Estimating of Earthquake Risk in Northeast Ohio

Senior Thesis

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TABLE OF CONTENTS

Abstract

Other than isolated cases such as Charleston, South Carolina in 1886 and New Madrid in 1911-12, mid-continent earthquakes are not studied as much as plate boundary earthquakes. However, the Ohio Seismic Network monitors earthquakes in Ohio, and a high magnitude earthquake centered in the Northeast Ohio Seismic Zone could cause extensive damage. Maximum expected magnitude, expected depth, and site class for Ohio were studied and compared to results from the 1935 Timiskaming, Canada, 1989 Loma Prieta, California, 2009 L'Aquila, Italy, and 2010 Oaxaca, Mexico earthquakes. Based on the locations of greatest damage resulting from these earthquakes and the surficial geology in Ohio, the Northeast Ohio Seismic Zone is at a high risk area for earthquakes.

List of Figures and Tables

Introduction

Along with being located in the periphery of the New Madrid Seismic Zone, Ohio contains basement structures capable of producing earthquakes, primarily in the Western Ohio Seismic Zone and the Northeast Ohio Seismic Zone (Hansen, 2009). Northeastern Ohio Seismic Zone earthquake epicenters have been located in Ashtabula, Cuyahoga, Lake, Lorain, Mahoning, and Summit counties (Ohio DNR). According to the Ohio Department of Natural Resources, there have been over 100 earthquakes with epicenter locations in these counties between December 1951 and March 2011. Figure 1 shows earthquakes in this region with instrument detected epicenters in red and historical epicenters represented by blue circles. Details from these events are provided by the Ohio Seismic Network and displayed in table 1. Figure 2 shows an increase in earthquake frequency in Ohio since 1950, likely due to increased and more accurate earthquake monitoring in this region, meaning this area could have been more active in the past.
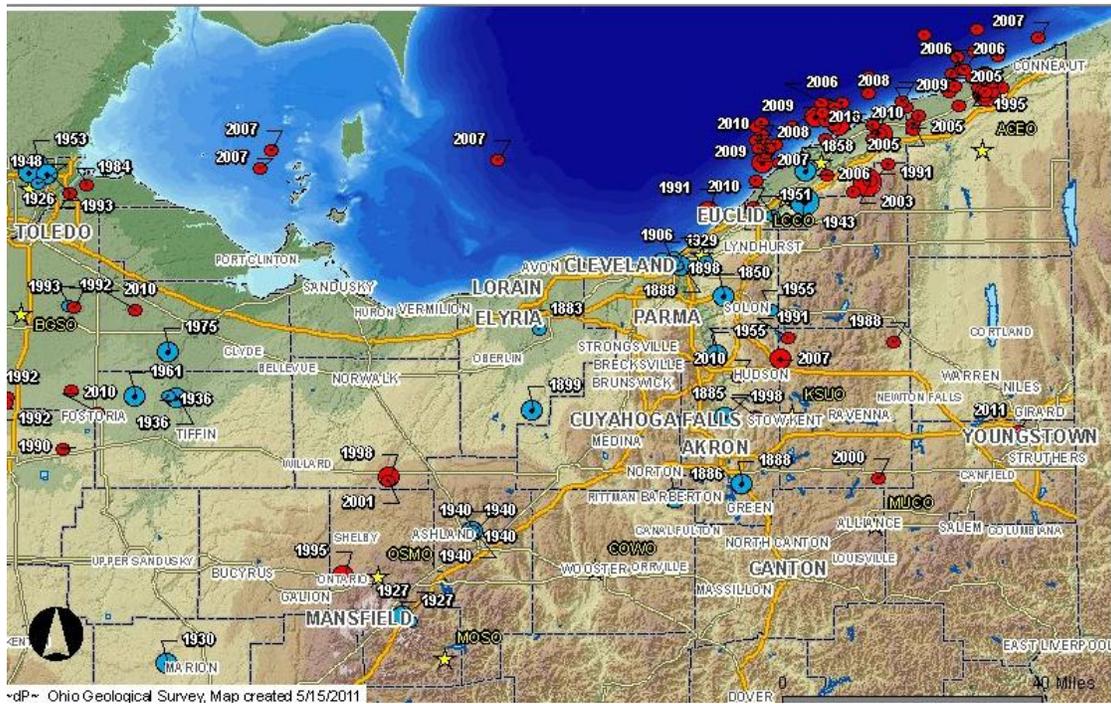

Figure 1: Earthquake epicenter locations in northeast Ohio (ODNR)

Table 1: Northeast Ohio earthquake data (ODNR)

| YEAR	MO	DA	HR	MN	SEC	LAT °N	LON °W	DP	MAG	MT	MMI	FA	COUNTY	SOURCE
1951	12	3	7	2		41.75	81.4		2.9	2	IV	0.3	LAKE	NCE/OSN
1955	5	26	18	9		41.29	81.57		3.3	2	V	1	CUYA	NCE
1955	6	29	1	16	33	41.39	81.41		2.7	2	IV	1.1	CUYA	NCE
1983	1	22	7	46	58	41.75	81.02		3.3	1			LAKE	NCE
1983	11	19	16	22	19	41.83	81.09	5	2.5	1			LAKE	GSC
1986	1	31	16	46	42.3	41.65	81.16	5	5	1	VI	322	LAKE	USGS
1986	2	7	18	36	22.3	41.65	81.16		2.5	1			LAKE	USGS
1987	7	13	5	49	19.41	41.903	80.758	2	3.8	1	IV		ASHT	JCU
1987	7	13	5	58	52.31	41.87	80.74		2.2	1			ASHT	JCU
1987	7	13	7	52	12.88	41.898	80.757		3	1			ASHT	JCU
1987	7	13	13	5	23.6	41.899	80.768		2.9	1			ASHT	JCU
1987	7	13	18	25	11.98	41.88	80.75		2.8	1			ASHT	JCU
1987	7	13	19	0	8.5	41.899	80.768		2.3	1			ASHT	JCU
1987	7	13	19	39	19.44	41.899	80.768		2.1	1			ASHT	JCU
1987	7	13	20	53	5.46	41.899	80.768		2.2	1			ASHT	JCU
1987	7	13	23	49	14.5	41.902	80.75		2.4	1			ASHT	JCU
1987	7	14	7	47	27.26	41.902	80.75		2.4	1			ASHT	JCU
1987	7	14	14	51	11.67	41.902	80.75		2.8	1			ASHT	JCU
1987	7	16	4	49	40.66	41.895	80.751		2.7	1			ASHT	JCU
1987	7	16	6	2	25.54	41.895	80.751		2.4	1			ASHT	JCU
1988	6	27	4	46	31.34	41.818	81.229		2.7	1			LAKE	JCU
1989	8	1	16	12	48.75	41.898	80.758		2.8	1			ASHT	JCU
1989	8	1	16	50	30.74	41.893	80.752		2.9	1			ASHT	JCU
1989	8	3	4	7	48.64	41.89	80.74		2.2	1			ASHT	JCU
1990	1	1	23	3	4.89	41.902	80.799		2.2	1			ASHT	JCU/OSN
1990	7	24	23	4	38.01	42	80.94	2.6	2.3	1			ASHT	JCU/OSN
1990	9	26	6	13	4.89	41.91	80.76		2.3	1			ASHT	JCU/OSN
1990	11	18	9	20	52.81	41.96	80.79		2.3	1			ASHT	JCU/OSN
1991	1	27	3	21	24.23	41.61	81.594	9.7	3.5	1			CUYA	JCU
1991	10	13	2	26	38.47	41.711	81.054		2	1			LAKE	JCU
1992	3	15	6	13	56.66	41.817	81.226		3.4	1			LAKE	JCU
1992	3	15	14	49	40.02	41.8	81.217		2.2	1			LAKE	JCU
1992	3	26	3	43	15.27	41.87	80.87		2.5	1			ASHT	JCU/OSN
1992	3	28	8	22	44.06	41.9	80.75		2.9	1			ASHT	JCU/OSN
1992	3	31	1	54	52.11	41.913	80.86		2.5	1			ASHT	JCU/OSN
1992	4	7	1	35	22.12	41.883	80.85		2.0?	1			ASHT	JCU
1993	10	16	6	30	5.32	41.82	81.27		3.6	1	IV		LAKE	GSC
1995	2	23	9	32	11.99	41.84	80.84		2.9	1			ASHT	GSC/OSN
1995	4	9	11	37	29.01	41.87	80.77		2.4	1			ASHT	GSC/OSN
1998	1	27	0	38	30.24	41.87	81.11		3	1			LAKE	GSC
1998	1	30	4	59	18	41.91	81.11		2.4	1			LAKE	GSC
1998	11	25	2	55	7.52	41.02	82.543		3.2	1	III	0.7	HURO	GSC
1998	12	25	21	22	3.1	41.15	81.46		2.8	1			SUMM	GSC
1999	9	22	10	2	18.8	41.68	81.45		2.8	1	III		LAKE	OSN
2000	6	7	6	19	18	42.01	80.78		2	1			ASHT	GSC
2000	6	7	6	55	8.42	41.88	80.71		2.4	1			ASHT	GSC/OSN
2000	10	20	23	26	26.54	41.91	80.77		2.5	1			ASHT	GSC/OSN
2001	1	20	2	5	7	41.88	80.78		2.6	1	III		ASHT	OSN
2001	1	26	3	3	20.63	41.87	80.76	2.5	4.5	1	VI	35	ASHT	OSN
2001	1	26	3	11	30	41.87	80.76		2	1			ASHT	OSN
2001	1	26	3	45	25	41.87	80.76		2.2	1			ASHT	OSN
2001	1	26	5	11	5	41.87	80.76		2	1			ASHT	OSN
2001	1	26	5	36	58	41.87	80.76		3.2	1	III		ASHT	OSN
2001	6	3	22	36	46.39	41.87	80.76	2.5	3.2	1	III		ASHT	OSN
2001	6	5	8	27	15	41.88	80.76		2.2	1	II		ASHT	OSN
2001	7	26	10	46	51.4	41.01	82.55		2.7	1	III	0.4	HURO	OSN
2002	4	28	0	7	20.9	41.85	81.37		2.7	1	II		LAKE	OSN
2002	8	17	8	26	31.89	41.79	80.98		2	1	NF		ASHT	OSN
2003	2	10	5	34	43.07	41.95	80.72		2.4	1	F		ASHT	GSC/OSN
2003	5	2	15	59	7	41.67	81.11		2	1	NF		LAKE	GSC/OSN
2003	6	30	19	21	17.2	41.8	81.2	4.6	3.4	1	IV	3.2	LAKE	OSN/GSC
2003	7	17	0	44	10	41.86	80.76	2.5	2.5	1	III	0.3	ASHT	OSN/USGS
2004	3	14	5	5	10.28	41.77	81.24	5	2.4	1	III	0.25	LAKE	OSN
2004	6	30	4	3	14.58	41.78	81.07	5	3.3	1	III	1	LAKE	OSN
2005	2	1	13	1	13.3	41.8	81.1	5	2.5	1	F		LAKE	OSN/GSC
2005	2	23	6	12	9.66	41.82	80.96	5	2	1	F		ASHT	OSN/GSC
2005	3	2	6	53	16.93	41.8	80.98	5	2.2	1	NF		ASHT	OSN/GSC
2005	11	13	11	2	15.77	41.84	81.21	6.4	2.2	1	F		LAKE	OSN/LDEO
2005	12	11	5	20	2.38	41.95	80.84	9.9	2	1	F		ASHT	OSN/LDEO
2006	1	6	3	2	2.69	41.77	81.45	5	2.6	1	F		LAKE	OSN/GSC
2006	1	13	15	32	17.55	41.8	81.45	7	2.3	1	F		LAKE	OSN/LDEO
2006	2	10	13	30	42	41.75	81.41	5	2.6	1	F		LAKE	OSN/GSC
2006	2	27	20	53	20.48	41.92	80.83	5	2	1	NF		ASHT	OSN/GSC
2006	3	11	12	27	15.16	41.76	81.39	5	3	1	F		LAKE	OSN/GSC
2006	3	27	17	24	30.35	41.75	81.41	5	2.1	1	NF		LAKE	OSN/GSC
2006	4	10	5	55	52.49	41.92	80.82	10	2	1	NF		LAKE	OSN/LDEO
2006	5	21	14	15	28.63	41.81	81.43	5	2.2	1	NF		LAKE	OSN/GSC
2006	6	20	20	11	18.54	41.84	81.23	4	3.8	1	F		LAKE	OSN
2006	6	20	20	57	22.94	41.81	81.24	5	2.2	1	NF		LAKE	OSN
2006	6	22	10	9	45.48	41.85	81.25	5	2.3	1	NF		LAKE	GSC
2006	6	28	13	18	28.38	41.69	81.24	5	2.3	1	F		LAKE	GSC
2006	7	1	5	25	53.19	41.83	81.25	5	2.1	1	NF		LAKE	GSC
2007	1	22	6	17	10.2	41.83	81.21	6	2.2	1	NF		LAKE	OSN
2007	8	27	23	26	44.07	41.72	81.38	5	2.1	1	F		LAKE	OSN
2007	9	28	8	46	5.81	41.99	80.6	5	2.8	1	F		ASHT	OSN
2007	10	16	17	5	1.55	41.76	81.42	5	2.4	1	NF		LAKE	OSN
2007	10	17	20	4	9.74	41.75	81.42	5	3.2	1	III		LAKE	OSN
2007	10	18	22	23	4.23	41.73	82.22	5	2.7	1	NF		LORA	GSC
2008	1	9	1	34	46.7	41.72	81.43	5	3.1	1	F		LAKE	OSN
2008	8	14	18	32	16.44	41.85	81.01	5	2.3	1	NF		LAKE	OSN
2008	9	18	1	4	16.57	41.78	81.43	5	2.8	1	F		LAKE	OSN
2008	9	20	19	16	43.19	41.74	81.42	5	2.3	1	NF		LAKE	OSN
2009	2	14	13	16	27.16	41.84	81	5	2.6	1	F		ASHT	OSN
2009	2	23	23	32	27.26	41.75	81.44	5	2.2	1	NF		LAKE	GSC
2009	10	21	17	59	46.85	41.8	81.34	5	2.4	1	NF		LAKE	OSN, GSC
2010	2	4	17	44	21.3	41.62	81.46	5	2.1	1	II	F	LAKE	OSN
2010	4	25	2	0	39.26	41.78	81.08	5	2.9	1	III	-	LAKE	OSN
2010	5	17	21	29	5.65	41.24	81.51	5	2.5	1	-	NR	SUMM	OSN
2010	6	7	16	22	32.16	41.77	81.1	5	2.3	1	II	F	LAKE	OSN
2010	6	10	16	32	22.31	41.76	81.43	5	2.5	1	II	F	LAKE	OSN
2011	3	17	10	42	20.22	41.11	80.7	5	2.1	1	-	NF	MAHON	OSN
2011	3	17	10	53	9.32	41.11	80.7	5	2.6	1	III	F	MAHON	OSN

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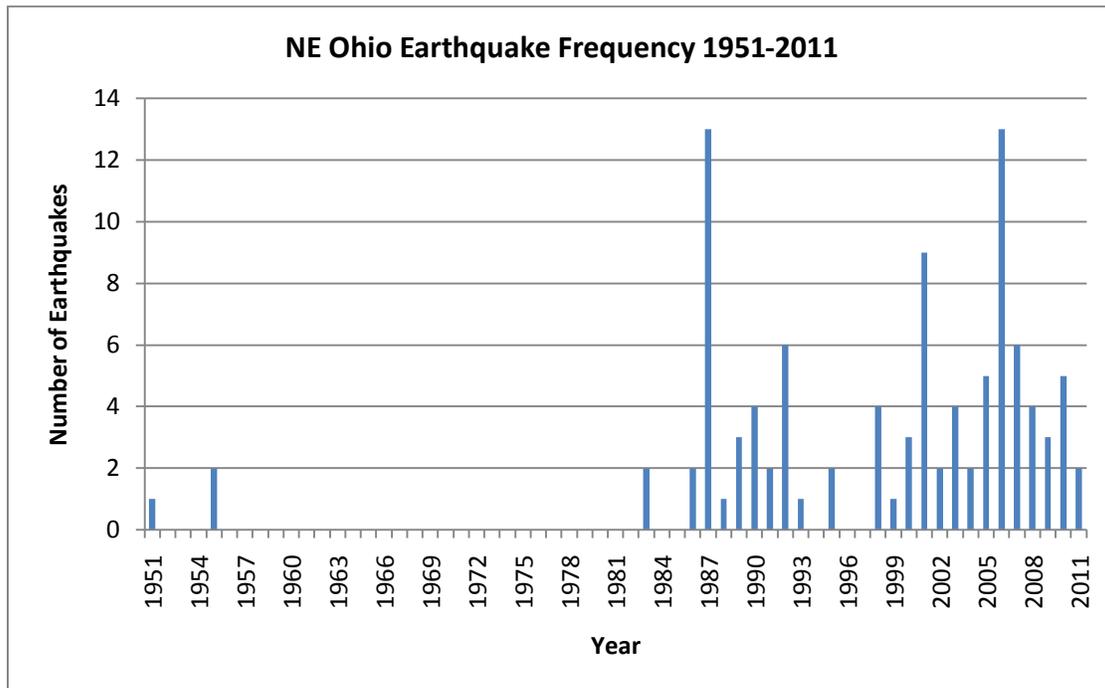
Figure 2: Northeast Ohio earthquake frequency (ODNR)

The largest known earthquake in this area occurred January 31, 1986. This was an important and highly studied earthquake, because it was the first earthquake in Ohio in which injuries were recorded, and the earthquake resulted in the shutdown of the Perry Nuclear Power Plant for over a year. The magnitude 5.0 was felt in parts of 11 states and southern Ontario. Most of Ohio and western Pennsylvania experienced particularly strong vibrations that were noted by numerous individuals.

Only two injuries were caused directly from the earthquake, and destruction in the epicentral area was relatively minor, but one major concern was the condition of the Perry Nuclear Power Plant following the event. Located in northern Lake County 11 kilometers north of the epicenter, the plant was not operating at the time of the earthquake due to a scheduled fuel rod loading the next day. Officials declared a precautionary site area emergency immediately after the earthquake but downgraded this to alert status within a shortly after. Accelerometers on

site at the Perry plant recorded accelerations as high as 0.19 to 0.23 g (Ahmad, 1988); the plant is designed to withstand 0.15 g. Inspections of the plant after the earthquake found only minor cracks in concrete and small leaks in noncritical water pipes. Due to this event, the plant was later retrofitted to standards to withstand a magnitude 6.0 earthquake.

The sections below present the geological setting, infrastructure background, and earthquake scales for Ohio. Earthquake risk in northeast Ohio is evaluated in terms of earthquake magnitudes, focal depths, and surficial geology and compared to other earthquakes with similar parameters.

Geological Setting

Northeastern Ohio is primarily covered by glacial deposits of Pre-Illinoian, Illinoian, and Wisconsinan age. These deposits include mostly unconsolidated sediments such as till, boulders, gravel, sand, silt, clay, and organic debris. The glacial deposits cover Paleozoic sedimentary and Precambrian bedrock (Fenneman, 1928). The Akron-Suffield Fault System is the likely cause of the earthquakes in the region, and the faulting is associated with the magnetic boundary shown in figure 3. These faults are located in near one billion year old basement rocks 5-10 kilometers below the surface, and some serve as sites for periodic release of strain constantly building in the North American continental plate due to tectonic plate movement. The faults reflect the effects of ancient orogenesis and continental collisions in the Earth's crust, and do not appear to continue to the surface as no fault scarps have been produced (Hansen, 2009).
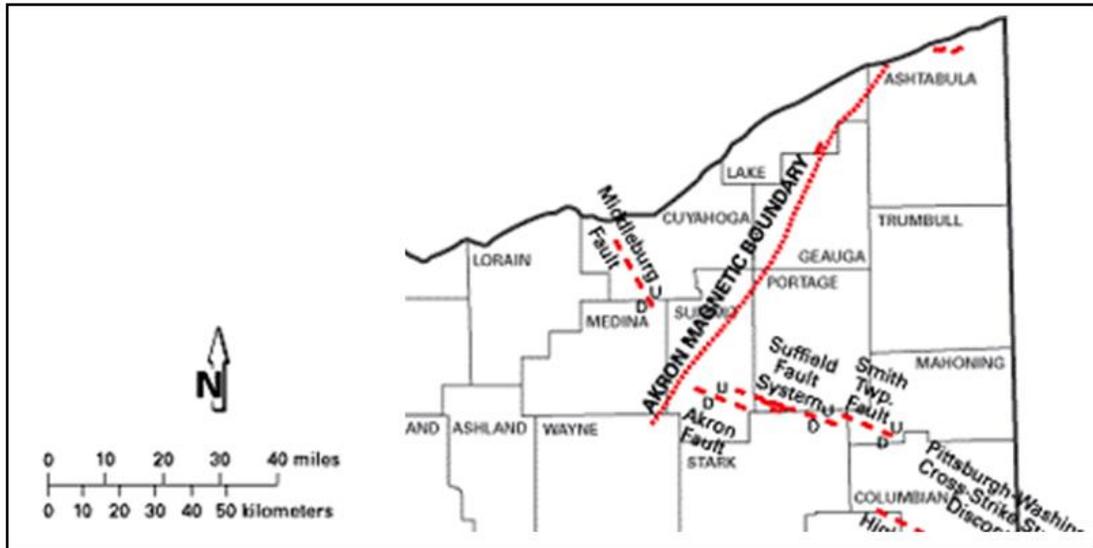
Figure 3: Basement structures in northeast Ohio (Hansen, 2009)

Background Information

Infrastructure of the Region

Over 2.9 million people live in the counties included in the Northeast Ohio Seismic Zone according to the 2010 United States Census. Supporting facilities include the Perry Nuclear Power Plant, and water, oil, and gas pipelines, highways, rail, and large numbers of urban structures. As table 2 shows, the American Society of Civil Engineers (ASCE) sees the need for great improvement to Ohio's infrastructure complex, but has not called for earthquake resistant construction as a priority. However, figure 1 illustrates that the population is largely concentrated around seismically active areas.

Table 2: 2009 Ohio infrastructure report card (ASCE)

ASCE®
American Society of Civil Engineers

Ohio Council Of Local Sections
Akron-Canton, Central Ohio, Cincinnati, Cleveland, Dayton, Toledo

2010 UPDATE – 2009 OHIO INFRASTRUCTURE REPORT CARD

Subject	Grade	Comments
Aviation	C-	Ohio ranks third in the nation with 124 paved and lighted general aviation airports. Only 58% of runways, 57% of taxiways and 62% of aprons meet the satisfactory condition index. These percentages are below ODOT Office of Aviation established goals. Ohio's commercial service airports are meeting capacity requirements.
Bridges	B-	Bridges in Ohio are crucial components of one of the largest transportation systems in the country. Ohio has the second largest inventory of bridges in the United States. It is estimated that it would cost $3.6 billion to replace all the structurally deficient bridges and two-thirds of the functionally obsolete bridges in Ohio.
Dams	C	There are more than 2,600 dams in the State of Ohio. Nearly 70% of Ohio dams are privately owned. There were 1,597 state-regulated dams in Ohio in 2007. Of the state-regulated dams, 33% are deficient. It is estimated that the repair cost for Ohio's deficient dams is approximately $300 million.
Drinking Water	D+	Approximately 90% of Ohioans receive water for daily needs from one of the more than 6,000 public water systems. An estimated 99% of the burden for funding public water supply systems is borne by local government. It is estimated that Ohio has $9.68 billion in drinking water infrastructure needs.
Electricity	C+	Electric generation, transmission and distribution systems in Ohio are satisfactory, reliability problems are relatively few, and those that exist are being addressed by system improvements. However, mandates related to alternative energy and environmental protection may pose problems for Ohio's electric utilities in the future.
Parks and Recreation	C-	Park systems in Ohio provide a crucial economic element in terms of jobs and financial impact. An additional $26.5 million is needed each year to properly operate the state parks and other divisions, and an additional $29.9 million annually is needed to eliminate the maintenance backlog over the next 10 to 20 years.
Railroads	C	Railroads provide critical services to industries important to Ohio's economy, hauling raw materials, parts, and finished products. Railroads are an important industry, employing more than 8,000 workers and paying approximately $500 million in wages. ODOT estimated that the cost to improve thirty railroad choke points is $1.19 billion.
Roads	D	With over 125,000 miles of roads, Ohio has one of the largest and most utilized roadway networks in the United States. 43% of Ohio's roads are in critical, poor, or fair condition. It is estimated that by the year 2014, Ohio will have a highway budget shortfall of more than $10 billion at the state government level alone.
Schools	C	The quality of schools in Ohio is crucial to the state's long-term viability and ability to compete in the global marketplace. The American Federation of Teachers estimated in 2008 that Ohio schools require $9.32 billion in infrastructure investment. This ranks Ohio 6th in the country for total funds needed.
Transit	D	An average of 500,000 riders use public transit daily, making Ohio 12th highest in ridership rate in the nation. Ohio ranks 40th in the nation in percentage of state transportation funds expended on public transit. Less than 1% of Ohio's state transportation funds go towards public transit.
Wastewater	C-	Aging systems discharge billions of gallons of untreated wastewater into U.S. surface waters each year. An estimated 95% of the burden for funding municipal wastewater treatment systems is borne by local government. It is estimated that Ohio has $11.16 billion in wastewater infrastructure needs.

Earthquake Scales

Magnitude and intensity scales are used to describe earthquakes in this paper. The Richter Magnitude Scale and the Moment Magnitude Scale are used to compare energy generated from different earthquakes. The Richter Magnitude Scale uses distance from the epicenter and recorded seismograph amplitude to calculate magnitude of an earthquake. A seismic wave will lose energy as it propagates, so amplitude decreases as distance from the epicenter increases.

The magnitude (M) is determined from the logarithm of the greatest amplitude in millimeters (A) of surface waves recorded by seismographs and estimated distance using S and P wave arrival times in seconds as:

$$M = LogA + 3Log[8(S - P)] - 2.92$$

Magnitude is expressed as real numbers where each whole number increase in magnitude represents a tenfold increase in measured amplitude because of the logarithmic scale. A whole number increase in magnitude represents an increase of about 32 times of the energy released from an earthquake.

The intensity is a subjective measure of the effect an earthquake on surface objects. A common scale for measuring intensity in the United States and other western countries is the Modified Mercalli Intensity (MMI) scale which categorizes earthquakes using a series of certain key responses. This qualitative scale is based on observed effects following an earthquake as opposed to qualitative estimates of earthquake size. The intensity value assigned to a specific site can be a meaningful measure of severity as it gives information on effects of the earthquake at that location. The MMI scale description used by the United States Geological Survey is shown in table 3.

Intensity	Description
I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Methods

Important factors to consider when determining earthquake risk are the depth and magnitude of the anticipated earthquake along with how the geology of the area will impact the degree of damage. Methods will be used to determine these three factors to give an idea of destruction an earthquake in Northeast Ohio could cause. Once expected magnitude and depth of the earthquake are found, information from historical earthquakes with similar magnitudes and depths can be used to determine how surficial geology affected damage in those instances.

Maximum potential earthquake magnitude

The maximum magnitude earthquake thought to be possible in a region, M_{max}, has been estimated by various methods for mid-continent locations in North America (Wheeler, 2009). Three major assessments of M_{max} at multiple mid-continent locations have been conducted by experts from the Lawrence Livermore National Laboratory (LLNL), the Electric Power Research Institute-Seismicity Owners Group (EPRI-SOG), and the United States Geological Survey (USGS).

In these studies, the three most used methods for determining M_{max} were finding the largest observed magnitude in a specified region, M_{obs}, determination of seismic frequency, and recognition of geophysical anomalies of an area. Using the M_{obs} gives the largest observed earthquake, not the largest to ever occur in the region, and in the case of the billion year old faults located in northeastern Ohio bedrock, it is not likely the largest earthquake occurred in the last one hundred years. The entire magnitude history is not available since the earthquake study occurs on an extremely short interval of the geologic time scale, but this provides a lower bound for M_{max}. Another method used the observed frequency of earthquakes to predict M_{max}. This method is effective, because as earthquake frequency increases, the likelihood of a larger

earthquake also increases. Because of the sporadic nature and relatively long intervals of large mid-continent earthquakes, it is questionable as to whether this method is as effective in mid-continent as it is at plate boundary earthquakes. Geophysical properties and anomalies of an area, such as details of fault zones are used to estimate M_{max}. Factors such as large magnetic or gravity anomalies, relative rock competence, as well as size and orientation of faults can provide information in determining M_{max} (Wheeler, 2009). Values of M_{max} in the Ohio region range between 5.2 and 8.4 with an average M_{max} equal to 6.31 (Wheeler, 2009).

Depth

The depth of an earthquake has a large influence on the amount of damage that can be expected. In fact, small amplitude recorded on a seismogram from a large earthquake is an initial indicator the earthquake had a deep focus. Generally, a deeper earthquake will cause less damage than a shallow earthquake of equal magnitude. An example of this is the 1994 magnitude 6.7 Northridge earthquake which killed 60 people and caused between $13M-$20M in damages (USGS), whereas the 2001 magnitude 6.8 Nisqually earthquake resulted in zero deaths and little damage. The major difference between these two earthquakes was Northridge occurred at a depth of 5-18 km and Nisqually was at 51 km depth (USGS).

A common technique used to determine depth involves observation of seismic wave signatures from seismograms. After the *P* wave arrival, a second *P* wave, known as the *pP* wave, arrives. Due to inhomogeneities in the Earth's subsurface, the seismic waves will reflect and refract according to Snell's Law when they encounter points of differing acoustic properties. Since the two waves began as one wave, and the *P* wave velocity of rock they propagate through remains constant, the time between *P* wave and *pP* arrival depends directly on the hypocenter's depth. The depth can be calculated by $(pP - P) = 2d/v$, where $(pP - P)$ is the two-way travel time

difference, d is hypocenter depth, and v is the average *P* wave velocity above the source (USGS).

To determine the likely depth of a future earthquake in the Northeast Ohio Fault Zone, data from the Ohio Department of Natural Resources on previous earthquakes occurring in the area can be used. Many of the earthquakes in Ohio do not produce seismic readings significant enough to determine depth. Often a depth of 5 kilometers is used as a default in Ohio when depth cannot be determined. As shown in table 1, the deepest earthquake is 10 km from the 2006 magnitude 2.0 in Lake County and the shallowest is 2 km from the 1987 magnitude 3.8 in Ashtabula County.

Soil amplification

The properties of the ground also contribute to the damage caused by an earthquake at a specified site. The site amplification can be estimated using a variety of different methods, and is often calculated at different locations surrounding a large earthquake epicenter. A method used to determine site amplification without requiring a large earthquake involves using the average shear wave velocity, V_s30, of the uppermost 30 meters of the subsurface (Wills, 2000). The shear velocity can be measured using a variety of different geophysical measurements both in the field and in the laboratory.

Inhomogeneities in the subsurface often cause differences in Vs30 values from close, adjacent locations, so a range of V_s30 values are often grouped into five different site classifications (Di Alessandro, 2009). The site classifications range from A-E with A having the highest shear velocity. Tables 4 and 5 show these velocity ranges and the soil type associated with each site class. The Northeast Ohio Seismic Zone has a site class ranging from C-D based on V_s30 values from the USGS earthquake hazards program for this area. The V_s30 map, figure 4, shows how these values change geographically.

Table 4: Site classification by average Vs30 (Di Alessandro, 2009)

CLASS	Average Shear-Wave Velocity (V_{S30}) (m/s)	
	NEHRP	CEN
A	> 1500	> 800
B	760 − 1500	360 − 800
C	360 − 760	180 − 360
D	180 − 360	< 180
E	< 180	Surface alluvium layer with Vs values of type C or D and thickness between 5 and 20 m, underlain by stiffer material with Vs > 800 m/s

Table 5: Site classification by soil type (Di Alessandro, 2009)

Site Class	Soil Type
A	Hard Rock
B	Rock
C	Very Dense Soil & Soft Rock
D	Stiff Soil (Default Site Class)
E	Soft Clay Soil
F	Liquefiable Soils, Quick Highly Sensitive Clays, Collapsible Weakly Cemented Soils, & etc. These require site response analysis.
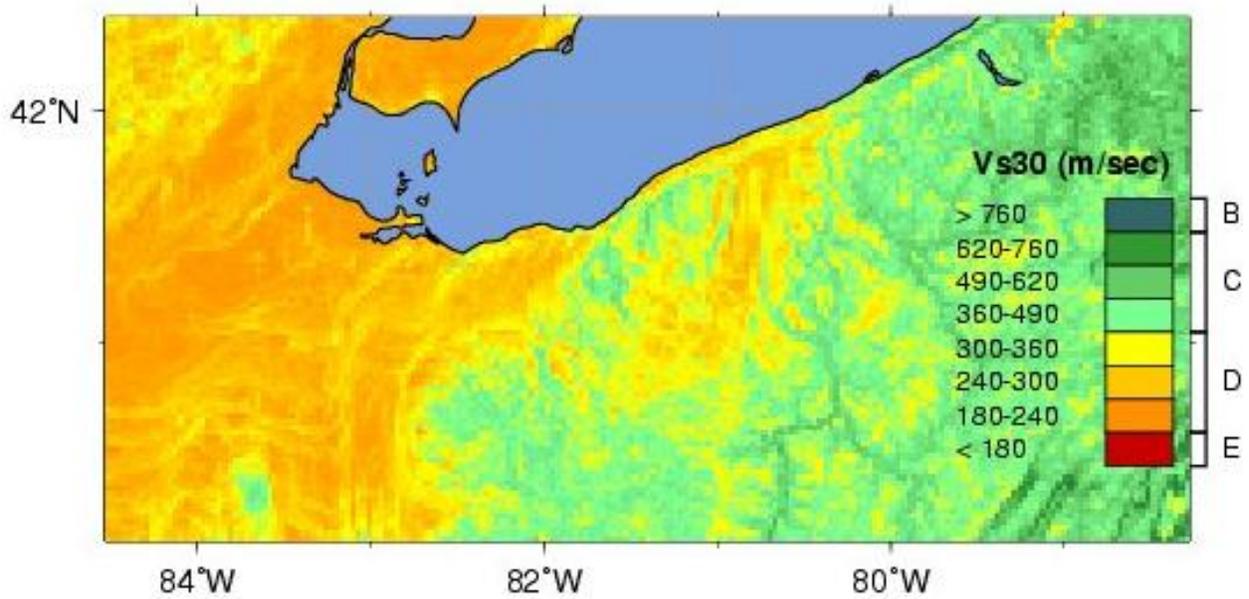
Figure 4: Northeast Ohio V$_s$30 map (USGS)

Risk Assessment

Comparing these results with those of other earthquakes with similar site parameters can yield insight on the potential hazards that Ohio earthquakes may pose. Specific events considered here include the 1935 Timiskaming, Canada, 1989 Loma Prieta, California, 2009 L'Aquila, Italy, and 2010 Oaxaca, Mexico earthquakes.

1935 Timiskaming, Canada

The effects of a higher magnitude earthquake in the Cleveland, Ohio area can likely be compared to those of the 1935 Timiskaming magnitude 6.2 earthquake. As one of the largest instrumentally recorded earthquake to have occurred in southeastern Canada, this was unexpected and occurred in a region of similar surface geology to Ohio's. Figure 5 shows V$_s$30 in the epicentral region of this earthquake is similar to the V$_s$30 in northeast Ohio, and figure 6 shows the extreme geographical area this event affected.

Figure 5: V$_s$30 map of Timiskaming (USGS)
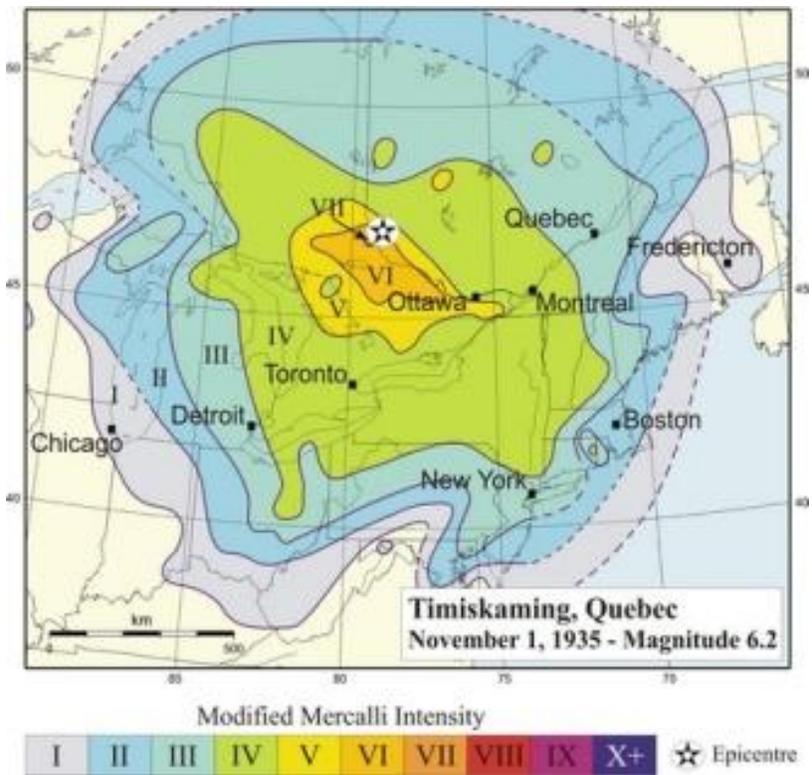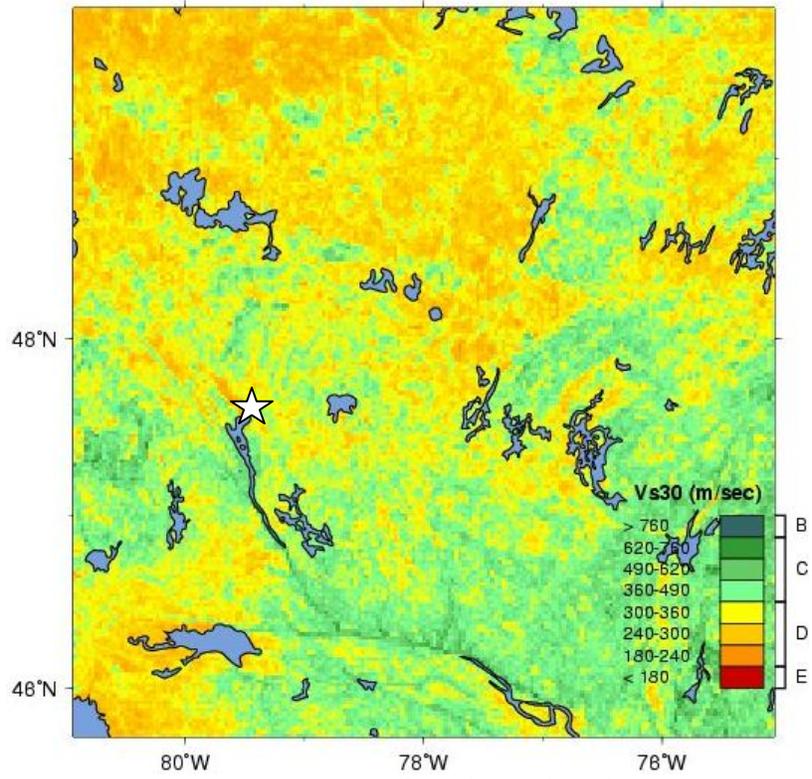
Figure 6: MMI map of Timiskaming (NRCAN)

With a large area affected and high intensity levels at great distances from the epicenter, a remote epicentral location was attributed to the absence of severe destruction in this case as the largest city of Ottawa was located a distance of nearly 300 kilometers to the east. The earthquake is credited with causing numerous landslides, caused sediment disruption in lakes, and resulted in a collapsed railroad embankment nearly 300 kilometers from the epicenter. It was felt across 17 states and three Canadian provinces, and caused chimney and masonry damage in the state of New York. This event produced readings on many seismograms in the region, and that information has shown that the earthquake was a result of a thrust faulting event on a northwest striking plane (Bent, 1996).

1989 Loma Prieta, California

The earthquake was responsible for 62 deaths, over 3700 injuries, and over $6 billion in structural damage (USGS). Although the 6.9 magnitude is stronger than the projected 6.3 magnitude in Ohio, the 1989 Loma Prieta earthquake showed site amplification has a great influence on damage resulting from an earthquake as shown in the Mercalli and V_s30 maps, figures 7 and 8. A particular point of interest is the region just south of the San Francisco Bay. The site class transitions from a category D to category E at the same point the Mercalli damage transitions from level VIII to level VII. This earthquake is important to analyzing site effects due to the extreme and rapidly changing surficial geology in a small geographic region as MMI range from VI to IX in a small geographic area. Accounts of extreme damage were concentrated in pockets where highway and bridge collapsing occurred, and minor in other areas, such as buildings at the University of California at Berkeley which sustained only minor cracks (Bolt, 1991).

Figure 7; Loma Prieta V$_s$30 map (USGS)

Figure 8: Loma Prieta MMI map (USGS)

2009 L'Aquila, Italy

The magnitude 6.3 earthquake in L'Aquila, Italy in 2009 resulted in 287 people killed and over 1,000 injured (USGS). Of the near 73,000 population, an estimated 40,000 people were left homeless (Dolce, 2009). This event occurred as a result of normal faulting on a NW-SE oriented structure and east-west extensional tectonics in the region. The site class and MMI scale maps, figures 9 and 10, show there is a small circular region surrounding the city of L'Aquila where there was extensive damage. This area has similar surface geology to Ohio and is classified as site class D with low V_s30, whereas the surrounding area, which saw less intense damage, is site class C and B with harder more dense rock.
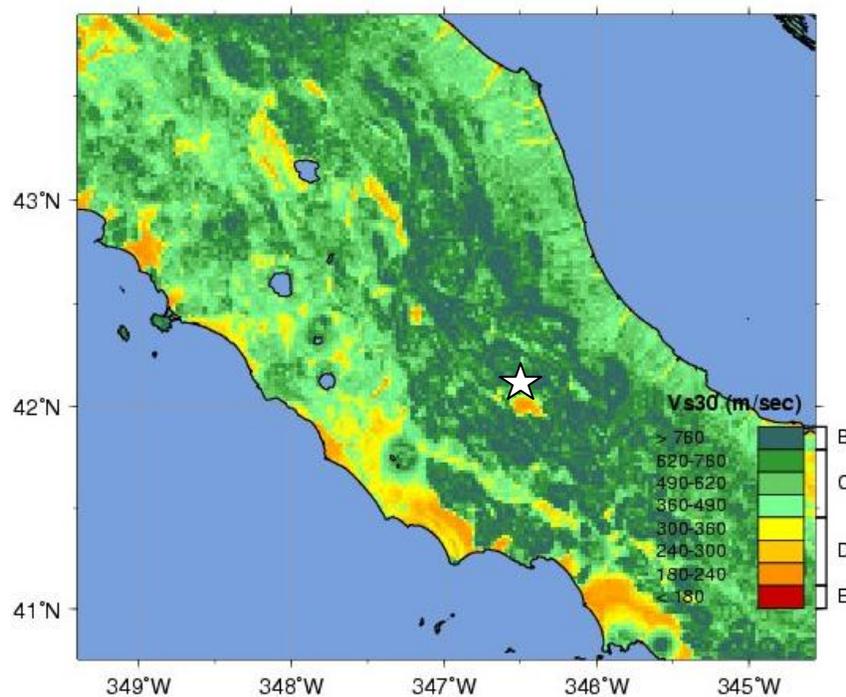

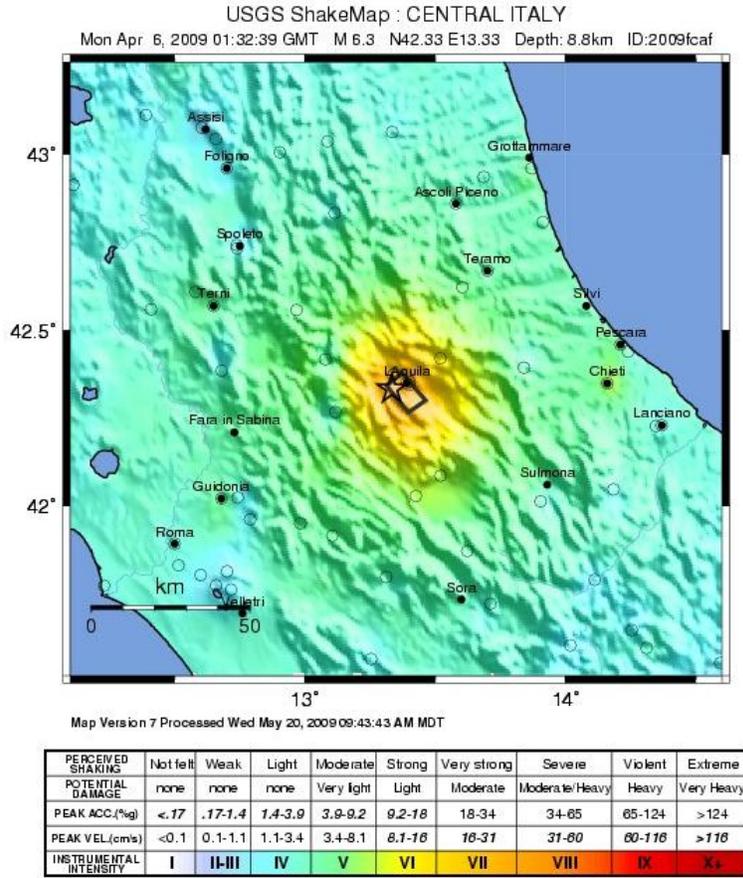**Figure 9: L'Aquila V$_s$30 map (USGS)**

USGS ShakeMap : CENTRAL ITALY
Mon Apr 6, 2009 01:32:39 GMT M 6.3 N42.33 E13.33 Depth: 8.8km ID:2009fcaf

Map Version 7 Processed Wed May 20, 2009 09:43:43 AM MDT

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 10: L'Aquila MMI map (USGS)

2010 Oaxaca, Mexico

Unlike previous high magnitude earthquakes in the region, the 2010 magnitude 6.2 earthquake in Oaxaca, Mexico resulted in relatively minor damage and caused one death. The epicenter was 20 kilometers below a generally hard rock surface in a mountainous region (USGS). The site class in the area in A-C with small geographic areas of site class D near the pacific coast. Figures 11 and 12 show the small area of minor intensity compared to the Vs30 map.
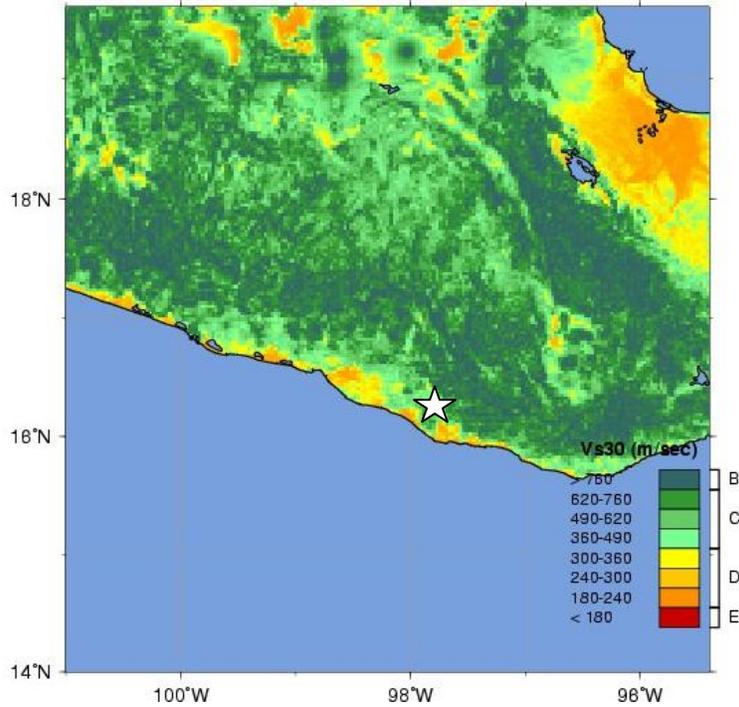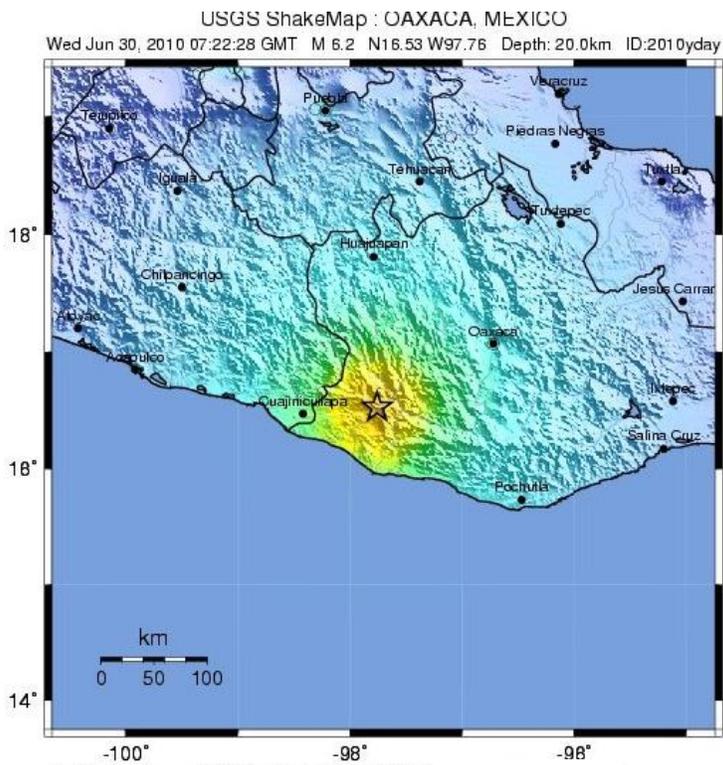
Figure 11: Oaxaca V$_s$30 map (USGS)

Figure 12: Oaxaca MMI map (USGS)

Discussion

The characteristics of these earthquakes and their locations are able to give insight on how a future earthquake may affect the Cleveland, Ohio region. Table 6 shows how the characteristics of a projected magnitude 6.3 earthquake compare to the conditions of the four historical earthquakes. These characteristics can be used to determine earthquake risk in Ohio due to the similarities in earthquake depths and magnitudes compared to Ohio and the range of site class covering that of Ohio. A comparison Vs30 and MMI map for these earthquakes predicts potentially high earthquake intensities due to Ohio's site class.

Table 6: Summary of earthquake characteristics

	Site Class	Depth (km)	Magnitude	Maximum Intensity
Northeast Ohio	C-D	*5-10	*6.3	
L'Aquila, Italy	B-D	8.8	6.3	VII
Oaxaca, Mexico	A-C	20	6.2	VI
Loma Prieta	B-E	18	6.9	VIII
Timiskaming	C-D	10	6.1	VI

* Projected

Consideration of the results of this study shows that soil amplification is a significant factor in determining earthquake intensity when magnitude and depth were not dramatically changed. All earthquakes studied showed negative correlations between intensity and V_s30. This was particularly true in the Loma Prieta and L'Aquila earthquakes where distinct zones of different intensity can be mapped. The wide area affected by the Timiskaming earthquake can also be attributed to the low V_s30 values in the epicentral region. The shallow, magnitude 6.2 earthquake in Oaxaca, Mexico resulted in minor damage. The V_s30 values in Oaxaca are considerably higher than those of the other three earthquakes studied.

The surface in Ohio contributes to this seismic region having low site class values. This site class is similar to the Timiskaming area due to the close geographic proximity and same

glacial coverage affecting Ohio and the Timiskaming area. The site class in Ohio is also similar to those areas of the Loma Prieta and L'Aquila earthquakes that sustained extreme damage where Mercalli intensities of VIII and VII were common. It has been determined Ohio could experience a similar magnitude earthquake to these, and earthquakes in Ohio occur at more shallow depths making them more intense.

Northeast Ohio's population of 2.9 million people results in a higher population density than L'Aquila, and could sustain more initial injuries and fatalities. A greater concern is the emergency and lifeline operations in the hours and days following the earthquake. With improvements already needed according to the ASCE, the infrastructure necessary for medical purposes and clean water could be severely damaged. The close proximity of the Perry Nuclear Power Plant has already given the region a scare, and the amount of damage it sustains would be extremely important following a large earthquake. The plant provided close to 7.6 million MWh of electricity in 2009 (EIA, 2009), which would need to come from other sources if the plant were to shut down, and radiation effects would be severe in this densely populated area. Due to the high concentration of infrastructure on loose sediment, a magnitude 6.31 event in this seismically active region could result in billions of dollars worth of damage.

Conclusions

Earthquakes in Cleveland are caused by nearly billion year old faults located in the basement rock which periodically release stress built up in the North American plate. Earthquakes have occurred in the past in the region and there could be a future magnitude 6.3 earthquake in the Northeast Ohio Seismic Zone. The geologic conditions, including Vs30 values, as well as depth and magnitude characteristics of the projected earthquake could result in major damage based on the results of the 1935 Timiskaming, 1989 Loma Prieta, 2009 L'Aquila, and

2010 Oaxaca earthquakes. Earthquake consideration and preparedness needs to take place in this region due to this risk of extensive damage.

Recommendations for Future Work

With all research concerning earthquakes, determining when and where the next one will occur is always a goal. This is especially true with midcontinent earthquakes because of the long lapse period between large earthquakes. These faults release stress in intervals longer than the time they have been studied, so there has not been a proven method for estimating recurrence of earthquakes in the region.

Concerning earthquake risk assessment, building codes and construction techniques need to be analyzed. Proper earthquake construction and maintenance on infrastructure will result in fewer people affected and less property damage after an earthquake occurs. Northeast Ohio is not particularly known for damaging earthquakes and earthquake resistant construction is not always considered, but by determining how Northeast Ohio construction compares to that of the other areas studied, a better idea of how the area will be affected in the event of a magnitude 6.3 earthquake. Studying other areas in which an earthquake has occurred also gives an idea of which techniques work and which ones do not when attempting earthquake resistant construction.

Acknowledgements

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