

Earthquakes in Minnesota—Are We Getting a Fair Shake?

Few natural phenomena attract as much public attention as earthquakes. Seldom does a month go by that we do not hear of a destructive earthquake somewhere in the world. Events like the earthquake–tsunami sequences during March, 2011 in Japan and December, 2004 in Sumatra are grim reminders that earthquakes and their consequences can cause almost unimaginable destruction and loss of life. Although much less severe, events such as the August, 2011 earthquake in Virginia and the April, 2008 earthquake in Illinois are sobering reminders that destructive earthquakes can occur, even in what are generally thought to be stable continental areas. Consequently, a strong public interest exists in Minnesota regarding earthquakes, as does some concern about the potential of destructive earthquakes ever occurring here.

What Causes an Earthquake?

Earthquakes are produced by movement of rock in the Earth's interior. In volcanic regions, movement of molten rock and associated steam can result in earthquakes. Most earthquakes, however, occur when solid rock masses move past one another along fracture planes called faults. To produce movement, stress must build up along a fault plane until it overcomes internal friction and the rocks to either side elastically snap or *rebound* to relieve the stress.

In large earthquakes, such as the San Francisco earthquake of 1906, displacements of tens of feet can occur along many miles of the fault plane, whereas smaller earthquakes may be associated with displacements of only a few feet along a few hundred feet of the fault plane. In either case, the fault movement creates a series of waves through the Earth, and we perceive these waves at the surface as the shaking of an earthquake.

Most commonly the *focus*—the center of the main rupture—is at least several miles below the land surface, and may produce little or no surface evidence of the sense of movement. The surface location directly above the focus is called an *epicenter*, and large earthquakes are sometimes referred to by the geographic location of the epicenter. The direction and distance of fault movement, as well as focal depth and overall strength, are usually determined by analysis of earthquake-wave records from a network of sensitive instruments called *seismographs*, which are located around the world.

Most earthquakes are related to plate tectonic processes or what used to be understood as *continental drift*. In the plate tectonic model, the Earth's outermost shell consists of a number of rigid plates that are roughly 60 miles (97 kilometers) thick and include both the Earth's crust and the uppermost mantle. These rigid plates are in a state of continual, but very slow movement (about an inch per year, or about as fast as a fingernail grows) over the less solid mantle material, with new plate material being created and pushed outward by volcanic processes at mid-ocean ridges, called *spreading centers*. Some earthquakes are generated by faulting and magma movement at spreading centers. Generally, larger and more destructive earthquakes occur along faults where plates are grinding together. Such earthquakes are common where one plate is driven under the other in a *subduction zone*, as is occurring in the active earthquake regions of the circum-Pacific, including Japan, Alaska, and South America¹.

Destructive earthquakes also occur where plates shear past one another horizontally on what are sometimes called *transform faults*; the San Andreas fault system in California is a famous example. Although much of the differential movement between plates may be taken up along a single fault that forms the plate boundary, significant movement can occur along hundreds or even thousands of faults that flank the plate boundaries. For example, the deadly 1994 Northridge earthquake near Los Angeles occurred along a previously unknown off-shoot of the San Andreas fault.

How Are Earthquakes Measured?

Two numbers are commonly given to describe earthquakes—intensity and magnitude. Intensity, commonly referred to as the *Mercalli scale*, is a number based on people's observations (or "felt reports"). It is related to the damage caused by local ground shaking and ground failure. This scale, expressed in Roman numerals, ranges from I, which is noticed by almost nobody, up to XII, which includes virtually total destruction of all human-made structures. Significant damage to buildings occurs at Mercalli intensities of VII or greater. Intensity decreases with distance from the epicenter, but local soil conditions—for example, the loose artificial fill near the shore of San Francisco Bay in the 1989 Loma Prieta earthquake—can cause higher intensity values at distant sites.

Magnitude, commonly referred to as the *Richter scale*, quantitatively describes the strength of an earthquake. It is usually based on the maximum amplitude of certain types of seismic waves recorded on a seismograph. The Richter scale was originally developed in the 1930s by seismologist Charles Richter for the analysis of earthquakes in southern California. In the following years, Richter's scale was applied to earthquakes worldwide, and several new ways of computing magnitude from seismograph records were developed. For earthquakes that were not recorded on seismographs, methods have been developed to estimate magnitude from intensity data. These methods result, at least in principle, in essentially the same magnitude estimates for most earthquakes, but they can be considerably different for very large or very deep-seated earthquakes. Moment magnitude, which is sensitive to the moment (the torque or cranking force) that is associated with the actual fault movement, is one of the more consistent magnitude estimates to be used in recent years. Regardless of how it is calculated, magnitude is expressed on a logarithmic scale, meaning that an increase in value of one digit equates to a 10-fold increase that may in turn equate to approximately 30 times more energy. The largest known earthquakes have had magnitudes around 9.0, such as the March 11, 2011 earthquake near Tohoku, Japan. In comparison, the famous San Francisco earthquake of 1906 is estimated to have had a magnitude around 8.0, or about 30 times less energy. Although there have been notable exceptions, earthquakes with magnitudes less than 5.5 usually do not cause major damage or injuries.

¹On June 9, 1994 some Minnesotans had the almost unbelievable experience of feeling a subduction-related earthquake that occurred deep below Bolivia, South America. The unusually large size (magnitude 8.2) and focal depth (390 miles; 630 kilometers) contributed to its being weakly felt over a wide region of North America. In the history of seismology, this appears to be the greatest distance that an earthquake has ever been felt.

Are Earthquakes Increasing?

It is commonly believed that earthquakes are becoming more frequent, but only in one special case is this true. Earthquakes that are induced by injection of wastewater, much of it a by-product of oil and gas production, have indeed increased significantly over the last several years. So far these induced earthquakes have had small to moderate magnitudes, and are concentrated in areas that have recently undergone accelerated oil and gas development, such as parts of Oklahoma and Texas. Interestingly, increases in similar oil and gas activities in North Dakota have not led to a significant increase in induced earthquakes.

On the other hand, records kept by the U.S. Geological Survey's National Earthquake Information Center in Golden, Colorado, indicate that there has not been a significant increase in naturally occurring earthquakes. Earthquakes are very common on a global scale, and roughly 15,000 earthquakes are reported worldwide every year, with an average of 600 or so exceeding magnitude 5.5. The historic records of minor earthquakes are incomplete, but reliable records for major earthquakes (magnitude 7 or greater) go back over 100 years. Studies of these events indicate average annual occurrences of 15 earthquakes in the magnitude 7 range and one or two with a magnitude of 8.0 or greater. Although short-term departures from these averages occur from year to year, there has been no sustained departure over longer time intervals. The public perception that more naturally occurring earthquakes are happening is likely an artifact of more seismic stations to record earthquakes and more media coverage.

Can Earthquakes Be Predicted?

To be useful, an earthquake prediction must include concise information on where and how big, as well as when, all within reasonably tight limits. Thus defined, no consistently reliable means of earthquake prediction has been developed to date and none, in the opinion of most seismologists, is likely in the foreseeable future. This failure is not from lack of trying; a broad swath of approaches have been attempted in the past, including those based on Earth tides, animal behavior, geologic studies, earthquake patterns, various chemical and physical phenomena, and numerous stress/strain models; but so far, to no avail. The nature of fault movement is a much more complicated problem than initially conceived, and we still have much to learn. Generally, the most that can be done in an earthquake-prone area is to formulate forecasts, where the likelihood of an earthquake of a certain magnitude along a given fault segment is expressed as a percentage probability over a span of several decades. A related product is a seismic risk map, which expresses the probabilities of destructive ground movement over a region. Seismic forecasts and risk maps are usually based on historic earthquakes along known faults, and although such information provides a useful historic framework, their power as a predictive tool is limited. For example, the epicenter of the magnitude 9.0 Tohoku, Japan earthquake was in an area that was previously assessed to be at relatively low risk for an earthquake of this magnitude.

Why Do Earthquakes Occur in the Midwest?

The Midwest of the United States is far from any plate margin, but even here, earthquakes do occasionally happen. Although the earthquake-generating mechanism in the Midwest is incompletely understood, it may be related to the westward drift of the North American plate away from its spreading center, the Mid-Atlantic ridge, toward the subduction and transform zones along the Pacific coast. This westward drift sets up a subtle but pervasive compression that is oriented roughly east–west for most of North America, and this stress can reactivate minor movement along some ancient faults. The great forces that originally formed these ancient faults have long since vanished, but the faults themselves remain as zones of weakness that, if oriented appropriately to the modern stress field, could be slightly reactivated.

In general, earthquakes in the Midwest are less frequent and much smaller than those that occur near plate margins. However, there is one area, the New Madrid seismic zone between St. Louis, Missouri, and Memphis, Tennessee, that has elevated potential for generating major earthquakes. The zone has a fairly high incidence of small to moderate earthquakes, and it was associated with a tremendous series of shocks in 1811 and 1812². Four of these may have had magnitudes exceeding 7.0, and many aftershocks probably had magnitudes between 4.0 and 6.5. Such an earthquake sequence occurring today would be devastating to nearby cities, such as Memphis, and could cause severe damage throughout much of the middle Mississippi and lower Ohio River valleys; however, it probably would not cause major damage as far north as Minnesota. Historic investigations, together with geologic and archaeological studies of prehistoric disruptions of near-surface materials, indicate that four events likely associated with magnitudes of 7 or greater (counting the 1811 and 1812 sequence as one event) may have occurred over the last 2,000 years at intervals varying from 360 to 600 years. Thus at our current state of knowledge, New Madrid does not appear to be "...overdue for the big one." However, smaller but potentially destructive earthquakes, with magnitudes ranging from 5.5 to 6.5, likely have higher recurrence rates, and may pose a more immediate threat. Studies by several universities and the U.S. Geological Survey have related the New Madrid seismic activity to an ancient rift (an area where the continent was split), which imparted a relatively weakened crust and upper mantle that may tend to concentrate modern stresses into the shallow crust.

Minnesota Earthquakes

Minnesota has one of the lowest occurrence levels of earthquakes in the United States, but a total of 20 small to moderate earthquakes have been documented since 1860. The earthquake history of the state is summarized in Figure 1 and Table 1.

Earthquakes prior to 1900 are poorly documented. For example, the only account of the New Ulm earthquake (apparently there were two events a week apart) consists of a brief article in a German language newspaper. It translates as follows:

"An unusual phenomenon attracted the attention of a number of people which leads one to conclude that the reports are based on facts. It was reported that during the night of Feb. 5, an earthquake took place, which happened again the following Sunday night (Feb. 12) on several occasions, which caused damage to furniture in the residence of Rev. P. Berghold, and actually caused cracks in the house itself. Sisters in the nearby massive school building noticed the vibrations as well, and so did other people including Mr. J.C. Rudolph and Mr. W. Koch. It is presumed that there are some screws missing in the heavenly regions which the impertinent winter has amply indicated to this date."

The 1917 Staples (Fig. 2) and 1975 Morris earthquakes with magnitudes of 4.3 and 4.6 to 4.8, respectively, are the largest that are well documented. Both earthquakes caused objects to fall, cracked masonry, and damaged chimneys, equating to intensities of VI to VII. Both events were a little like a bit of California coming in for a visit! In the Staples earthquake, many windows were indeed broken, but contrary to the headline, apparently no houses were shaken down. Near their epicenters these events caused considerable alarm, but the only known earthquake-related injuries were

²No historic accounts apparently exist for Minnesota for the 1811 and 1812 New Madrid earthquakes, but more recent earthquakes in the New Madrid area have occasionally been weakly felt in southern Minnesota. The most recent such event was a magnitude 5.2 earthquake near Bellmont, Illinois on April 18, 2008. The earthquake was associated with the Wabash Valley seismic zone, which may represent an offshoot of the New Madrid seismic zone.

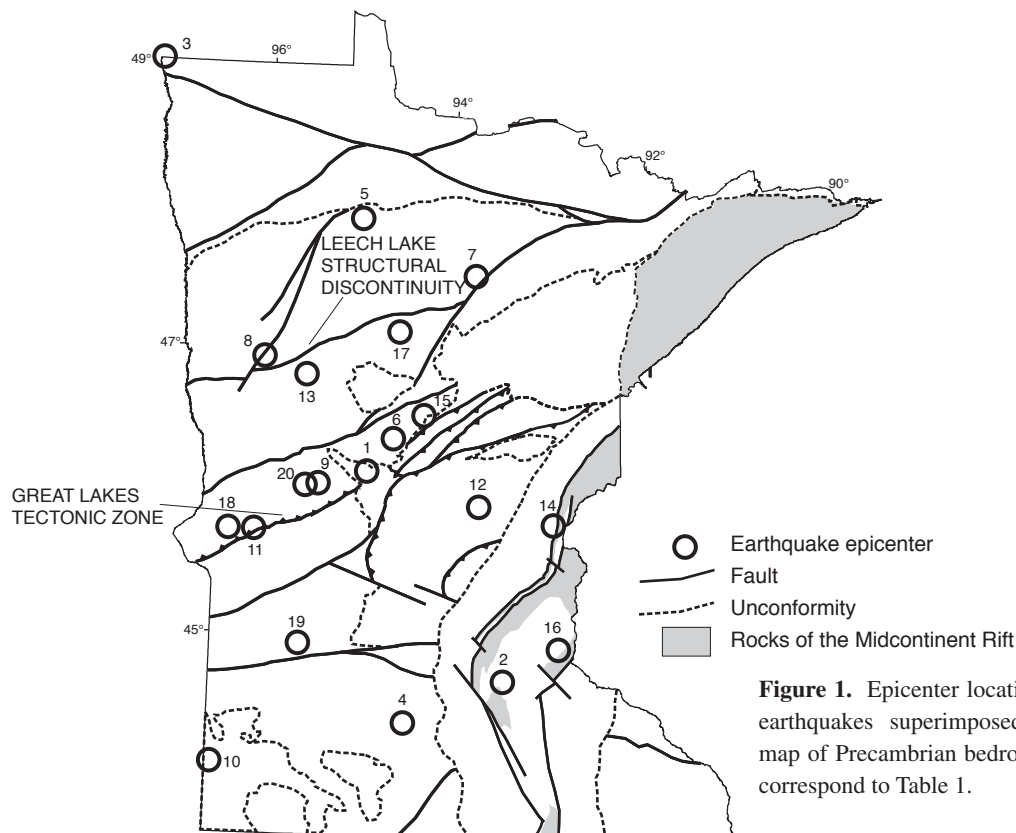


Figure 1. Epicenter locations of Minnesota earthquakes superimposed on a geologic map of Precambrian bedrock. The numbers correspond to Table 1.

Table 1. Historic seismicity of Minnesota. Asterisks denote earthquakes that were recorded instrumentally; all others and associated magnitudes are based solely on intensity data from felt reports. Locations are shown on Figure 1.

Name	Date	Latitude	Longitude	Intensity	Magnitude	Felt area (square kilometers)
1 Long Prairie	1860-61	46.1	-94.9	VI-VII	5	
2 New Prague	12/16/1860	44.6	-93.5	VI	4.7	
3 St. Vincent	12/28/1880	49	-97.2	II-IV	3.6	
4 New Ulm	2/5-2/12/1881	44.3	-94.5	VI locally	3.0-4.0?	
5 Red Lake	2/6/17	47.9	-95	V	3.8	
6 Staples	9/3/17	46.34	-94.63	VI-VII	4.3	48,000
7 Bow String	12/23/28	47.5	-93.8	IV	3.8	
8 Detroit Lakes	1/28/39	46.9	-96	IV	3-3.9	8,000
9 Alexandria	2/15/50	46	-95.4	V	3.6	3,000
10 Pipestone*	9/28/64	44	-96.4		3.4	
11 Morris*	7/9/75	45.67	-96.04	VI	4.6-4.8	82,000
12 Milaca*	3/5/79	45.85	-93.75		1	
13 Evergreen*	4/16/79	46.78	-95.55		3.1	
14 Rush City*	5/14/79	45.72	-92.99		0.1	
15 Nisswa*	7/26/79	46.5	-94.33	III locally	1	
16 Cottage Grove	4/24/81	44.83	-92.93	III-IV locally	3.6	
17 Walker	9/27/82	47.1	-94.6	II locally	2	
18 Dumont*	6/4/93	45.67	-96.29	V-VI	4.1	69,500
19 Granite Falls*	2/9/94	44.86	-95.56	V	3.1	11,600
20 Brandon*	4/29/11	45.986	-95.53		3.12	

EARTHQUAKE SHAKES CITY

Earth Tremor Felt All Over Northern Minnesota, According to Reports---Houses Said to Have Been Shaken Down at Bemidji---Chimney Knocked Down at Brainerd---No Damage Here, Although Shock Was Felt in Nearly Every Building---Roar Like That of Automobile Truck Engine Accompanies Quake.

An earthquake which shook nearly all of northern Minnesota was felt in Little Falls between 3 and 3:30 Monday afternoon. The shock was felt in every building in Little Falls and was strong enough to rattle glassware and windows in many buildings. The quake was accompanied by a roaring noise.

The shock was evidently of wide extent, as it was felt in points as far distant as International Falls, according to reports. It was said this morning that some houses had been shaken down at Bemidji. Brainerd, Motley, Pillager, Ft. Ripley and Pierz, among the nearer towns, felt the shock and it was apparently stronger in the more northern towns.

At Fort Ripley and Brainerd it was very pronounced and at Brainerd a chimney was knocked down in the northern part of the city. Except that reported from Bemidji, there was no other damage, as far as can be learned. At Lincoln, people in boats on the lake felt the quake.

The shaking of the buildings was like that produced by a heavy truck passing, according to many who felt it, and it was thought at first that a car was causing it, especially as a roaring noise accompanied the tremor. The noise was like that produced by a powerful automobile engine.

Little Falls experienced an earthquake tremor once before, several years ago. The shock was also very slight.

Monday's quake lasted about 20 seconds.

Figure 2. Article from the Little Falls Daily Transcript, September 4, 1917. Reports of the damage turned out to be somewhat exaggerated, but the excitement was genuine.

fortunately minor and in a way self-inflicted (one man fell out of a hayrack in his excitement).

Although less dramatic than the Staples or Morris events, the 1993 Dumont (Fig. 3) earthquake and the 2011 Brandon earthquake are more typical of those that occur in Minnesota. The magnitude 4.1 Dumont earthquake was felt over about 27,000 square miles (69,600 square kilometers), and was associated with intensity V to VI near the epicenter. The shaking near the epicenter was accompanied by a loud, explosive noise that alarmed many people, but no injuries or serious damage occurred. In contrast to the Dumont event, the weaker Brandon earthquake (magnitude 3.1) was not widely felt, but turned out to be the best recorded and most precisely located earthquake in Minnesota. This event occurred while surrounded by numerous, state-of-the-art seismographs that were part of the USARRAY component of the EarthScope experiment, a national project to image the crust and mantle beneath the entire United States. According to analyses of records from 40 of these seismographs (Fig. 3), the epicenter was about 3.5 miles (5.7 kilometers) northeast of Brandon, Minnesota, within or close to T. 129 N., R. 39 W., sec. 13, with an estimated focal depth of 9.7 miles (15.6 kilometers). In comparison, the epicenters of other historic earthquakes in Minnesota are likely to be located to within an error of a few miles at best, and focal depths are poorly constrained. In fact, the locational errors of the poorly documented events before 1900 may well be an order of magnitude greater.

Minnesota earthquakes, like those elsewhere in the Midwest, are attributed to minor reactivation of ancient (Precambrian) faults in response to modern stresses. The epicentral map in Figure 1 also shows the major faults and other geologic features that are associated with Minnesota's Precambrian bedrock. A significant alignment of seven historic epicenters occurs along the Great Lake Tectonic Zone, a major north-dipping fault zone that formed during the initial assembly of the North American crust about 2.6 billion years ago. Similarly to the north, four epicenters align roughly with the Leech Lake structural discontinuity, another north-dipping fault zone that likely formed 2.6 to 2.7 billion years ago. Finally, three epicenters are located near structures that are associated with the 1 billion year-old Midcontinent Rift System.

In summary, weak to moderate earthquakes do occur occasionally in Minnesota, but a severe earthquake is very unlikely. Although we cannot assign a zero probability of a seriously damaging earthquake occurring in the time span of a human life, the threat is very small compared to other

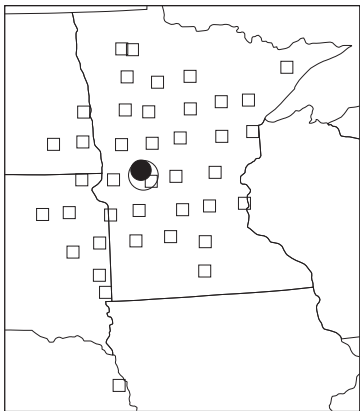


Figure 3. Epicentral map for the Brandon, Minnesota earthquake. The white circle represents the initial epicenter reported by the U.S. Geological Survey. The black circle represents the refined epicenter, based on USARRAY data (described in this brochure). Boxes represent locations of USARRAY seismograph stations, which were used to estimate the refined epicenter, as well as other technical information.

natural hazards that have well-proven records of destruction, such as winter storms, tornadoes, and flooding.

The late Harold Mooney of the University of Minnesota estimated average recurrence rates for Minnesota earthquakes as follows:

Magnitude 4 — 10 years

Magnitude 4.5 — 30 years

Magnitude 5 — 89 years

Magnitude 5.5 — 266 years

If earthquakes larger than magnitude 5.5 can occur in Minnesota, it is likely that their rate of recurrence would be many hundreds of years, or more.

Minnesota earthquakes are of scientific interest because they provide information on crustal structure and the regional stress field. If you think that you have ever felt an earthquake in Minnesota, we would like to hear from you! The most useful reports include the place, date, time of day, where you were (in a parked car, upper floor of a building, outdoors, at rest, walking, etc.), together with what you observed. The best way to contact us is by email at the following address: mgs@umn.edu.

If you want to learn more about earthquakes, several excellent websites currently exist. The U.S. Geological Survey Earthquakes Hazards Program maintains a multi-page website at: <https://www.usgs.gov/natural-hazards/earthquake-hazards/>. Much of the general information on earthquakes presented here is derived from this site.

The Incorporated Research Institutions for Seismology (IRIS) also maintains an excellent website at: <http://www.iris.edu/hq/>.

An interesting page at this site is the Seismic Monitor, which presents a continually updated global map of earthquake occurrences, which can be accessed at: <http://www.iris.edu/seismon/>.

For more information about the EarthScope experiment, mentioned above, one should go to: <http://www.earthscope.org/>.

Acknowledgements

In addition to the U.S. Geological Survey, several people and organizations provided useful information for this brochure. The Brown County Historical Society and Ross Gersten of the Mankato Free Press were instrumental in providing the translated account of the New Ulm earthquake. Robert Busby of EarthScope and Frank Vernon of the IRIS Consortium and Scripps Institute of Oceanography generously provided technical information regarding the Brandon earthquake as well as the data used in Figure 3. Mark Jirsa of the Minnesota Geological Survey provided the geologic map used in Figure 1.

Minnesota at a Glance is produced by the
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