Spatial Analysis of Seismic Activity in the Central Great Plains

By: Ryan Korth

2013 Senior Thesis, Department of Geography/Geology

University of Nebraska at Omaha
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Abstract

Midcontinent seismic activity is not well understood and is understudied in the Central Great Plains. The main purpose of the project was to analyze seismic activity spatially to determine whether it is clustered (as seen in SW and Central Nebraska); or if another component of random seismic activity is present. Whether seismicity is related to underlying tectonic structures, regional stresses or oil production is also of interest to this project. Earthquake data were collected from multiple sources (listed below) and plotted using ArcGIS to assess if this seismic activity is random or clustered. Most of the data fell into one of the clusters, while there was a significant amount of data that did not (about one third). An anisotropy analysis was also done with the data to determine possible orientations of active faults. Six center-points were picked and used for localized anisotropy analysis. It has been determined that there are anisotropies present in the data. The direction was mostly NE-SW in nature, which is consistent with regional stresses and/or underlying structural features.

Purpose of the Project

The particular area of focus for this project is the central Great Plains, or more specifically; South Dakota, Nebraska and Kansas. Most of the recent (1970s-present) seismic data used in this study were gathered from the Incorporated Research Institutions for Seismology (IRIS) database, which also includes data collected by USGS. Data for the IRIS database were gathered by a transportable array of seismometers placed on the surface in a given location, the data used for this project ranged from 1975-2012. IRIS is a consortium of universities that is sponsored by the National Science Foundation (http://www.iris.edu/hq/). Other historical earthquake data incorporated into the analysis were taken from the work done by South Dakota, Kansas and Nebraska Geological Surveys (Steeples et. al 1998; Steeples et al 1990; Chadima 1992; Burchett 1979).

A purpose of this project is to establish if there are clustered patterns of where earthquakes occur in the Great Plains, or if they are simply random. The pattern of seismic activity could also be a mix of clustered and random points (migrating/concentrating with time) or even a uniform distribution. In particular we analyzed location data, rather than magnitude and depth, which were considered beyond the scope of this effort. Subsequent analysis would include consideration of magnitude, which could help determine the spatial distribution of the amount of energy released during seismic activity. The approach used here analyzes point (where the event happened) data in two-dimensions, using ArcGIS. Depth does not vary much, especially to the relativity of horizontal distances involved. Therefore, depth was not deemed important to this project.

Testing for anisotropy gives us potential information about active faulting. It is also possible that if there is a strong anisotropy present in the data, the pattern could be weakly clustered or not clustered at all. If the pattern is clustered, it will give insight into predicting future seismic activity. And if the pattern is simply random or more scattered, this will also give us some insight into underlying tectonic activity for the Central Great Plains, and also has implications for seismic hazard assessment.

Spatial Earthquake Patterns

The components of a pattern we are most interested in for this project are random, clustered or a uniform and it is possible that they all exist in combination in this region. If the earthquakes are random, this means that the processes involved have operated independently from those which caused other events. A random component would mean the stresses causing seismic activity are not focused in a general area. Also, the given earthquakes have an equal probability of occurrence in each section of the
total area. Non-randomness can also occur when analyzing spatial patterns. Anisotropy would fall under this category, and linear trends would be seen in this case. “Linear trends can readily be detected by calculating or measuring bearings between all pairs of points in the chosen area. (And) higher frequencies will be observed of directions in which linear trends are oriented” (Swan and Sandilands 1995). Clusters would be expected if the stresses were localized in an area over a given amount of time, or if weak surfaces exist. If seismic activity is caused by purely slippage on a fault plane, linear trends would likely be seen. Statistical assumptions are required to resolve any high non-random component that may occur (Swan and Sandilands 1995). A test for linearity (using Microsoft Excel) will be used to determine if there is any linearity or anisotropy present for seismic activity in the Great Plains.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random</td>
<td>Each point is likely to occur at any location. Weak accidental clusters are possible.</td>
</tr>
<tr>
<td>Clustered/Non-random</td>
<td>The points are unlikely random and are more concentrated.</td>
</tr>
<tr>
<td>Uniform</td>
<td>Each point occurs equally away from one another.</td>
</tr>
<tr>
<td>Isotropic</td>
<td>No preferred direction for any given set of points.</td>
</tr>
<tr>
<td>Anisotropic</td>
<td>A linear trend is seen for a given set of points.</td>
</tr>
</tbody>
</table>

Table 1: Description of Spatial Patterns.

Intraplate vs. Plate Boundary Earthquakes

An earthquake is produced by a fault that slips when stress exceeds frictional strength. When analyzing earthquakes in an intraplate region, one must first understand some of the differences between a midcontinent earthquake and one that occurs along plate boundaries. It is easier to predict (not all the time) both where an earthquake will occur along plate boundaries and the average recurrence interval of a future large earthquake (Stein 2007). However, it is not as well-understood where earthquakes will occur in the middle of a plate. Earthquake hazard assessment in a midcontinent region relies heavily on a relatively short historical record, which can be a problem for estimating a large earthquake (Stein and Liu 2009).

Microearthquakes seen in a midcontinent region could also be aftershocks of a larger event that occurred centuries ago. Stein and Liu (2009) suggest, “Aftershocks result from changes of stress and fault properties induced by the main shock. At a plate boundary steady plate motion quickly reloads the fault after a large earthquake and overweights the effects of the main shock. Within continents, however, the faults are reloaded much more slowly, allowing aftershocks to continue much longer.” This is where a problem lies when trying to predict future large events.
Mid-continent faults act as a complex system, from which stresses are generated from multiple sources (Stein et al. 2009). The processes that can cause stress to occur are: “stresses imparted by neighboring plates and generated within the plate, tractions from mantle flow, regional loads such as glacial isostatic adjustment, and local effects such as sedimentation or denudation” (Stein et al. 2009). While sedimentation and denudation will likely not cause seismicity (rather have an effect on the local stress field), changes in pore pressure can (fluid injection related seismicity). This leaves multiple possibilities for the cause of microearthquakes in the Great Plains, and there is likely not one simple determinant of their spatial distribution.

Variable fault behavior is often seen in continental interiors. “In midcontinents, the tectonic loading is shared by a complex system of interacting faults spread over a large region, such that a large earthquake on one fault could increase the loading rates on remote faults in the system (Li et al. 2009).” Stein et al. (2009) suggest that because of this, an earthquakes cluster occurs on a specific set of faults for a period of time before it migrates to another set to continue relieving stress. “Thus, mid-continental faults “turn on” and “turn off” on timescales of hundreds of thousands of years, causing large earthquakes that are episodic, clustered, and migrating” (Stein et al 2009). This would be a problem for assessing when the next large earthquake will occur in a midcontinent region, given the short historical record available. Because there is a low tectonic loading rate in the midcontinent region, faults will bear less stress than on a plate boundary, causing earthquakes to migrate and be episodic (Liu et al. 2011). Liu et al. (2011) also suggest that individual faults will remain silent for a long period of time, and then an event will occur. This has been seen in the recent geologic past along the Meers Fault in southern Oklahoma. There is known deformation that resulted from surface faulting in the late Holocene with associated seismic activity inferable (Crone and Luza 1990), but associated modern seismicity is absent.

Continents are typically thought to be rigid and not easily deformed. For example, Townend and Zoback (2000) state that, “faulting keeps intraplate crust strong by preventing pore pressures greater than hydrostatic from persisting at depth.” This is true because frictional strength of a faulted rock depends highly on the pore pressure (Hubbert and Rubey 1959). Faulting creates an escape route for fluids so they are able to migrate and reduce pore pressure. Also, because the crust is cool and brittle in an intraplate environment, frictional strength is dependent upon pore pressures at depth (Sibson, 1973; Brace and Kohlstedt, 1980). Therefore, Townend and Zoback (2000) suggest that seismicity in an intraplate setting, will migrate with time and become anti-clustered.

Northern China
Northern China allows us to more accurately examine midcontinent earthquake movement and is of interest to scientists studying midcontinent earthquakes. The difficulty with doing this in the Great Plains is that the historical record is short. To address this, Northern China was examined because it holds a long historical record of earthquakes. Liu et al (2011) tell us, “the complex spatiotemporal pattern of earthquakes in North China does not result from their random occurrence in isolated faults but reflects long-range migration between mechanically coupled fault systems in the continental interior.” This is the same idea that is suggested above for the occurrence of earthquakes in the Great Plains.

The geology of North China is similar to that of the Great Plains (specifically South Dakota, Nebraska and Kansas); with the largest difference being the active India-Asia plate collision to the south. However, because there is nearby tectonic activity in the region, deformation is greater. North China Plain consists of a complex system of basement faults (much like the Great Plains) and blanketed by thick sediment (Liu et al. 2011). The literature indicates that the earthquakes do not share a consistent epicenter, rather epicenters are migrating within the fault zones (Liu et al. 2011). Large earthquakes have occurred in the recent past on previously unrecognized faults in the Northern China Plain (Liu et al. 2011). Thus, the occurrence of earthquakes is not as predictable as once thought for a midcontinent region. Northern China has given insight to the fact that large earthquakes are possible in a midcontinent region, and can be hard to predict since movement is possible along basement faults. “No large earthquakes in North China have ruptured the same fault segment twice in the past 2000 years” (Liu et al. 2011). This is evidence to suggest that large earthquakes relieve the local stress, and slow loading will then keep it quiet for a long time.

Geologic Setting

The Great Plains has a few major structural features that might be associated with seismicity and are thus of interest for this project. These include the Midcontinent Geophysical Anomaly, Cambridge Arch-Central Kansas Uplift, the Nemaha Ridge, and the Colorado lineament. The central Great Plains hasn’t seen any significant deformation since the Late Paleozoic, and is considered to be the most stable part of the North American Continent, tectonically speaking. The Midcontinent Geophysical Anomaly (MGA) or Midcontinent Rift runs from SE Nebraska, Iowa and Minnesota before petering out in somewhere in Oklahoma or even northern Texas (Steeples et al. 1990). The MGA is a very large positive gravity anomaly, and also is distinguished by a band of subsurface mafic igneous rocks that lie in an aulacogen dormant since the Paleozoic (Steeples et al. 1990; Ocola and Meyer, 1973).
Basement faults are one possible idea, and could be of interest to explain seismicity in the area of the Sleepy Hollow Oil Field. The Sleepy Hollow Oil Field is located in south-central Nebraska along the Kansas border.

The Nemaha Ridge (similar in age to the Cambridge Arch-Central Kansas uplift); is another uplift that runs from east-central Nebraska down to central Oklahoma. This is a place where some seismic activity is seen and is considered to be Precambrian in age as well, likely influenced by the Midcontinent rift (Steeples et al. 1990). The Nemaha Ridge is important because it is a major fracture zone in the area of interest. Basement mylonites and crushed/sheared rocks are seen in association with the Nemaha Ridge (Steeples 1981). A fault zone is often a common place for microearthquakes as faults slip and slide, as is seen on both sides of the Nemaha Ridge. “Recent geophysical evidence (Steeples, 1982, 1989) indicates that a zone of faulting perhaps tens of kilometers wide exists along both sides of the Nemaha Ridge” (Steeples et al. 1990). The Humboldt fault zone lies along the east side of the Nemaha Ridge. This is a place where there is dense seismic activity seen according to the results of the project.

Lastly, the Colorado Lineament could be responsible for some of the seismicity seen in NW Nebraska and throughout South Dakota. It is proposed that there is a linear feature from SW-NE through South Dakota that would represent the extension of the known Colorado Lineament boundaries. Brill and Nuttli (1983) suggest that, “The rate of earthquake activity is too low to determine if the seismicity is uniform throughout the Colorado Lineament, or to determine recurrence rates for the entire lineament or parts of it. On the basis of the seismicity rate in historic times, it is likely that only moderate-sized earthquakes will occur within the lineament in the present geologic environment.” The Colorado Lineament is parallel to major underlying Precambrian basement structural trends (Carlson 2007). This would be important when assessing the possibility of a large earthquake in the NW Nebraska and South Dakota. The literature suggests that the seismicity east of the Rockies is much different than that one the west side. Brill and Nuttli (1983) also suggest that seismicity is not found as frequently in the Great Plains. This is because the moderate-sized earthquakes occurring west of the Rockies are much more diffuse, than seen in the Great Plains (Wong 1981). Brill and Nuttli (1983) suggest that because the rate

![Figure 3: Precambrian Basement map for Nebraska](http://snr.unl.edu/data/geographygis/NebrGISgeology.asp#precamb)
of seismic activity is much too low to be able determine if there is a concentrated component along the Colorado Lineament. Also, given the underlying geology in the region, the lineament could be a likely source for seismic activity.

**Methodology**

Seismic event data were collected from multiple sources and analyzed in ArcGIS and Microsoft Excel. Data were plotted in ArcGIS using latitude and longitude coordinates on top of the Geologic Map of North America produced by USGS (Garrity and Soller 2009). Once the data were entered, seismic activity was analyzed using the Point Density tool. It simply calculates the density of how many points fall around any other given point in a given radius (about 1 ft). More specifically, “Point Density” calculates the density of point features around each output raster cell. Conceptually, a neighborhood is defined around each raster cell center, and the number of points that fall within the neighborhood is totaled and divided by the area of the neighborhood” (ESRI 2011). Thus, it allows for a spatial analysis of how many points fall within a circular area of each given point. A neighborhood of 100 km was used to analyze seismic data for the anisotropy analysis.

A test for linearity/anisotropy was modeled using Microsoft Excel using UTM (Universal Transverse Mercator) values that were extracted from ArcGIS. A center point was selected by eye for each cluster (indicated by a star on map in Appendix 1) and the seismic events that fell within a 100 m radius were then used to determine if a linearity/anisotropy was present in that area. The center point was placed in an area where an anisotropy was thought to exist to the naked eye. To determine if an event fell within the radius of a center point the Pythagorean Theorem was employed. The distance between the points was calculated using the following formula in Excel: =DEGREES(ATAN((X1-X2)/(Y1-Y2))). These values were then used to develop a histogram to determine if there is linearity/anisotropy for the given earthquakes (bin values were 5). Histogram plots are provided along with number of events and center point in the Analysis section. Chi-square tests for randomness were also done to affirm the results.
Results

According to the density map provided below (Figure 7), some distinct clusters can be seen with the eye. Two clusters are very dense and show up as red on the map; one is in SW Nebraska and the other in NW Kansas. Much of this seismic activity is likely associated with oil production in the area. There is also a distinct cluster (although more distributed) in Central Nebraska, with no underlying structures to account for this. Two more clusters are seen in NE Kansas and SE Nebraska, underlying structural features include the Midcontinent Rift, Nemaha Ridge and Humboldt Fault zone. The last cluster that can be seen is in the Toadstool, Nebraska region which is located along the considered boundary for the Colorado Lineament.

A test for anisotropy was employed in six locations in the study area. The first place analyzed was in NE Kansas where a preferred direction was seen at about 15°. This is consistent with the underlying Nemaha Ridge, and the very low Chi-squared number clearly indicates that these points are non-random. The cluster in Central Nebraska was also analyzed and there is a strong preferred direction at 60°. Because of the underlying structural features in the area, an anisotropy analysis was done for SE Nebraska that revealed a strong preferred direction at 10°. To determine if anisotropy occurs outside of a cluster; analysis was done in South Dakota, where less seismic activity is seen. Preferred directions were at both 20° and 60°. The Sleepy Hollow Oil Field was of interest for an anisotropy analysis because the seismic activity is very dense. Sleepy Hollow Oil Field was also of interest because there is debate as to whether injection or tectonics is the underlying cause of seismic activity. It is interesting to note that there are two preferred directions at 15° and 70°, consistent with NE Kansas, SE Nebraska, South Dakota and Central Nebraska. The Chi-squared test affirmed that these points are non-random and that there is only an extremely small chance that they came from a uniform population in all areas. The only anisotropy analysis that was done which didn’t have similarities with other areas was in the area of Toadstool Geological Park in NW Nebraska. There is no preferred direction to the naked eye, and the Chi-squared test confirmed that there was a small chance that these points came from a uniform population.

When the data for magnitude were plotted using ArcGIS an interesting pattern is revealed. Larger earthquakes are only seen in the northern half of Nebraska and all of South Dakota, and are almost absent in Kansas. The amount of smaller earthquakes is absent for northern Nebraska and South Dakota. This could be considered an observational bias because there are less data for this area. In the southern half of Nebraska and all of Kansas it seems there is a substantial amount of very small earthquakes.

<table>
<thead>
<tr>
<th>Geographic Area</th>
<th>Total Events</th>
<th>Percentage of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toadstool NE</td>
<td>49</td>
<td>7%</td>
</tr>
<tr>
<td>Sleepy Hollow Oil</td>
<td>96</td>
<td>15%</td>
</tr>
<tr>
<td>NE Kansas</td>
<td>88</td>
<td>14%</td>
</tr>
<tr>
<td>SE Nebraska</td>
<td>54</td>
<td>8%</td>
</tr>
<tr>
<td>South Dakota</td>
<td>29</td>
<td>4%</td>
</tr>
<tr>
<td>Central NE</td>
<td>66</td>
<td>10%</td>
</tr>
<tr>
<td>All Other Events</td>
<td>273</td>
<td>42%</td>
</tr>
</tbody>
</table>

Table 2: Percentage of data that fell into clusters used for anisotropy analysis.
**Discussion**

**Oil Production Induced Seismicity**

Distinct clusters can be seen when a point density function is employed in ArcGIS. Two of the clusters that can be seen are located in northern Kansas and SW Nebraska. One likely scenario that these areas are distinct on the map is the presence of oil drilling in these areas, which can also cause an increase in seismic activity (Figure 5 from KGS, Steeple et al. (1988), Steeple et al. (1990), Merriam (1955), Rothe and Lui (1983)). A large part of the seismic data used in this study falls into one of these two “hot spots” that are thought to be related to oil production.

The Sleepy Hollow Oil Field (SW Nebraska) is located near a distinct cluster of seismic activity, and needs to be considered as part of the analysis because seismicity is associated with it. Sleepy Hollow Oil Field is historically the most productive field in Nebraska, and is “located on the western flank of the Cambridge Arch where this structure bends to the south and meets the Central Kansas Uplift” (Evans and Steeple 1987). Because of the Central Kansas Uplift there are competing ideas to explain the origin of the microearthquakes for this area. Because the oil field is injected with water for enhancing oil productions, microearthquakes are more prone to occur (Evans and Steeple 1987). Tectonic activity also needs to be considered as a cause for earthquake activity. “There is geologic evidence … to suggest that the earthquakes are tectonic in origin and are related to uplift along the axis of the Cambridge Arch, on which the field is located” (Evans and Steeple 1987). It is possible that both water induced seismicity and tectonics contribute to seismicity in the area.

Water is injected in the ground during oil production to help increase the amount produced. This causes a differential in pore pressure and could possibly activate/reactivate faults in the area, hence causing more microearthquake activity (Haimson 1973). As pore pressure is increased, the normal forces on the slip surfaces are reduced, and slip is more likely to occur. Evans and Steeple (1987) tell us that there is evidence to prove otherwise because injection pressures do not temporally correlate with microearthquake occurrence. “The Reagan Sandstone is very permeable and continuous for several miles to the west of the field. Furthermore, increased
injection would be accompanied by increased production, which serves to decrease pressure. Thus, even if the surface of the granite basement is highly fractured, it would be difficult to transmit the injected fluids 1 or 2 km into the basement, the depth at which many earthquakes are observed” (Evans and Steeples 1987). If a highly fractured basement is present, it brings up an interesting point when trying to assess if water injection is responsible for the spike in seismicity in the area of the Sleepy Hollow Oil Field. However, because the oil fields sit directly above tectonic structures, seismic activity is possible without water injection. Shallow faults are connected to deeper faults and therefore the stress on the deeper faults would change and create deeper and larger earthquakes. Therefore, it is also possible that movement along shallow faults can help to trigger deep faults with the injection of water.

From reviewing the literature there seems to be suggestions that the Cambridge Arch is still active or was in the recent geologic past; Stanley and Wayne (1972), Evans and Steeples (1987, Rothe and Lui (1983). It is interesting that there is an increase in seismic activity for the same area that oil production is occurring. Evans and Steeples (1987) suggest that there is a spatial correlation between the earthquakes and the oil field to suggest that seismic activity is related to water injection/oil production. But, “Geologic, historic, and injection data...suggest that at least some of the earthquakes have a tectonic origin” (Evans and Steeples, 1987). Other work suggests that there is tectonic uplift along the Cambridge Arch. Rothe and Lui (1983) say that there have been verbal reports by nearby residents saying that seismicity has been felt in the area, even before the oil field came into production. “Fluvial sediment patterns across the arch were controlled by spasmodic uplift of the arch as recent as the Pleistocene” (Stanley and Wayne, 1972). Also, “the presence of distinct knickpoints in all major rivers flowing across the arch suggests continued subtle uplift since that time” (Stanley and Wayne, 1972). The literature also suggests that there is a set of subparallel faults to Cambridge Arch in the nearby region. “Earthquakes in and near the Sleepy Hollow oil field may be activated along a set of subparallel faults that have been mapped in the basement (Carlson, 1967; Rothe and Lui, 1983). This hypothesis explains the large scatter in hypocenters and the potpourri of observed first motions, since earthquakes may be occurring on different faults (or within a network of faults) rather than a single structure (Evans and Steeples, 1987). These ideas suggest that tectonic stress could be concentrated in this area, and therefore could be the ultimate cause of the earthquakes near the Sleepy Hollow Oil field. It is interesting to note that other areas along the Cambridge Arch that don’t produce a cluster of seismic activity.
A “hotspot” of seismic activity is seen south of the Sleepy Hollow oil field in north-central Kansas (Figure 7). There is/was oil and gas production here as well (“Oil and Gas Fields of Kansas” 2009). It is likely that production is similar to the Sleepy Hollow Oil field that uses water injection to increase the amount of oil output; thus creating more seismic activity than would otherwise be seen from tectonics. This is also where the most oil was produced in Kansas during 2012 according to Figure 5. Merriam suggests that, “in the area of the Central Kansas uplift it seems that some of the northeast-southwest structures (e.g. the Walz field) are sharper than those which trend in a northwest-southeast direction. As suggested by Lee and Merriam (1954, p. 20) these northeast-southwest trending folds, which parallel the Nemaha anticline, may still be developing (Merriam 1955).” This is important to note because it hints at the underlying structural trend that could be responsible for seismic activity. Basement structural activity could very well be possible for weakness along developed faults and contribute to increased tectonic activity not associated with oil production.

**Tectonic Seismicity**

Other clusters not associated with hydrocarbon production are seen when the seismic data are plotted in ArcGIS. One of the distinct clusters to the naked eye is located in central Nebraska. There are no known tectonic features in this area or oil fields to account for the increase in seismicity, likely because of a thick layer of sediment that includes, overlying fluvial deposits of the Ogallala and the Quaternary eolian deposits of the Sand Hills. It seems that this cluster could have a linear component running NE-SW, as evident in the data provided in the anisotropy analysis (Figure 7). The Colorado Lineament also trends in this direction, which is consistent with the Precambrian basement. More research needs to be done to determine why there is frequent seismic activity in this area.

Another distinct cluster is seen in NE Kansas and SE Nebraska where there are known underlying structural features. The structural features of interest include the Nemaha Ridge and Humboldt Fault Zone. Seismic activity would be expected to occur in area where there is a small-scale fault zone. From the data collected, it does not seem that microearthquakes occur frequently or release a large amount of energy. It is likely that these underlying structural features (buried rifts) play a significant role in seismic activity for this region because there is not a significant amount/if any oil production in this area (Johnston and Kanter 1990).

Lastly, there is a cluster seen up near the Black Hills region. The Colorado Lineament is thought to run through in this area of the Great Plains. Conceptually, it would make sense that some faults would be present in this area as a result of fault reactivation.
Seismic Activity in the Central Great Plains

Figure 7: Point Density Analysis produced by author in ArcGIS.
Seismic Activity in the Central Great Plains

Figure 8: Anisotropy Analysis. Produced by author in ArcGIS.
Anisotropy Analysis

To the naked eye some linear trends are visible in the direction suggested by the histogram plots provided. It is possible that these linear trends seen in the seismic data represent movement along unmapped and/or buried faults in the study area. Much of the data (that isn’t associated with oil production) seems to fall into small clusters in the central Great Plains, rather than randomly distributed. But there is also a large percentage of data that isn’t associated with any clusters. The large percentage of data associated with other clusters suggests that there are tectonic stresses forcing seismic activity in zones where the material is much weaker and prone to movement. These tectonic stresses could also be related to the underlying Pre-Cambrian rocks that also share this same linear trend. The Pre-Cambrian trend would be a preferred direction (NE-SW) for underlying faults to develop/move in this direction for the study area. Underlying structural features include the Nemaha Ridge and Midcontinent Rift in SE Nebraska and NE Kansas. On the east side of the Central Kansas Uplift, the underlying structures creating seismic activity would make sense conceptually.

An additional place of interest was in western South Dakota. The known structural features here include the Colorado Lineament and the Black Hills uplift. When looking at the map generated by ArcGIS there are no clusters, but it appears that on the histogram there is a linear trend running NE-SW in this area as well. The NE-SW trend is consistent and on line with the Colorado Lineament (Brill and Nuttli 1983) which could be responsible. In this case it could be basement reactivation.

From the Kansas histogram and map produced in ArcGIS it is determined that there is some anisotropy seen in the area of the Nemaha Ridge/Humboldt Fault zone. Anisotropy seen in Kansas is slightly different than that seen in Nebraska or South Dakota because there is also a NW-SE component. The anisotropy is most likely related to a large tectonic structure (Nemaha Ridge) in the vicinity of the sample area. In Nebraska, it is unclear what is producing anisotropy within the data. With no known tectonic structures, it becomes much more difficult to assess. One thing is clear however, there is a consistent strong NE component within the data, which is indicative of a fault trend. It is possible that there are some unknown basement faults in the area producing seismicity, but more research needs to be done. The Precambrian structural grain seems to run to the NE in this area (Figure 3), and gives some insight to a possible explanation for the seismicity.

In South Dakota there is a much stronger anisotropy present. There are no known large tectonic structures in this area, and it isn’t clear if the Colorado Lineament extends this far (Brill and Nuttli 1983). The results of this work suggest Colorado Lineament might extend this far. The same component is seen in all three histograms is a NE-SW trend. The anisotropy could be related to the underlying Pre-Cambrian strata, which also runs in this general direction (Seen in Appendix 1). Seismicity could also be related to a local stress field that runs in roughly the same direction. More research and analysis needs to be done to determine what could be the cause for a linear trend in Nebraska and South Dakota.

Anisotropy analysis was also done for other parts of Nebraska to see if there is a common trend. The first area was in the Sleepy Hollow oil field. There is a large amount of data from this area because seismic stations were set up in the area for a number of years (Steeples et al. 1988); which may be partial explanation of why this cluster is so well developed. From the orientation histogram plots it seems there are two preferred directions at about 10° and 70°, which could mean that induced seismicity could focus on areas of weakness in the underlying basement rocks (faults or joints). The idea of an active underlying basement seems to fit in a model where injected water flows through the rocks in fractures and/or faults to allow movement. Note that neither of these directions are parallel to the
underlying Chadron Arch, and so the connection with the arch would have to be more complex than simple reactivation of faults parallel to the arch.

Another area that was analyzed is near Toadstool Geological Park in NW Nebraska. There is no distinct trend seen here, possibly because of the proximity to the Black Hills that trends N-S. The Colorado Lineament is thought to extend this far and some of the seismic activity could be associated with the structural feature. Toadstool Geological Park in NW Nebraska lies at an intersection to these structural features. No trend would be produced in the anisotropy analysis because of the limited data and variation in structural features.

The final area that was analyzed to determine if there is an anisotropy present is in SE Nebraska. There are two underlying geological structures in this area, the Nemaha Ridge and Humboldt fault zone. It is apparent that there is seismic activity in this region when viewing the map. After analysis of both the histogram and circular-histogram it appears that there is anisotropy for this region. It is at about 10°, which is consistent with the orientation of both underlying structural features.

To fully analyze if the anisotropy results were random or not, the chi-square test was employed. From the results gathered, it is fairly certain that the seismic activity is non-random. However, in the Sleepy Hollow Oil field the chi-square test result was 0. This is likely because of water-induced oil production and difference in pore pressures.
Magnitude

The distribution of earthquake magnitude was also taken into consideration for this project and a map was produced to show this (Figure 7). It must be noted that all of the data is a post-hoc combination from many sources. Therefore historical data was recorded using the Mercalli-Intensity scale rather than Richter-Magnitude. Historical data was converted into magnitude using the scale provided by Burchett (1979) and is included below in Figure 5. It must also be noted that there is more data for Nebraska and Kansas from which many of the smaller magnitudes are contained, South Dakota is mainly historic data. Therefore this data could be considered an observational bias.

With the points above taken into consideration, it seems there is a widespread range in magnitude for the Central Great Plains. South Dakota appears to have the largest earthquakes in the area. But because the data is mostly historic this is likely false, since the smaller earthquakes would have gone unnoticed and unrecorded. Instruments for measuring seismic activity before the past 50 years was sporadic in this region and also not as sensitive. It is interesting to note that there is an absence of large earthquakes in Kansas and Nebraska. Perhaps there is an additional stress component in South Dakota such as glacial unloading to produce larger earthquakes. Both Kansas and Nebraska have a wide range of magnitudes but the majority of the data is very weak seismic activity (likely a result from oil production). Future work could be done with weighting magnitudes for the different regions. This would help to understand how much energy is release during a microearthquake that is related to tectonics and could help to filter out results that is a result of oil production.
Figure 9: Magnitude Map produced by author in ArcGIS.
Conclusions

Earthquakes in the Central Great Plains (CGP) cluster in areas, with significant noise in the background. Some of these clusters are associated with oil production, while others are very likely associated with underlying structural features. The increased activity near the oil fields could be caused by some tectonic activity in combination with increased fluid pressures during oil recovery.

After anisotropy analysis of the seismic data, it appears that there are local anisotropies of earthquakes in the CGP. Currently unmapped faults, structural features, and/or other tectonic forces unknown; could cause movement of seismic activity in a linear fashion at this time. To assess when and where a large earthquake will happen in the CGP, more historic data is needed such as the extensive list for Northern China. The recurrence interval for a large event in a midcontinent setting is very small and can take as much as decades or centuries between large events. “The present methods of earthquake hazard assessment, which are based on the assumption of quasi-periodic earthquakes on recently active faults, need modification to describe the complex earthquakes in midcontinents” (Liu et al., 2011).

Historical seismic data are difficult to locate for this region in the literature. It could be difficult to find because the activity is often very shallow or weak, which older seismic stations would have left undetected; and/or because seismic stations were very sparse in this region until relatively recently. Future research could include more analysis focused on the amounts of energy released from these seismic events, and also more localized anisotropy analysis.

Acknowledgments

I want to thank Dr. Harmon Maher for his advice, support and guidance on this project; and for his patience and suggestions throughout the writing process. I would also like to thank Dr. Robert Shuster for his revision suggestions.
Sources:


Appendix 1

South Dakota

Central Nebraska

Kansas

Toadstool

Sleepy Hollow

SE Nebraska