Earthquake Hazards and Probabilities in North Dakota and the Magnitude 9.0 Indonesian Earthquake of December 26th, 2004

Fred J. Anderson

Introduction

Indonesia was rocked by the megathrust earthquake which occurred on December 26, 2004 registering a Richter magnitude of 9.0. This earthquake or "seismic event" is the fourth largest on record and one of only four magnitude 9.0 events that have been recorded from around the world since 1900 (USGS, 2005).

The energy released during this event traveled through the Earth in the form of seismic waves. These waves were felt and recorded at seismic monitoring stations around the globe. It was determined by scientists at NASA that the energy released from this quake, and resultant change in symmetry of the Earth's crust, was enough to induce a slight "wobble" in the Earth's rotation.

The displacement of oceanic crust occurred along the low angle subduction zone thrust fault (also known as a megathrust) that traverses an area from just off the west coast of Burma to southeast of Jakarta and is located along the Sunda Trench (Figure 1). The shift of oceanic crust also resulted in the creation of the most devastating tsunami (seismic sea wave) in recorded history.

The wave that was created from the displacement of ocean water resultant from fault motion caused massive destruction and loss of life in all areas of the Indian Ocean basin. Damage was induced as far away as the west coast of Africa along the Somalian coast. The tsunami was even recorded along the west coast of the United States. Estimates of the loss of life associated with the earthquake and tsunami are greater than 280,000 people dead and over 1.1 million displaced. Further, over 14,000 people have been listed as missing. The cost of repairing the destruction from this catastrophic event continues to measure in the billions of dollars.

Earthquake monitoring stations from around the globe and near North Dakota were able to record the seismic wave energy created from this earthquake. From the information recorded at these stations, and the use of current global seismological models, it is possible to determine the arrival times of the seismic waves generated by the earthquake throughout North Dakota.

Here we will review the locations of current and proposed seismic monitoring stations in and around the state, discuss seismic wave arrival time estimates generated from contemporary global seismological models, review the number and occurrence of past earthquakes in North Dakota, and briefly highlight current assessments of seismic hazard and probability in North Dakota.

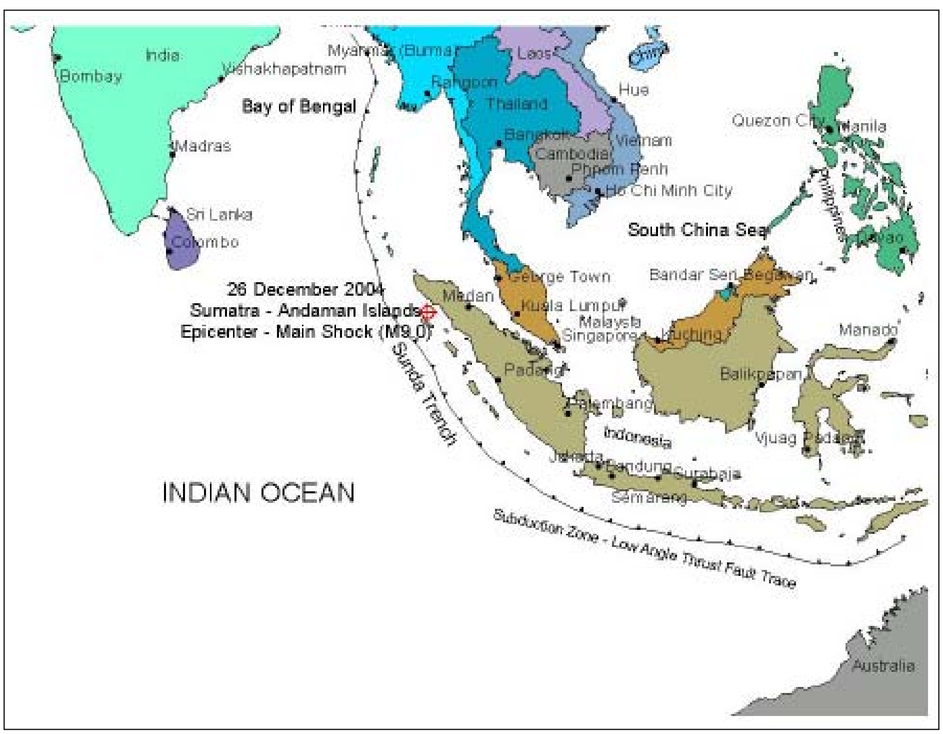

Figure 1. Location of the magnitude 9.0 Indonesian earthquake of December 26, 2004. Long black line with triangles depicts the trace of the low angle thrust fault that runs the length of Indonesia and adjacent areas. Triangles are depicted on the upthrown or overriding portion of the fault block or "plate."

Monitoring Stations in and Around North Dakota

Currently there is one set of three strong motion sensors that have just recently been installed at the Garrison Dam site, near Riverdale, by the United States Army Corps of Engineers (USACE). Strong motions are defined as the motions of intense ground shaking that occur during a large earthquake that have the potential to induce damage or failure to engineered structures due to the intense amplitude of the seismic waves and the extended duration of ground shaking. Sustained strong motions can also induce other ground failures such as landslides. This subdiscipline of seismology, called strong motion seismology, utilizes specially constructed sensors, called accelerometers, to record these ground motions and their effects to engineered structures. This information can then be used to upgrade and enhance the design knowledge when attempting to construct earthquake resistant structures. Also, interpretations of fault motions can be completed and the quick response and timely direction of emergency personnel to areas of greatest ground shaking can be more readily affected.

There are seven active seismic monitoring stations surrounding the state that are focused on general earthquake monitoring. One station is located just north of the Black Hills in South Dakota. Interestingly, this station was initially installed in a joint effort between the U.S. and Soviet governments for the purpose of monitoring nuclear testing in support of the Comprehensive Nuclear Test Ban Treaty (CTBT). This station is now under the operation of the USGS. There is also one relatively newer station that was recently deployed in northeastern Montana near the town of Dagmar. This station is operated by the Montana Bureau of Mines and Geology, Earthquake Studies Office. Four additional seismic monitoring stations are located in southern Canada in the Provinces of Manitoba and Saskatchewan. Two are located in Manitoba at Flin Flon and Lac du Bonnet, and two others are located relatively close to each other at Bergheim and Blackstrap, Saskatchewan. Near the eastern boundary of the state, one station is located in Ely, Minnesota. Three new stations, one to be installed as a part of the EarthScope program in Minnesota and the other two as a part of the Advanced National Seismic System (ANSS) network to be located in central North Dakota and north central South Dakota, have been proposed. If constructed a seismic monitoring station designed for general seismic monitoring located in North Dakota along with the current strong motion sensors installed at Garrison Dam would provide for an enhanced understanding of North Dakota seismology. It would also be the first such station of its kind marking the beginning of modern global seismology in our state. The geographic center of North America near Rugby could be an interesting location for a new broadband seismic monitoring station.

Effects of the Magnitude 9.0 Indonesian Earthquake in North Dakota

The energy released during an earthquake is transmitted elastically through the earth in the form of seismic waves. Generally speaking, and when we look at a simplified conventional seismogram obtained from a seismograph, we see two basic types of waves; body waves (waves that travel within a body of rock) and surface waves (waves that travel along the surface of a body of rock). There are two types of body waves that have been named based on their waveforms; a primary or "P" wave as it is called in seismological shorthand, and a secondary or "S" wave. There are also two types of surface waves (the wave forms that are responsible for much of the near surface ground shaking and resultant damage to structures); a Rayleigh wave and a Love wave (one may wish to refer to Bob Biek's excellent review of North Dakota Earthquakes in Vol. 23, No. 1 of the NDGS newsletter for a more in depth discussion of the different types and properties of seismic waves).

By employing some of the currently available modeling tools produced by seismologists within the global seismological modeling community one can determine the arrival times of all the theoretical seismic wave forms produced by the Indonesian earthquake for selected locations throughout the state. Since North Dakota is well within the seismic wave shadow zone created by the liquid outer portion of the Earth's core (S waves cannot travel through a fluid medium as a fluid will not propagate a sense of shear motion and P waves are diffracted) and as such imparts a "shadow zone" on an area of the globe opposite from the seismic event across a window of 104° to 140° from the earthquake. The wave forms that could be expected to be recorded would be dominantly in the form of the *diffracted* P and S waves and typical surface wave forms. Theoretical arrival times and recordable durations of seismic wave energy were determined for selected cities throughout North Dakota.

If we could envision a hypothetical ND-based seismographic network, with earthquake monitoring stations located at each one of our major ND cities, we could then calculate, from the geographic positional information in hand for each location, that recordable seismic wave energy in the form of the diffracted P, diffracted S, (diffracted P and S waves actually bounce off of and travel along the core mantle boundary), and surface waves created by the Indonesian earthquake of December 26, 2004 would have been recordable first at the City of Williston on December 25, 2004 at 7:14:30 PM Central Standard Time (CST). These seismic waves would have continued to travel through the earth and across the state rather quickly and would have been received lastly at the City of Wahpeton station at 7:14:45 PM CST, only 15 seconds later.

For all practical purposes, it would be plausible to say that the seismic waves generated from the Indonesian earthquake would have theoretically arrived in ND at approximately 7:14 PM CST on December 25, 2004. So, how do we determine if this earthquake was actually felt here in ND? One answer, is that until we establish a seismic monitoring station somewhere in the state (the geographic center of North America just outside of Rugby would seem to be an interesting probable location), we will have to be content to estimate what the effects would be from observational data, by those who may have felt an earthquake (information from which arose the modified Mercalli Earthquake Intensity Scale) and data provided by neighboring

North Dakota City	P Wave Arrival Times	S Wave Arrival Times	Surface Wave Arrival Times	Duration of Recordable Seismic Wave Energy (minutes)
Williston	7:14:30	7:27:43	7:52:10	43:32
Minot	7:14:32	7:27:47	7:52:54	43:45
Rugby	7:14:33	7:27:49	7:52:28	43:49
Devils Lake	7:14:35	7:28:10	7:52:41	44:00
Dickinson	7:14:36	7:27:55	7:52:46	44:05
Grand Forks	7:14:38	7:27:58	7:52:54	44:13
Bismarck	7:14:39	7:28:00	7:53:01	44:19
Jamestown	7:14:40	7:28:03	7:53:11	44:29
Valley City	7:14:41	7:28:04	7:53:14	44:31
Fargo	7:14:42	7:28:06	7:53:21	44:38
Wahpeton	7:14:45	7:28:11	7:53:37	44:53

Since North Dakota lies well within the earthquake shadow zone for this particular event, the P and the S wave arrival times presented here are for the diffracted P (Pdiff) and diffracted S (Sdiff). The first arriving wave form of the surface waves generated (i.e. the Love wave) are also presented. All theoretical seismic wave arrival times are calculated using the seismic wave propagation model based on the International Association of Seismology and the Physics of the Earth's Interior (IASPEI) 1991 global seismological model.

earthquake monitoring stations and the National Earthquake Information Center (NEIC). Perhaps it is time to consider what the potential value would be for creating and operating a seismic monitoring station in North Dakota.

Previous Earthquakes in North Dakota

The first instrumentally verified earthquake in the state was recorded on July 8, 1968 in the vicinity of Huff, North Dakota, just south of the Bismarck-Mandan area. This earthquake has been recorded as a Richter magnitude 3.7 event. Several other earthquakes have been felt within the state beginning as far back as October 9, 1872 (Figure 2). As of this writing a total of nine earthquakes have been determined to have occurred within the state and five additional earthquakes were recorded to have been felt within the state although they did not originate within state boundaries (Biek, 1997).

The largest earthquake to have been felt in North Dakota in the recent past was a magnitude 7.3 earthquake that originated at Hebgen Lake, Montana in 1959. This quake was felt in the westernmost portion of North Dakota with reported Mercalli intensity scale IV effects. It is interesting to note that based on this historical record, an earthquake, either originating within the state or being felt within the state, occurs, on an average, of approximately once per decade (Figure 2).

North Dakota Seismic Hazards

In order to determine what the earthquake risk would be for a particular area, seismologists compile a seismic risk map, based on the probability that a particular seismic event (earthquake) of a certain energy value will occur within a specific time frame within a specified distance from a particular location. It is important to consider just how North Dakota compares to the rest of the U.S., on the matter of seismic hazard. From a seismological perspective we can look at this in a couple of different ways.

One way to evaluate the seismic hazard of a particular area is to consider what the probability would be that an earthquake of a given magnitude would occur at a particular location of interest during a specified period of time. If one were to consider what the probabilities of an earthquake of magnitude 5.0 or greater (earthquakes of magnitude 5.0 or greater are generally considered to be of a destructive character) occurring within the next 1000 years (roughly 14 lifetimes) at a range of 50 km (around 31 miles) from each major North Dakota city we would find a less than 10 percent chance of experiencing this kind of an earthquake within the next 1000 years (Figure 3). The cities of Wahpeton and Bismarck have slightly higher probabilities than other cities in North Dakota. The city of Williston has the highest probability. This is due to their location to preexisting, deeply buried fault structures at the northwestern and southeastern boundaries of the state and on the configuration of the Precambrian basement rocks, previously summarized as related to earthquakes in North Dakota by Bluemle (1989).

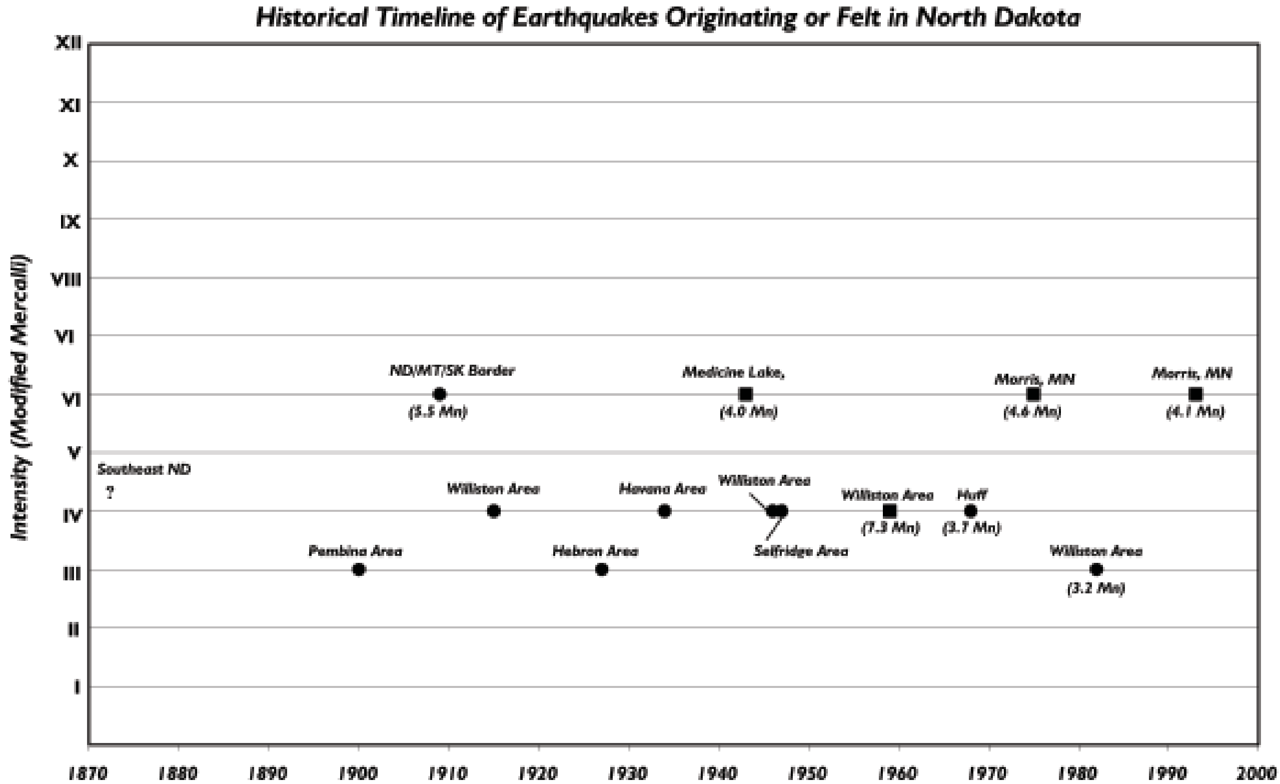

Figure 2. Historical timeline of earthquakes originating within (circles) or felt (squares) in North Dakota. The approximate locations of each event are provided above the time marker. Available calculated Richter magnitudes (Mn) are presented below the time marker. The earliest recorded event of October 9, 1872, location undetermined, is denoted with a question mark.

Probability ranges[1,2] of an earthquake greater than or equal to a Magnitude 5.0 event occurring within 1000 yrs and 50 km of selected North Dakota Cities

North Dakota City	Probability Range	Relative Ranking
Williston	0.30-0.40	1
Wahpeton	0.15-0.20	2
Bismarck	0.10-0.20	3
Fargo	0.06-0.10	4
Valley City	0.06-0.10	5
Minot	0.05-0.10	6
Grand Forks	0.06-0.08	7
Jamestown	0.06-0.08	8
Devils Lake	0.05-0.06	9
Rugby	0.05-0.06	10
Dickinson	0.04-0.06	11

[1]Values obtained from the USGS seismic hazard probability calculator.

[2]To provide a bit of perspective here, the probability range for the occurrence of a magnitude 5.0 earthquake within 1000 years and 50 kilometers of Los Angeles is 0.9-1.0 (or a 90-100% probability of occurrence).

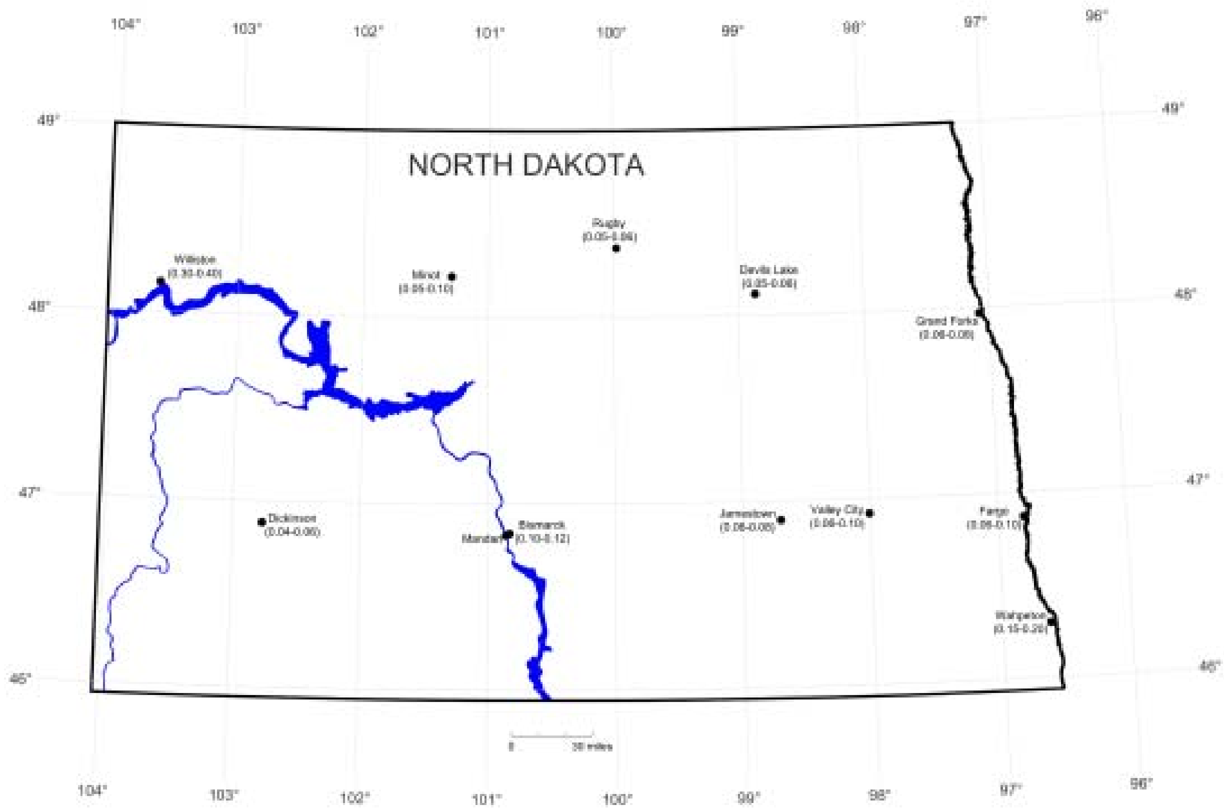

Figure 3. Map of major North Dakota cities and the range of probabilities associated with the occurrence of an earthquake within a 1000 year time period within a distance of 50 kilometers. It is important to note that compared to the rest of the continental U.S. these probabilities are among some of the lowest calculated.

Another way to characterize seismic risk is by way of ground acceleration presented as ground shaking hazard, which is the rate of horizontal ground motion for a particular area calculated from the frequency and number of previous earthquakes of various magnitudes and currently available information on fault-slip rates.

Compared to the rest of the U.S., North Dakota is well within the area with the lowest potential ground shaking hazard (Figure 4) of 0-2% g (when an earthquake occurs the forces caused by ground shaking can be measured and expressed as a percentage of g or the force of gravity at the surface of the earth). The reason for our low probability of earthquake occurrence and low potential for ground shaking hazards is simply due to our distance from active seismic areas and major fault systems within the southeast central (New Madrid) and the western (San Andreas) U.S. and on the configuration of our Precambrian basement.

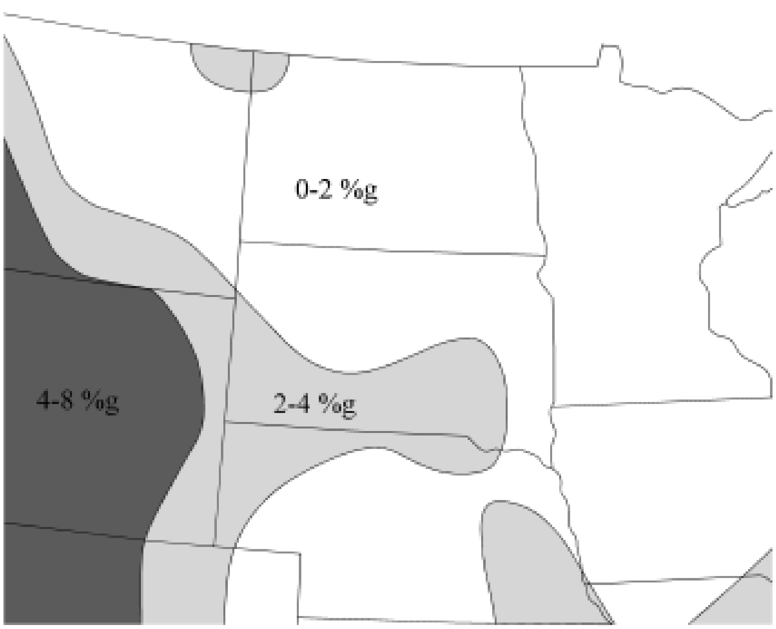

Figure 4. Portion of the simplified 2002 USGS U.S. National Seismic Hazard Map which depicts horizontal ground accelerations that would have a 10 percent probability of being exceeded within the next fifty years for a site with a firm rock condition. The majority of the state of North Dakota is contained within the lowest range of potential shaking hazard of 0-2 % g (modified from USGS, 2002).

It is likely that in our lifetimes we will not witness such a devastating event as the December 26th, magnitude 9.0 Indonesian earthquake and tsunami. It is plausible and probable, however, that some of us in North Dakota, will experience the effects of a moderate to low level quake in North Dakota within our lifetimes. For all of us in North Dakota, who live in the relatively stable and seismically quiescent environment of the North American craton (not to be confused with crouton, which we may enjoy on a salad), we should pause and reflect on just how fortunate we are that the spectre of recurring earthquakes and tsunami are not a part of our daily lives.

National Earthquake Information Center

Since we currently do not have an operating seismic station in North Dakota that is designed specifically for global earthquake monitoring we will continue to rely upon stations located in neighboring states, the recently installed strong motion sensors at the Garrison Dam, and on the information provided by the NEIC. The NEIC is operated by the USGS, located in Golden, Colorado on the campus of the Colorado School of Mines. The NEIC is the central location for all seismic related information for the United States and the world. The mission of the NEIC is to rapidly determine the location and size of all destructive earthquakes worldwide and to efficiently make this information available to all persons concerned including government agencies, scientists, and the public. The NEIC also manages an extensive global seismic database on earthquake parameters and their effects that serves as a fundamental tool for earthquake geologic research and seismology.

Selected References

Bolt, B.H., 1988, Earthquakes, (3rd ed.): New York, W.H. Freeman and Company, 282 p.

Biek, B., 1997, Earthquakes in North Dakota, North Dakota Geological Survey Newsletter, Vol. 23, No. 1, pp 17-23.

Bluemle, J.P., 1989, Earthquakes in North Dakota, North Dakota Geological Survey Newsletter, No. 6, pp 21-25.

Kennett, B.L.N. and Engdahl, E.R., 1991, Traveltimes for global earthquake location and phase identification, Geophys. J. Int., v 105, pp 429-465.

United States Geological Survey, 2005, M9.0 Sumatra-Andaman Islands Earthquake of 26 December 2004, Earthquake Summary Map XXX.

Web Sites of Interest

Earthquakes in North Dakota, North Dakota Notes, North Dakota Geological Survey website:
http://www.state.nd.us/ndgs/Earthquakes/earthquakes.htm

National Earthquake Information Center, United States Geological Survey:
http://neic.usgs.gov/

United States Geological Survey, Earthquake Hazards Program:
http://earthquake.usgs.gov/

Montana Bureau of Mines and Geology, Earthquake Studies Office:
http://mbmgquake.mtech.edu/

"Rocks are records of events that took place at the time they formed. They are books. They have a different vocabulary, a different alphabet, but you learn how to read them."

John McPhee