parker, 2007). The area is mainly comprised of Proterozoic and early Tertiary to late Cretaceous granitic rocks and Paleozoic sedimentary rocks. There are several faults
in the area that have been active in the past 2 million years (Young and Peachtree, 2014). There is no mapped fault that can be traced continuously between the mine and the magnitude 5.3 earthquake but there are numerous faults that appear to trend in approximately the right direction, northwest-southeast, to suggest a structural connection could exist.

The Morenci mine is the largest copper mine in Arizona. The mining operation began in 1873 as an underground mine and the current open-pit mining began in 1942 (Fig 2.2). There was a peak in mining activity in about 1997 with major activity continuing to the present.

2.4 Observations of Earthquakes

We collected 594 earthquake records in the study area (Fig 2.3) for events between 1981 to 2014 from the IRIS DMC earthquake catalog. The earthquake magnitudes range from 0 to 5.3. Based on the spatial and temporal patterns of the earthquakes (Figs 2.3 and 2.4) we made the following observations:

1. One hundred and twenty-three earthquakes were within the boundaries of the mine pit, have hypocentral locations at the surface (0 m depth) and occurred between 10 am and 7 pm. (Fig 2.3).

2. Only 43 earthquakes are reported in the IRIS catalog as originating below the surface (Fig 2.3). All others are located by IRIS at the surface.

3. There is a prominent southeast-trending zone of earthquakes connecting the Morenci mine to the location of the M 5.3 earthquake (Fig 2.3) that did not exist before 1999 and is not highly active after 2002 (Fig 2.4).

4. All but one of the events between 1999 and 2002 occurred between 10 am and 7 pm.
2.5 Discussion of Observations

The first observation, that a significant number of events were located within the mine, at the surface and occurring between 10 am and 7 pm (approximately working hours at the mine) strongly suggests they were explosions related to the mining operation rather than actual earthquakes. However, that explanation does not work very well for the more than 400 events that occurred outside the boundaries of the mine at the surface between 10 am and 7 pm. The region surrounding the mine has a relatively low population, but it is inhabited and includes small communities and farms that are not likely places for blasting on a regular basis. Our first thought was that the locations of the events might be in error. In particular, we felt the depths were likely to be incorrect. To test this hypothesis, we selected a small set of events at random from the group of shallow events outside the mine in addition to other events chosen for relocation. We downloaded seismic data from IRIS for relocation using the software package SEISAN (Table 2.1).

2.5.1 Relocation of Randomly Selected Earthquakes

We selected 24 events from our data set for relocation to test the depth and location of earthquakes in the IRIS catalog. The 24 events included 2 events chosen randomly between 1981 to 1998 (Group 1), 4 events between 1999 to 2002 (Group 2), 14 events between 2003 to 2013 (Group 3), 4 events in 2014 (Group 4). The stations we used for relocation were located in Arizona, New Mexico, California, Texas. We used the program Hypocenter (Lienert and Havskov, 1995) from the SEISAN software package (Otemöller et al., 2017) for the relocation. The relocation shifted events on average by approximately 10 km, except two events that were shifted 115 km and 120 km respectively. The relocation depths of these 24 events are different from the IRIS depths with 6 located on the surface after relocation compared 20 on the surface from IRIS. The
differences in the calculated depths may be due to differences in, for example, the pick of the p-wave arrival or different measurements of amplitude. In general, depth of small earthquakes is a very hard parameter to determine. Table 2.1 shows that the depth of the four earthquakes we selected from Group 2 for relocation are as the same as those reported by IRIS.

2.5.2 Waveform and Spectrum Analysis

We selected 6 seismograms recorded in Tucson, Arizona (station IU.TUC) from our dataset to compare the waveform features (Fig 2.7). These included 3 events from group 2 and 3 events from groups 3 and 4 combined. Figure 7 shows that the P arrival of group 2 events have larger amplitudes than group 3 and 4 earthquakes. We also calculated the stress drop (ST) for all of them. The stress drop values are 0 for all group 2 events (Fig 2.8) while group 3 and 4 earthquakes have 2.1, 15.7, 2.9 Mpa respectively (Fig 2.9). There are two curves for each spectrum (Figs 2.7-2.9), one is the displacement spectrum curve and the other is the noise spectrum curve. Figure 7 shows that all group 2 events’ displacement spectrums are very close to the noise spectrum. In contrast, all group 3 and 4 earthquakes’ displacement spectrums are very easy to recognize because the noise spectrums are very different from the displacement spectrums (Fig 2.9).

2.5.3 B-value Calculation

Earthquake occurrence per magnitude follows a power law introduced by Ishimoto and Iida (1939) and Gutenberg and Richer (1944). The Gutenberg-Richter Relationship is given as:

$$\log_{10}N = a - bM$$
where $N$ is the cumulative number of events having a magnitude $\geq M$, $a$ and $b$ are constants. $B$ is the most intriguing constants of this formula for most seismologists. The $b$-value is a measure of the relative number of small to large earthquakes that occur in a given area and in a given time period. In this formula, the $b$-value is the slope of the frequency-magnitude distribution (Ishimoto and Iida, 1939; Gutenberg and Richer, 1944). Studies have shown that observed variations in $b$-values relate to material heterogeneity (Mogi, 1962), thermal gradient (Warren and Latham, 1970), applied stress (Scholz, 1968; Wyss, 1973; Urbancic et al., 1992; Schorlemmer et al., 2004; Schorlemmer and Wiemer, 2005; Schorlemmer et al., 2005), Aftershocks have large $b$-values, foreshocks, on the other hand, show low $b$-values (e.g. Suyehiro et al., 1964). In tectonically active areas, the $b$-value is generally around 1.0 on global average (Frolich and Davis, 1993). In some wastewater disposal areas such as Dallas-Fort Worth, Texas, Sichuan Basin, China, the $b$-value is around 1.4 (Lei et al., 2008; Frohlich et al., 2011).

### 2.5.3.1 $B$-value as A Function of Space

Four areas were divided naturally by tectonic setting (Fig 2.1 and Fig 2.10). Events in the area above the Morenci mine (blue dots in figure 2.10) have a $b$-value of 0.84. The Morenci mine events (green dots) has a $b$-value of 0.96. The events in red between the Morenci mine and the M 5.3 earthquake has a $b$-value of 0.90. The pink area which is the M 5.3 earthquake area has a $b$-value of 0.78. We can see a trend of variation for $b$-value which is decreasing from open pit mine toward the north and south.

### 2.5.3.2 $B$-value as A Function of Time

The earthquake sequence can be divided into subswarms for four periods by years (Fig 2.12 and Fig 2.13). We calculate $b$-value for group 1, group 2, group 3 and group 4 respectively.
Each group has different $b$-values. Figure 2.15 shows the variation of $b$-value as function of time. The maximum b-value is reached in the year 2000 with b-value equals 0.9 (Fig 2.15).

2.6 Earthquakes Distribution as a Function of Time

We divided the earthquake distribution by months during 1999 to 2002 and found that earthquakes are randomly distributed (Figs 2.16, 2.17, 2.18). The distribution does not follow any identifiable pattern that would suggest a systematically moving source such as fluid migration or seismic data acquisition.

2.7 3D Finite Element Modeling

Following the relocation of events, we looked at whether the mining could be producing a significant change in the stress field in the region due to removal of rocks or subsurface fluid migration. A similar example is Reservoir-Induced Seismicity that is thought to occur in two ways: by the addition (or removal) of the water weight of a reservoir or by the water that seeps into cracks increasing the pore pressure along a fault. The first case is very similar to an open pit mine. The Wenchuan M 8.0 earthquake is a typical example of a reservoir-induced earthquake (International rivers). Many scholars believe that the impoundment of Zipingpu dam caused the very large earthquake. We developed a 3D Finite Element Model (FEM) to calculate the change of stress due to removal of material at the Morenci mine (Figs 2.19 and 2.20). The objective was to investigate if the modeled stress changes are of the order that has been reported to trigger earthquakes in other tectonic environments, that is ~10kPa (see e.g., Reasenberg and Simpson, 1992; Gonzalez-Huizar and Velasco, 2011; Chao et al., 2013; Aiken, et al, 2016).

Table 2 gives the parameters for the mine that were used in the FEM model. The dimensional parameter for the mine were measured from Google Earth (Fig 2.19). We treated the
change in mass at the mine as an instantaneous event because that would produce the maximum change in the stress field during the time of interest.

We calculated the weight of rocks removed from the open-pit mine and calculated the stress change caused by the removal of this weight. We used the open-source FEM package LISA (Sonnenhoff, 2015) (Fig 21). The surface area of the mine modeled has a perimeter of 21 km (Fig 2.20). In some places the mine is almost 1 km deeper than the undisturbed surrounding ground. An average rock density of 2700 kg/m³ is used for the model because the major rock type present is granite. Similar to Parson (2011), for simplicity, we do not consider any particular fault orientations or regional stress field. Fig 21 shows some results from FEM analysis. The model suggests that dilatational stress changes in the vertical direction larger than 20 kPa occurred as deep as 3 km below the surface. Indicating a large potential for nearby overstressed faults to be triggered by these stress changes.

3 Discussion and Conclusions

We examined 594 earthquakes that occurred in an area encompassing the Morenci mine and the epicentral location of a M 5.3 earthquake in southeastern Arizona to determine whether mining activity contributed to the M 5.3 earthquake and also to define the properties of all events to distinguish what may be anthropogenic events from tectonic earthquakes in this area. We noted that 123 earthquakes were within the Morenci open pit mine and all 123 of them occurred at the surface during likely working hours between 10 am and 7 pm. This observation strongly suggests those 123 events were mine blasts and not naturally occurring earthquakes.

Indeed, of the 594 earthquakes we studied, only 43 occurred below the surface (Fig 2.3) according to the earthquake catalog from IRIS. Most of the earthquakes occurred at the surface between 1999 and 2002 (Fig 2.5) which corresponds to a time of very active mining (Fig 2.2). In
addition, most of the earthquakes with zero depth occurred between 10 AM and 7 PM (Fig 2.6), which suggests they were related to human activity rather than changes in the stress field or tectonic forces. However, the area where the surface events occurred is sparsely populated with small farms and towns and the events in question did not occur in any pattern that would make blasting a likely direct source. In addition, those surface events fall along a trend that clearly connects the Morenci mine with the epicenter of the M 5.3 earthquake. For that reason, we are hesitant to remove those events from the search for a connection between the mining activity and the earthquake.

Figure 6 shows that the earthquakes located below the surface mainly occurred during non-working hours which suggests they were natural earthquakes potentially related to tectonics. As we can see from figure 4, there are three periods that have low earthquake activities compared with the peak period between 1999 and 2002. We observe that the earthquakes are scattered around the Morenci area except the M 5.3 event and aftershocks (shown in red). We relocated 24 (Table 1) earthquakes and 22 of them relocated very close to the positions reported by IRIS, only two earthquakes shift around 120 km from original location. This suggests that the location reported by IRIS are reliable. The depths of these 24 events do differ from IRIS with only 6 on the surface after relocation compared to 20 on the surface from IRIS. The depth is a parameter that is very difficult to determine with precision. So, it’s hard to say the values of depth are accurate from either the IRIS catalogue or the relocation. This suggests that the depths of the events may not be a usable criterion for assigning events to anthropogenic or tectonic causes. It is worth noting at this point that the M 5.3 earthquake was located at a depth of 7 or 5 km by the various methods so it is within the depth range of the relocated events in most cases.
We randomly selected 3 seismograms that IRIS located on the surface and 3 seismograms below the surface from the IRIS catalog to compare their waveforms (Fig 2.7) and spectrum features (Fig. 2.8 and Fig 2.9) and calculate parameters from their spectrums. We calculated b-values based on the distribution and location of events (Figs 2.10, 2.11) and time (Figs 2.12, 2.13, 2.14) to analyze seismicity in this area.

The comparisons of the waveforms and spectrums for events between zero depth events and deeper earthquakes showed:

- zero depth events have higher amplitude P arrivals than deep earthquakes;
- the values of stress drop are around zero for most of zero depth events, and between 2 and 15.7 Mpa for deep events;
- the spectrums of zero depth events are similar to noise spectrums while the deeper events are clearly distinct from the noise spectrums;
- b-values calculation and calculation experiment based on different areas shows high b-values in green and red group areas and low b-value in M5.3 area (Fig 2.10);
- b-values calculations based on different times shows low b-value in the areas that have all earthquakes below surface and high b-value in the areas that have all earthquakes on the surface (Fig 2.12 and Fig 2.13).
- through our observation on monthly distribution on group 2, we find that instead of following a regular distributed pattern that radiates from Morenci mine toward M5.3 earthquake, seismic events in group 2 are randomly distributed.

Based on our observations, we suggest that most of the events are related to human activities. There are several reasons to support this interpretation. First, most of them occurred at
or near the surface; and second, they occurred during the day between 10 AM to 7 PM. Third, a high b-value suggests that the shallow earthquakes are induced. Forth, the highest b-value matches peak highest events period (group 2) according to b-value variation curve (Fig 2.16). Those observations strongly suggest the earthquakes are related to human activity. The mining activities are the most likely source in this area.

The FEM model suggests that dilatational stress changes in the vertical direction larger than 20 kPa occurred as deep as 3 km below the surface. Indicating a large potential of nearby overstressed faults to be triggered by these stress changes. However, FEM suggests that the stress change caused by the removal of material from the mine can only affect an area that is very close to the open pit mine and the M 5.3 event was over 50 km away.

Perhaps the most interesting observation is the northwest-southeast trending zone of earthquakes that was only significant over an approximate 3-year period from 1999 to 2002 when the mining activity was at its peak. This zone directly connects the Morenci mine to the M 5.3 earthquake, but the earthquake occurred 12 years after the seismic activity along the zone died out. In addition, the M 5.3 earthquake appears to have originated at a greater depth than the zone events. We cannot rule out the possibility that the M 5.3 event was tectonic and that its location along the zone is pure coincidence. However, the connection is intriguing. We do not know the source of the zone of earthquakes, but the timing and location suggests that extensive blasting at the mine may have produced sufficient stress on a fault or system of faults to move it closer to failure such that the M 5.3 earthquake happened a bit sooner or in a slightly different location than it might otherwise have occurred.
In conclusion, we suggest the M5.3 earthquake was likely to have a human contribution. We have not identified the direct link, but we infer that seismic activity related to the peak mining activity may have contributed to the event.
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A Faultline Runs Through It: Exposing the Hidden Dangers of Dam-Induced Earthquakes, (2009), International Rivers


TABLES

Table 2.1 24 randomly selected earthquakes for relocation. Locations are given in decimal degrees of latitude and longitude and depths are in km. The revised locations based on SEISAN are in the columns labeled “re-lat”, “re-lon”, and “re-depth”.

<table>
<thead>
<tr>
<th>Time(UTC)</th>
<th>Lat</th>
<th>Lon</th>
<th>Depth</th>
<th>Re-Lat</th>
<th>Re-Lon</th>
<th>Re-Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/30/1996</td>
<td>33.11</td>
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**Table 2.2** The parameter of open pit mine use for the FEM.

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<tr>
<td>The average density of rocks</td>
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Figure 2.1. Satellite image of southeastern Arizona and western New Mexico showing the location of the Morenci Mine (outlined in red) and the M5.3 earthquake (star). Mapped faults taken from Lundington et al., 2007 are superimposed on a Google Earth Image.
Figure 2.2. Annual copper production for Morenci mine between 1880 to 2015

[modified from David F. Briggs, 2016].
Figure 2.3. The distribution of earthquakes with different time of occurrence and depth.
Figure 2.4. The distribution of earthquakes with different period of time omitting the large group of earthquakes between 1999 and 2002 for clarity.
Figure 2.5. Number of Earthquakes per year between 1981 and 2014
Figure 2.6. Number of earthquakes per hour in 24 hours.
**Figure 2.7.** The waveforms of 6 events from group 2, group 3 and group 4.

The first three events are from group 2, and the rest of them are from group 3 and 4.
Figure 2.8. The Spectrum of 3 events between 1999 to 2002. (MO: log of moment, ST: Stress drop in bars, OM: log spectral level (nm-sec) not distance corrected, f0: corner frequency (Hz), R: source radius (Km), MW: moment magnitude, Vel: velocity used (km/sec), Dens: Density (g/cm$^3$)).
Figure 2.9. The Spectrum of 3 events between 2003 to 2014. (MO: log of moment, ST: Stress drop in bars, OM: log spectral level (nm-sec) not distance corrected, f0: corner frequency (Hz), R: source radius (Km), MW: moment magnitude, Vel: velocity used (km/sec), Dens: Density (g/cm³)).
**Figure 2.10.** The b-values for each subswarm divided tectonically are shown by different color.
Figure 2.11. Frequency-magnitude distribution in four different areas.

Vertical axis is the cumulative number of earthquakes cumulative number of events having a magnitude $\geq M$ and horizontal axis is the number of earthquakes of magnitude $M$. 
Figure 2.12. The b-values for each subswarm divided temporally are shown by different color.
Figure 2.13. The b-values for subswarm between 1999 and 2002.
Figure 2.14. Frequency-magnitude distribution for 4 different time windows (from 05/04/1981 to 12/31/2014). Vertical axis is the cumulative number of earthquakes cumulative number of events having a magnitude $\geq M$ and horizontal axis is the number of earthquakes of magnitude $M$. 
Figure 2.15. Graph showing the evolution of the b value as a function of time for Morenci area.
Figure 2.16. Earthquake distribution for January (left) and February (right) of 1999.
Figure 2.17. Earthquake distribution for January (left) and March (right) of 2000.
Figure 2.18. Earthquake distribution for January (right) and February (right) of 2001.
Figure 2.19. Satellite image of Morenci copper mine.
Figure 2.20. The finite element volume used to calculate the differential stress change produced by the removal of material from the mine. Surface values were measured on Google Earth images of the mine.
**Figure 2.21.** FEM predicted differential stress changes A. with depth and B. on the surface of open pit-mine due to the removal of mass from the pit.
CHAPTER 3

IS WASTER WATER INJECTION BY SHALE GAS WELLS RELATED TO SEISMICITY IN NUEVO LEON, MEXICO?

3.1 Abstract

In this work, we investigate a potential case of earthquakes induced by fluid injection. We examined 281 earthquakes in Nuevo Leon to determine whether these earthquakes correlate to fluid injection by shale gas wells. Based on our observations, we suggest that earthquakes that surround to shale gas wells Tangram-1, Nerita-1, Batial-1 and Kerner-1 are induced by their fluid injection. Earthquakes that are in the mountain or close to mountain front are tectonic earthquakes. We performed b-value analysis that suggest earthquakes that surround to shale gas wells are induced earthquakes, and earthquakes that close to Mojave-Sonora megashear are tectonic earthquakes. We further performed temporal and spatial analysis for the distribution of all earthquakes which support the suggestion of b-value analysis.

3.2 Introduction

Most earthquakes occur along active tectonic boundaries where their cause generally can be attributed to the interactions between two or more moving plates. In contrast, intraplate earthquakes are less common, they occur far from plate boundaries, and their causes are often unclear (Scholz et al., 1986, Stein, 2007). Intraplate earthquakes can be divided into two groups, natural and induced earthquakes. Natural earthquakes are inferred to be due to the accumulation of stresses from mountain building, sediment loading, and isostatic changes due to, for example, melting glacial ice. Induced earthquakes are caused by human activities such as construction of dams, hydrofracturing for petroleum recovery, and waste water injection.
In this study, we focus on recent earthquake swarms that have caused considerable damage to houses and schools in the state of Nuevo Leon in Mexico. There is strong evidence that both natural and induced earthquakes are a factor (e.g. Martinez, 2014) in the local events. We used b-values, temporal and spatial variations and other geophysical data to help distinguish events that were likely to be natural from those that are probably induced. We examine whether variations in the b-values provide a valid tool for discriminating between probable causes of intraplate earthquakes in this region. Our results show that while earthquakes close to the mountain front are probably tectonic earthquakes and those close to particular shale gas wells are probably induced, there are also a number of local regions close to waste water injection sites with b-values that suggest the events are natural rather than induced or some combination of both causes. This may indicate there are faults in those areas that are close to rupture and the water injection is sufficient to trigger one or more events.

### 3.3 Intraplate Earthquakes

Large intraplate earthquakes can cause widespread damage because energy attenuation is relatively low inside plates (Hanks and Johnston, 1992; Crone et al., 2003; Montalvo-Arrieta et al., 2015). In addition, intraplate earthquakes can lead to greater stress drops (by a factor of 3) than interplate earthquakes because the stress drops increase with the period of recurrence (Scholz, 2003). Intraplate earthquakes can occur in areas that do not have a history of earthquakes where the building codes were not designed for earthquakes with magnitudes greater than 3.0 (National Research Council, 2013) (Fig 3.1).

In most intraplate regions the cause of earthquakes is not certain but may be associated with natural causes such as, glacial rebound in the northeastern U.S. and eastern Canada or possible sediment loading along the Mississippi river valley. In the past 10 to 20 years, however, there
has been a dramatic increase in intraplate seismicity particularly in regions where petroleum recovery involves either hydrofracturing or waste water injection into deep wells (Figure 3.1). The likelihood that human activity is inducing earthquakes in those areas suggests that it may one day be possible to control and predict such events but in order to approach that goal, we first need to understand the mechanisms for induced earthquakes and distinguish them from natural events.

There are several possible explanations for the induced seismicity, such as artificial lakes, mining, waste water disposal wells, hydrocarbon extraction and storage, groundwater extraction, hydraulic fracking, etc. As oil and gas production from unconventional reservoirs expands, it seems likely that the occurrence of induced earthquakes associated with these activities will also increase (Mcgarr, 2013). A very specific example is state of Oklahoma where there was an average of 2 magnitude 2.7 or greater earthquakes annually between 1980 and 2000. The annual numbers of earthquakes increased to about 2500, 4000, and 2500 in 2014, 2015, 2016 respectively. Researchers believe that these earthquakes are man-made and triggered by wastewater injected into deep underground wells from gas recovery operations. These injected fluids can cause pressure changes that make some faults move and induce earthquakes. The recent earthquakes in midcontinental North America have not caused any fatalities yet, but some of these events have reached magnitudes of 5.0. Globally, earthquakes increased sharply starting around 2009 (https://earthquake.usgs.gov /research/induced/images/hockey-stick.png, 2018) like the 1986 San Salvador, El Salvador intraplate earthquake (M=5.8) that killed more than 1500 people, injured more than 10,000 and left 100,000 homeless [Ellsworth 2013; Harlow et al, 1993]. Although losses of this scale are unlikely in the U.S., the hazard in countries like Mexico where poor construction practices and few regulations could increase the damage from a moderate size earthquake.
3.4 Geological and Tectonic Settings

The State of Nuevo León is located in northeastern Mexico, on the border of two geological provinces, the Sierra Madre Oriental and the Gulf Coastal Plain. The geology of Nuevo Leon is dominated by sedimentary rocks. The sediments accumulated in the bottom of the primitive seas and became limestone, shale and sandstone throughout the region. In the Gulf Coastal Plain there is alluvium, as well as shales and sandstones, which are mixed to form conglomerates.

The structural configuration and sedimentation processes in northeastern Mexico are the result of a complex tectonic evolution (Goldhammer, 1999; Dickinson and Lawton, 2001). There are several main tectonic events that have affected this area: (1) The separation of the supercontinent Rodinia during early Neoproterozoic-Paleozoic (Torsvik, 2003) that generated the Iapetus ocean, in the southeastern continental margin of North America (Stewart, 1988). (2) The Pangea Supercontinent was shaped by the process of collision of the Gondwana and Laurasia landmasses during the Paleozoic (Sedlock et al., 1993). (3) The split of Pangea initiated in the Late Triassic in Northeastern Mexico (Goldhammer, 1999; Padilla y Sánchez, 1985). This is the beginning of the rifting process which formed the Gulf of Mexico (Padilla y Sánchez, 1982; Goldhammer et al., 1991; Goldhammer, 1999). (4) The Sierra Madre Oriental was created by the beginning of the Laramide Orogeny in the Late Cretaceous and Early Tertiary with the development of the detachment of the Mesozoic sedimentary sequence. (SMOr; Padilla and Sánchez, 1982; 1985; Eguiluz de Antuñano et al., 2000). (5) The Cenozoic is represented by extensive deformation along normal faults, which are part of Llanura Costera del Golfo Norte de Mexico (LICGNM) (Echánove, 1986; Ortiz Ubilla and Tolson, 2004). Several major faults cross in the region (Fig. 2) including: the San Marcos fault, La Babia fault (Charleston, 1981), the Galeana fault, the Torreón Monterrey fault, and the Mojave-Sonora megashear (Anderson and
Schmidt, 1983; McKee et al., 1984, 1990) (Fig. 3.2). Each of these faults represents a potential seismic hazard because they could be reactivated by movement in the region.

### 3.5 Observations of Earthquakes

Northeastern Mexico is relatively tectonically stable with low seismicity (Galván-Ramírez and Montalvo- Arrieta, 2008) so there is no continuous earthquake monitoring in the region. Thus, earthquakes with magnitudes $M \leq 3.7$ are not registered by stations of the National Seismological Service (SSN). Even with this limitation, Galván-Ramírez and Montalvo-Arrieta (2008) presented a catalog of 118 historical earthquakes with magnitudes between 2.4 and 6.5 in northeastern Mexico for the period between 1847 and 2006.

We used open source data from Pemex for the period of operation of shale gas wells, the historical earthquake catalog for the period between 1847 to 2006 (Galván-Ramírez Montalvo-Arrieta, 2008) and the SSN earthquake catalog between 2006 to 2015 to look at seismicity patterns in the study area. The earthquake magnitudes range from 0 to 4.5. Based on the spatial and temporal patterns of the earthquakes (Figs 3.3 and 3.4) we made the following observations:

1. Three hundred and two earthquakes were observed between 1847 to 2015 in the study area according to the earthquake catalogs from SSN, and Galván-Ramírez and Montalvo-Arrieta (2008) (Fig 3.3). Of those 302 earthquakes, 15 occurred between 1847-2006, 13 between 2006-2011 and 194 earthquakes between 2012 to 2015 according SSN.

2. Before 2006, there were 14 earthquakes in the mountain area (Galván-Ramírez and Montalvo-Arrieta, 2008). During 2006 and 2011, the majority of the earthquakes occurred in the mountain area and a few earthquakes occurred near a Pemex shale gas well which used hydrofracturing for the extraction of the hydrocarbons (SSN).

3. During July through December of 2012, a group of small earthquakes ($M \leq 3.6$) occurred
near the Sierra Madre Oriental where the city of Linares is located.  

4. During October of 2013 to September of 2014, another sequence of earthquakes occurred in or close to the area where Pemex shale gas wells were located.  

5. There is an observable correlation between some groups of earthquakes and specific shale gas wells (Fig 3.5).  

3.6 Discussion of Observations  

The first observation, that a significant number of earthquakes were located near the mountain front or near the areas where operating shale gas wells were located, strongly suggests that earthquakes near the mountain front were related tectonic activity, and the earthquakes near operating shale gas wells were related to waste water injection. However, that explanation doesn’t work very well for several earthquakes that were far away from the mountain front and also far away from operating shale gas wells.  

In order to examine this problem further, we divided the earthquakes into 8 groups based on their time of occurrence (Figs. 3.3 and 3.4). Group 1 (1847-2006) includes all earthquakes prior to modern continuous recording equipment in the area, group 2 (January 2006 to September 2011) is defined by the time when modern records were readily available but waste water injection had not started, groups 3 through 8 correspond to the times of operation of specific injection wells in the region. Figure 3.5 shows the 8 groups with different colors. According to Figure 3.3, the average earthquakes for group 1 to 8 annually is listed on Table 3.1.  

Figure 3.6 shows each group individually with different size of dots for different magnitudes. Prior to 2012, which we called pre-injection period, most of the earthquakes in the state of Nuevo Leon Mexico were roughly distributed along the Curvature of Monterrey (Fig 6A and Fig 6B). Figure 6C to Figure 6H show earthquakes that occurred during May of 2012 to
December of 2015 separately based on the consistency of earthquake occurrence. It is likely that many of the events close to shale gas wells were induced earthquakes related to the petroleum extraction processes, and earthquakes that occurred near or in the mountain area related to tectonic activity. However, in all cases each group includes earthquakes in both regions so it is not a simple matter of assigning cause based on location. The relatively short history of possible induced earthquakes and the longer history of natural events in this area, combined with the availability of data from Pemex on their activities in the region make this a good place to examine methods to distinguish induced earthquakes from natural events. To test this hypothesis, we started temporal and special analysis for earthquakes and shale gas wells (Fig 3.7 and Fig 3.8). we selected part of group 2 and all groups between group 3 and group 8 for relocation. We downloaded seismic data from IRIS for relocation using the software package SEISAN.

3.6.1 Temporal and Spatial Correlation between Seismicity and Wastewater Disposal Wells Operation

Because the first shale gas well started to operate at 2012, and the earthquakes number started to increase dramatically at the same time, we choose groups 3 to 8 for our main focus. We obtained data for some wells in the study area from Pemex, (Table 3.2) that include GPS information and the period of operation for eight shale gas wells. Figure 3.8 shows a clear temporal correlation between seismicity and shale gas wells. But this does not indicate that all the events in the region during those times are induced by wastewater disposal.

3.6.2 Relocation of 281 Earthquake Events

SSN started to record the location of earthquakes in northeastern Mexico in 2006 with one permanent station until December of 2012 (Gómez-Arredondo, 2016). The data were obtained
from a single 3-component station (one station method, e.g. Alessandrini et al., 1994; Agius and Galea, 2011). This location method has proved reliable in the absence of more than one seismic station (Frohlich and Pulliam, 1999). To test SSN’s accuracy on locations of earthquakes and get more accurate locations of earthquakes, we downloaded seismic data between 2010 and 2015 from IRIS. We used seismic stations shown in figure 3.9 for relocation. These seismic stations were distributed in Texas, New Mexico, and Chihuahua and Nuevo Leon States of Mexico. All Stations in Chihuahua were deployed by UTEP during 2014 and incorporated into the IRIS network.

We used the UTC time of 281 earthquake events from the SSN earthquake catalog, then relocated the earthquakes by using the program Hypocenter (Lienert and Havskov, 1995) from the SEISAN software package (Otemöller et al., 2017). Figure 3.10 shows the relocations for all 281 earthquake events. As we can see from figure 3.10, the relocation of earthquakes in groups 4 through 8 matches with SSN’s report pretty well, but some earthquakes from the group 3 shift their locations to the mountain region. The results of the relocation of group 3 is confirmed by the previous relocation work that was done by Carmen M. Gómez-Arredondo, 2016. She used more stations to relocate earthquakes between July of 2012 to December of 2012, and her results showed that the majority of earthquakes of group 3 were near the mountain front where we would have assumed they were tectonic in origin.

3.6.3 B-value Calculation and Analysis

The Gutenberg-Richter relationship is expressed in the equation:

$$\log_{10} N = a - bM$$

In this equation, M is the earthquake magnitude of interest, N is the number of earthquakes with magnitudes greater or equal to magnitude M, b is a constant that describes the slope of the distribution or relative frequency of large and small earthquakes, a is another
constant value that describes the productivity of a sequence. The \( b \) value is the constant of interest to many seismologists because it puts a number on the magnitude distribution of a given group of earthquakes. High \( b \) values indicate an abundance of small magnitude events; lower \( b \)-values describe more large magnitude events than small magnitude events. It is often believed that the overall \( b \)-value should be close to one. However, this may apply only to the case for natural seismicity sampled over a large enough volume (C.E. Bachmann, W. Foxall and T. Daley, 2014).

\( b \)-values have been used to distinguish between induced and natural earthquakes with the suggestion that different \( b \)-values correspond to different earthquake characteristics (Jamie Farrell, 2009). For example, the \( b \)-value of a global average of all tectonic earthquakes is 1. Injection-induced earthquakes have larger \( b \)-values (National Research Council of the National Academies 2013). Values are observed as high as 2.0 during fracking of shale gas/oil field. Table 3 includes \( b \) values of different earthquakes from different places by different induced methods. Only one of the listed sites, in Arkansas, shows a \( b \)-value less than 1 for an injection-induced series of events.

3.6.3.1 \textit{B-Value as a Function of Space}

For this part of the study we omitted some earthquakes that are randomly distributed and selected earthquakes that concentrated to shale gas wells and also concentrated in mountain and mountain front, in this way, it can help us to calculate and distinguish \( b \)-value more accurately. Then we divided the earthquakes into 3 groups, designated the blue, orange and yellow groups, based on the spatial distribution of events after relocation (Fig. 3.11). The blue group mainly consists of time group 5, yellow color group mainly consists of time group 3, and the orange color group mainly consists of parts of group 3 to group 8. The blue group, where the area has maximum number of injection wells, has a \( b \)-value of 1.29 which suggests group 5 is induced. The yellow
group is close to the mountain front and has a $b$-value of 0.6 which suggests that yellow group is tectonic. The orange group has a $b$-value of 0.53 which suggests that orange group is tectonic also. We can see a very distinct difference between earthquakes in the waste water injection area and earthquakes in mountain front area based on the spatial $b$-value calculation.

3.6.3.2 $B$-Value as a Function of Time

We also calculated $b$-value for group 2 to group 8 (Fig 3.12) which are groupings based on time rather than space. The $b$-value from group 2 to group 8 are 0.53, 0.6, 0.67, 1.27, 0.7, 1.08 and 1.1 respectively (Fig 3.12). As we combine these numbers with period of operation of shale gas wells, we suggest that group 2 relates to tectonic activity because it was the pre-injection period. There was one well was operating before and during part of group 2’s time, but the location of the shale gas well Arbolero-1 is far from group 2. Groups 3 and 4 also appear to relate to tectonic activity because there was no injection during that period and both groups have low $b$-values. Group 5 appears to be induced by the operation of the shale gas wells because the time window of group 5 overlaps with the operation of shale gas wells and its $b$-value is high; group 6 is the combination of earthquakes that occurred in mountain area and earthquakes occurred near where shale gas wells located, so the $b$-value is a little higher than pure tectonic earthquakes; group 7 and 8 could be the residual effect of waste water injection because their $b$-values are also high but the injection has ceased.

3.6.4 Earthquakes Distribution during the Operation of Each Shale Gas Wells

In order to see a clear earthquakes distribution pattern that can correlate earthquakes with the operation of shale gas wells, and correlate earthquakes with tectonic activity, we plotted earthquakes distribution during the operation of each shale gas wells (Fig 3.13). From these
figures, we can see that Arbolero-1 does not correlate to any earthquakes because there were no earthquakes during the operation of Arbolero-1. For shale gas wells Anhelido-1, Nuncio-1, Serbal-1, Cefiro-1 and Mosquete-1, their distance is far from the earthquakes which suggests they did not induce earthquakes swarms during their times of operation. For shale gas wells Tangram-1, Kerner-1, Batial-1 and Nerita-1, their distance is very close to the earthquakes, which suggests that their operation induced the earthquakes.

### 3.6.5 Earthquakes Distribution as a Function of Time

Among the 8 groups, the most intriguing groups are group 3 and group 5. To further analyze the relation of the evolution of earthquakes of these two groups with the operation of shale gas wells, we break the earthquakes of group 3 sequentially into months. Figure 3.14 shows the distribution of earthquakes of group 3 during operation of Anhelido-1. Figure 18 shows the earthquakes distribution of group 3 in a monthly sequence from May of 2012 to October of 2012. We can see that the earthquakes mainly focus near the mountain front and don’t follow a discernable pattern.

Figure 3.16 shows the distribution of the earthquakes of group 5 during operation of tangram-1, Nerita-1, Batial-1, and Kerner-1, Cefiro-1, Nuncio-1, Mosquete-1 and Serbal-1. Again, we look at the earthquake distribution of group 5 by month. Figure 17 shows the earthquakes distribution of group 5 in a monthly sequence from October of 2013 to September of 2014. We can see a pattern of earthquakes which surrounded the wells Tangram-1, Nerita-1, Batial-1 and Kerner-1. There is no obvious relation between earthquakes and wells Cefiro-1, Nuncio-1, Mosquete-1 and Serbal-1 because the earthquakes appear to be far from those wells. In addition to the proximity of the group 5 events to the 4 wells identified in figure 16, there is suggestion that the location of some events may indicate a source that is moving away from the wells over time in
These observations strongly suggest the group 5 events are induced by waste water injection from the 4 wells.

In order to test residual effect of waste water injection, we calculated the b-value of the earthquakes close to shale gas wells. Figure 3.18 shows earthquakes that are close to shale gas wells during 2015 and the b-value of these earthquakes is 1.09.

3.7 Discussion

The major objective of this study was to try to find ways to distinguish between natural seismicity and that induced by wastewater disposal wells in the State of Nuevo Leon, Mexico. It is important because earthquakes in Nuevo Leon have caused damage. Research on induced earthquakes can help people in that area avoid building in areas where an induced earthquake is likely and it can help the local government to issue some regulations to prevent additional damage in the area. Induced seismicity is a controversial topic because limited research on the subject have produce mixed results.

We used earthquake data between 1847 to 2015 (Fig 3.3 and Fig 3.4) to analyze earthquake patterns in this area with a focus on events between 2006 and 2015 when relatively modern equipment was available to record events in the study area. Based on the consistency (Fig 3.3 and Fig 3.4) of earthquakes in time, we divided the earthquakes into 8 groups (Fig 3.6). The first two groups, 1 and 2, consist of events that occurred prior to waste water injection and we are not aware of any other likely human sources for these events so they provide a model for natural earthquakes in this region. Most of the events in groups 1 and 2 are along the mountain front (Fig 3.5, Fig 3.6A and Fig 3.6B) but a significant number are located in or near the area where the injection wells would be placed at a later date so we cannot rely on proximity to active injection wells alone to distinguish identify induced earthquakes in this area. The b-value for group 1 was not computed.
due to a lack of information but for group 2 the b-value is 0.53 which is consistent with the interpretation that all of the pre-injection events are natural.

The recent earthquakes, however, show mixed results. There is a dramatic increase in the number of earthquakes beginning in 2012. The majority of earthquake occurred near shale gas wells where the waste water was injected (Fig. 3.7) but there is also a significant number of events in these groups that are located along the mountain front. In order to verify the location of earthquakes reported by SSN, we downloaded data from IRIS to relocate 281 earthquakes by using SEISAN (Fig. 3.10). There are some differences between locations reported by SSN and our relocations. In particular, the relocation of group 2 moves most of earthquakes in that group close to the mountain front confirming the previous relocation of those events by Gomez-Arrredondo (2016) and consistent with our previous assumption that these were natural events. The relocation of groups 4 to 8 from SEISAN matches with result reported by SSN very well (Fig. 3.10).

The earthquake groups 3 to 8 correspond to the time of operation of shale gas wells and are mostly located near those wells. To analyze this correlation further, we calculated b-value spatially and temporally. We divided earthquakes of group 3 to group 8 into 3 subswarms spatially (Fig 3.11). In the place where subswarms are close or in the mountain which are the yellow and orange subswarms, the b-values are 0.53 and 0.6, respectively, which suggest that earthquakes in these subswarms are tectonic. Subswarm blue is close to shale gas wells and its b-values is 1.29 which suggests that earthquakes in this subswarm are induced by waste water injection. We also calculated b-values temporally based on different time range for eight groups (Fig 3.12). The b-values for groups 2-8 are 0.53, 0.6, 0.67, 1.27, 0.7, 1.08, 1.1, respectively. It is very obvious that group 5 which makes up most of the blue subswarm earthquakes has the highest b-value among eight groups which suggests that group 5 is induced earthquakes group. Group 3 mainly consists
of yellow subswarm earthquakes has $b$-value of 0.6 which suggest that group 3 is natural earthquake group.

To better understand the relation between earthquakes and operation of waste water injection by each shale gas wells. We plotted earthquake distribution during the operation period of each wells (Fig 13). Figure 13A shows that there were no earthquakes during the operation of Arbolero-1 which suggests that there is no correlation between seismic activity and Arbolero-1. Similarly, all of the wells except Nerita-1, Kerner-1, Batial-1, and Tangram-1, were located far from the seismic activity and that suggests they did not cause the earthquakes. Figure 3.13 shows that Nerita-1, Kerner-1, Batial-1, and Tangram-1 are located in the area of earthquake group 5 which suggests that they are correlated.

All shale gas wells had been shut down on 1/1/2015. Figure 3.6F, 3.6G, 3.6H show the earthquakes distribution during whole year of 2015. We can see that earthquakes are randomly distributed in research area, and several earthquakes are concentrated near shale gas wells Tangram-1, Batial-1, Kerner-1 and Nerita-1. We raised a question when we look at earthquakes surrounded shale gas wells. Why did these earthquakes occur after shutting down of shale gas wells. Then we calculated $b$-value of these earthquakes to see if they are tectonic or induced. The $b$-value for these earthquakes is 1.09 which suggests that they may be a mixture of induced and natural earthquakes (Fig 3.18).

Based on our observations and calculation, we suggest that earthquakes (group 3) that were close to mountain are natural and earthquakes (group 5) that are close to shale gas wells are induced. This leads to the obvious conclusion that earthquakes that were close to the mountains were tectonic, and earthquakes that are close to shale gas wells are induced by waste water injection. However, if you remove all of the inferred induced earthquakes from the time series
presented in figures 1, 3, and 4 there would still be a striking increase in the number of earthquakes beginning about the same time as the onset of waste water injection that need to be considered. Two possible explanations for the increased seismicity may be 1) coincidence and/or 2) better instrumentation in the region to record small events. Possibility 2 is certainly a likely factor in the increased observations. However, we would like to pose one more possibility based in part on the continued seismic activity after the injection period ended. That is, we feel it is likely that the induced events and the general process of fluid injection have a significant impact on the local stress field for many years after injection begins. That impact may cause some faults to rupture earlier than they might otherwise have ruptured or they may create an area of weakness where a fault may move that would not have moved without the “triggering” effect of the induced events or the movement of waste water in the subsurface.

In terms of the earthquake hazard in Nuevo Leon we think it would be important to gather additional information on why some wells appeared to induce earthquakes and others did not. Is it the character of the geology in the immediate area of the wells or is it something about how the water is injected, such as pressure or quantity of water. With additional knowledge, it is likely that some conditions can be created to control the likelihood of additional events by modifying where or how waste water is injected in this area.
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TABLES

**Table 3.1.** Average earthquakes annually of group 1 to group 8

<table>
<thead>
<tr>
<th>Group</th>
<th>Group</th>
<th>Group</th>
<th>Group</th>
<th>Group</th>
<th>Group</th>
<th>Group</th>
<th>Group</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Average earthquakes</td>
<td>0.094</td>
<td>0.18</td>
<td>14.5</td>
<td>1.18</td>
<td>11</td>
<td>7</td>
<td>3.5</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 3.2. Location and period of operation of Wastewater disposal wells (from Pemex)

<table>
<thead>
<tr>
<th>Well name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Beginning of injection</th>
<th>End of injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbolero-1</td>
<td>27.18</td>
<td>-99.97</td>
<td>1/8/2012</td>
<td>4/15/2012</td>
</tr>
<tr>
<td>Nerita-1</td>
<td>25.53</td>
<td>-99.69</td>
<td>8/26/2013</td>
<td>1/1/2015</td>
</tr>
<tr>
<td>Kerner-1</td>
<td>26.01</td>
<td>-99.52</td>
<td>4/19/2013</td>
<td>12/31/2013</td>
</tr>
<tr>
<td>Batial-1</td>
<td>25.85</td>
<td>-99.5</td>
<td>6/6/2013</td>
<td>1/1/2015</td>
</tr>
<tr>
<td>Tangram-1</td>
<td>25.55</td>
<td>-99.43</td>
<td>4/10/2013</td>
<td>12/31/2013</td>
</tr>
<tr>
<td>Cefiro-1</td>
<td>25.01</td>
<td>-98.78</td>
<td>8/11/2013</td>
<td>1/1/2015</td>
</tr>
<tr>
<td>Serbal-1</td>
<td>24.7</td>
<td>-98.36</td>
<td>3/20/2013</td>
<td>1/1/2015</td>
</tr>
<tr>
<td>Mosquete-1</td>
<td>24.85</td>
<td>-98.53</td>
<td>8/18/2013</td>
<td>1/1/2015</td>
</tr>
<tr>
<td>Anhelido-1</td>
<td>24.52</td>
<td>-98.37</td>
<td>7/7/2012</td>
<td>12/28/2012</td>
</tr>
</tbody>
</table>
### Table 3.3 Induced seismicity b values for different places and different processes

<table>
<thead>
<tr>
<th>Activity</th>
<th>Location</th>
<th>B value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater disposal</td>
<td>Dallas-Fort Worth, Texas, USA</td>
<td>1.3</td>
<td>Frohlich (2011)</td>
</tr>
<tr>
<td>Wastewater disposal</td>
<td>Sichuan Basin, China</td>
<td>1.3</td>
<td>Lei (2008)</td>
</tr>
<tr>
<td>Wastewater disposal</td>
<td>Guy, Arkansas, USA</td>
<td>0.8</td>
<td>(Huang and Beroza, 2015)</td>
</tr>
<tr>
<td>Gas injection</td>
<td>Offshore Spain</td>
<td>1.4</td>
<td>Cesca (2014)</td>
</tr>
<tr>
<td>Gas injection</td>
<td>In Salah, Algeria</td>
<td>1.5 – 2.0</td>
<td>Goertz- Allmann (2014)</td>
</tr>
<tr>
<td>Hydraulic Fracturing</td>
<td>Attica Dale, New York, USA</td>
<td>1.1 – 1.5</td>
<td>Fletcher and Sykes [1977]</td>
</tr>
<tr>
<td>Hydraulic Fracturing</td>
<td>Barnett shale, USA</td>
<td>1.5 – 1.9</td>
<td>Vermynlen and Zoback [2011]</td>
</tr>
</tbody>
</table>
**Table 3.4.** The b-values for eight groups respectively

<table>
<thead>
<tr>
<th>Group</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
<th>Group 5</th>
<th>Group 6</th>
<th>Group 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-value</td>
<td>0.53</td>
<td>0.60</td>
<td>0.67</td>
<td>1.27</td>
<td>0.70</td>
<td>1.08</td>
<td>1.10</td>
</tr>
</tbody>
</table>
Figure 3.1. Cumulative number of earthquakes with a magnitude of 3.0 or larger in the central and eastern United States, 1970–2016. The long-term rate is approximately 29
Figure 3.2. Major faults in state of Nuevo León, they are San Marcos, Torreón Monterrey, and Galeana.
Figure 3.3. Numbers of earthquakes versus time between 1847 to 2015. Color bars corresponds to groups discussed in the text.
Figure 3.4. Numbers of earthquakes versus time between 2006 to 2015
Figure 3.5. Eight groups of earthquakes displaying by different color
A. (Group 1)

B. (Group 2)
E. (Group 5)

F. (Group 6)
Figure 3.6. Eight groups of earthquakes displaying individually with different size.
Figure 3.7. Spatial correlation between earthquakes and wells for group 2 to group 8
Figure 3.8. Temporal relation between events and operation period of each shale gas well, the length of horizontal lines represents the time of operation of shale gas wells.
Figure 3.9. Location of seismic station used for relocation of 281 earthquake events
Figure 3.10. The comparison between relocation earthquakes and original earthquakes from SSN
Figure 3.11. The $b$-value for subswarms divided by spatial distribution of events
Figure 3.12. The b-values for eight groups respectively
A. Arbolero-1 (1/8/2012 to 4/15/2012)

B. Anhelido-1 (7/7/2012 to 12/28/2012)

D. Serbal-1 (3/20/2013 to 1/1/2015)
E. Tangram-1 (4/10/2013 to 12/31/2013)

F. Kerner-1 (4/19/2013 to 12/31/2013)
G. Batial-1 (6/6/2013 to 1/1/2015)

H. Cefiro-1 (8/11/2013 to 1/1/2015)
Figure 3.13. The earthquakes distribution during the operation period of each shale gas wells
**Figure 3.14.** Earthquakes distribution of group 3 during the operation of Anhelido-1
A. May to July of 2012

B. August of 2012
C. September of 2012

D. October of 2012

100
Figure 3.15. Earthquakes distribution of group 3 divided into six consecutive months during May of 2012 to October of 2012. (First map shows May, June, and July together)
Figure 3.16. Earthquakes distribution of group 5 during the operation of Kerner-1, Baital-1, Nerita-1, Cefiro-1, Nuncio-1, Mosquete-1 and Serbal-1.
A. October of 2013

B. November of 2013
C. December of 2013

D. January of 2014
E. February of 2014

F. March of 2014
G. April to June of 2014

H. July to September of 2014
Figure 3.17. Earthquakes distribution for five consecutive months during October of 2013 to March of 2014.
Figure 3.18. Earthquakes that are close to shale gas wells in 2015
CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This study addresses the potential correlation between earthquakes swarms and human activity in two areas, southeastern Arizona and Nuevo Leon, Mexico. The Arizona study looks at the potential relationship between blasting at the Morenci mine and a magnitude 5.3 earthquake while the Nuevo Leon study examines the relationships between tectonics, wastewater injection and earthquake swarms. The features of interest include the distribution pattern temporally and spatially associated with the earthquake swarms, b-values based on different time and spatial groupings, relocation of earthquakes, earthquakes distribution as a function of time, and proximity to potential sources.

Both study areas have a long history of naturally occurring earthquakes with relatively small magnitudes and a relatively short history (less than 20 years) of greatly increased seismic activity. The main difference between the two regions is the potential anthropomorphic mechanism for inducing earthquakes. At the Morenci blasting appears to induce earthquakes, while in Nuevo Leon the mechanism for inducing earthquakes appears to be wastewater injection. The apparent induced earthquakes near the Morenci mine are reported to be at zero depth, while the depth of earthquakes in Nuevo Leon are between 5 to 15 kilometers. The occurrence of events in Morenci mine were mainly concentrated between 10am to 7pm which is working hours while earthquakes of Nuevo Leon were occurred randomly. The $b$-values of induced earthquakes are different, with artificial mining blast $b$-value is around 1 while the $b$-value of waste water injection is around 1.27.
4.2 Recommendations and Future Research Plan

In this study, $b$-values are a very important factor that can be used to distinguish between anthropomorphic earthquakes and tectonic earthquakes. The research on $b$-values in this context is not extensive. Research has confirmed that $b$-values vary systematically for some different tectonic areas. For example, in tectonic areas, the $b$-value typically is around 0.49 to 0.81 (Mohammad Ashtari Jafari, 2008). In volcanic areas, $b$-values could be as high as 3.0 (Mcnutt, 2005). In the enhanced geothermal system areas, the $b$-value is typically between 1.1 and 1.6 (Bachmann, 2012). In the gas injection areas, the $b$-value is around 1.4 (Cesca, 2014). So, different $b$-values appear to characterize different mechanisms that trigger earthquakes.

In Morenci mine case, the $b$-value for mining blasts is around 1, and in the Nuevo Leon case, the $b$-value for induced earthquakes is around 1.27. The $b$-values for both Morenci mine and Nuevo Leon tectonic earthquakes are around 0.7 and 0.6 respectively. $B$-value application in our research successfully suggests that $b$-value are applicable for both open pit mine induced earthquakes and for waste water injection by shale gas wells in oil fields. However, no one yet has applied $b$-values to earthquake prediction such as, the prediction earthquakes using historical $b$-value maps in oil fields, geothermal areas, areas of active tectonic activity such as Los Angeles, San Francisco and for some water dam areas. For example, 2008 WenChuan M8.0 earthquake that killed more than 200,000 people because of poor building codes is considered to be an induced earthquake related to the Zipingpu water dam. Knowledge of the induced earthquake hazard in this area based on $b$-values could have led to the design of better building codes that require buildings be more resistant to high magnitude earthquakes to reduce fatality. We can also use $b$-value map in oil field areas to guide where we can build construction to avoid earthquakes or to enhance building codes in these areas.
Based on what I have done on my current research to date, I plan to continue to study b-values and their applications to distinguishing various causes of earthquakes in an effort to better serve our community and reduce earthquake fatalities.
CURRICULUM VITA

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