MINNESOTA GEOLOGICAL SURVEY

MATT WALTON, *Director*

EARTHQUAKE HISTORY OF MINNESOTA

Harold M. Mooney

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EARTHQUAKE HISTORY OF MINNESOTA

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EARTHQUAKE HISTORY OF MINNESOTA

By

Harold M. Mooney

INTRODUCTION

This report will present an earthquake history of Minnesota. At least ten earthquakes have taken place within the state during the last 120 years. A similar number that occurred outside of the state were felt within Minnesota. The former have ranged in estimated magnitude from m_b = 2.6 to 4.8. The most recent significant shock, in 1975, was felt over an area of 82,000 square km (31,500 square miles) and was recorded at seismic stations throughout North America.

An earthquake history for the state has significant implications for public policy. For example, the location and design of nuclear power plants must be guided by an assessment of the probability for a damaging earthquake. Minnesota has two nuclear plants in operation at present, at Prairie Island (near Red Wing) and at Monticello. A discussion of their locations in relation to earthquake epicenters is given below under Earthquake Risk.

Building construction codes present another aspect of public policy dependent upon earthquake history. Certain standards of construction must be met depending upon earthquake zoning classification. The Uniform Building Code assigns every location in the United States to a four-grade Seismic Risk Zone (0 = least risk, 3 = greatest risk).

The earthquake history of Minnesota can help to place future earthquakes in perspective, if they occur. Public interest is high, especially locally, after a significant earthquake like the 1975 event near Morris. The news media and the public wish to know whether the event is unusual and unexpected, whether it is likely to recur, whether a recurrence can be predicted, and what the risks of damage or injury may be. Such questions can be partially answered in terms of earthquake history.

Earthquake history is also useful in clarifying geologic relationships. Any earthquake must reflect present-day geologic processes in action. A pattern of earthquake activity must relate to major tectonic lineaments and fractures. I will show later that several earthquakes in Minnesota follow an east-northeast lineation across the central part of the state that is believed to coincide with a major tectonic boundary. I will also suggest a possible relationship of one event with the Midcontinent Gravity High, a major feature in the tectonics of North America.

In this report, I have attempted to compile most of the significant information relating to Minnesota earthquakes. Some previous results have been re-interpreted. Two especially useful sources have been Docekal (1970) and Coffman and von Hake (1973). Background information on frequently used terms such as magnitude and intensity is provided in the apppendices.

MINNESOTA SEISMICITY IN PERSPECTIVE

Minnesota is one of the least seismically active states in the United States, but this does not mean that it is free from earthquakes. At least ten have occurred within the state during the last century. Others from as far away as Quebec have been felt within Minnesota, and doubtless additional earthquakes have occurred within the state without being felt or reported by people. French traders and missionaries were active in the region that is now Minnesota as early as 1650, but population density remained small and concentrated until about 1850. The first record of an earthquake in Minnesota was in 1860.

In world perspective, most earthquakes occur around the margin of the Pacific Ocean. In the United States, this includes Alaska (highly active) and California-Nevada (moderately active). The Pacific-margin region accounts for about 80 percent of energy release in shallow earthquakes (that is, to depths of 60 km or 37 miles), 90 percent in intermediate-depth earthquakes (60-300 km or 37-185 miles) and nearly 100 percent in deep earthquakes (300-700 km or 185-438 miles). Most of the remaining worldwide energy release occurs in a Trans-Asiatic belt including Burma, northern India and the Himalayas, extending through to Iran, Turkey, and Greece.

Seismicity in eastern North America is more diffuse, although concentrations of activity appear in the St. Lawrence valley and the lower Mississippi-Ohio valley watersheds. The latter includes a series of major earthquakes near New Madrid, Missouri, in 1811-12. The most comprehensive recent report on these events is given by Penick (1976). Nuttli (1973a) assigns a magnitude m_b = 7.4 to the largest of these, on 7 February 1812. Extrapolation of his generalized isoseismal map suggests that these shocks should have been felt over much of Minnesota, although no felt reports exist, possibly because of low population density.

In the St. Lawrence valley, the two largest earthquakes during historic times were 5 February 1663 (felt as far west as Detroit) and 28 February 1925 (felt over an area, including Minnesota, that was 6 times greater than the 1906 San Francisco earthquake).

Scattered large earthquakes have occurred elsewhere in eastern North America, the most notable example being 31 August 1886 near Charleston, South Carolina, with maximum intensity of X and magnitude estimated at 7. (See appendices for an explanation of intensity and magnitude.) The felt reports included Milwaukee. The smoothed isoseismal contours include the southeastern corner of Minnesota, although no specific felt reports are known. Another somewhat isolated event of moderate size occurred on 18 November 1755 near Cape Ann, Massachusetts.

Figure 1, reproduced with permission from Docekal (1970), shows the general pattern of earthquake activity for historic times in the central United States. It should be noted that the coverage of Docekal's map is restricted to the Appalachian crest in the east, the Front Range in the west, and the Canadian border in the north. His results shown for Minnesota will be here revised and extended.

Docekal identifies an earthquake epicenter alignment which he calls the Midcontinent Seismic Trend. On Figure 1, it appears as many small earthquakes and a few large ones, extending from central Oklahoma to eastern Nebraska, with a possible extension into southern Minnesota and on to the Keweenaw Peninsula of Upper Michigan (the site of the Calumet m_b= 5.5 (estimate) earthquake on 26 July 1905). The Midcontinent Seismic Trend appears to be associated, especially along its southern part, with a major tectonic feature of the central United States. This feature includes the Nemaha-Table Rock uplift, the Keweenawan mafic belt, the Midcontinent Gravity High, and the St. Croix horst which is bounded by two major steeply inclined faults. The feature has been well documented in Minnesota (see for example Mooney and others, 1970a, 1970b), but I will show later that it correlates poorly with known earthquake epicenters in Minnesota.

A few earthquakes with epicenters outside of Minnesota have been felt within the state. I have not attempted a comprehensive listing, but they include:

1. Eastern Nebraska, 15 November 1877. Two felt reports in southern Minnesota.

2. Aurora, Illinois, 26 May 1909. Intensity IV or V reported in southeastern Minnesota.

3. La Malbaie, Quebec, 28 February 1925. Felt lightly in Minneapolis.

4. Timiskaming, Quebec, 1 November 1935. Intensity II-III reported in Minneapolis.

5. Sioux Falls, South Dakota, 11 October 1938. Intensity IV reported in Hills, Minnesota.

6. Central Illinois, 9 November 1968. Intensity I-IV effects over much of southern Minnesota including Austin, Glencoe, Minneapolis, Rochester, and St. Paul.

TABULATION OF MINNESOTA EARTHQUAKES

Table 1 presents a summary of the principal data for all known Minnesota earthquakes. Letters in parentheses refer to notes at the end of the Table. Figure 2 shows the distribution of these earthquakes on a state map. Further details on the individual earthquakes appear in the following section.

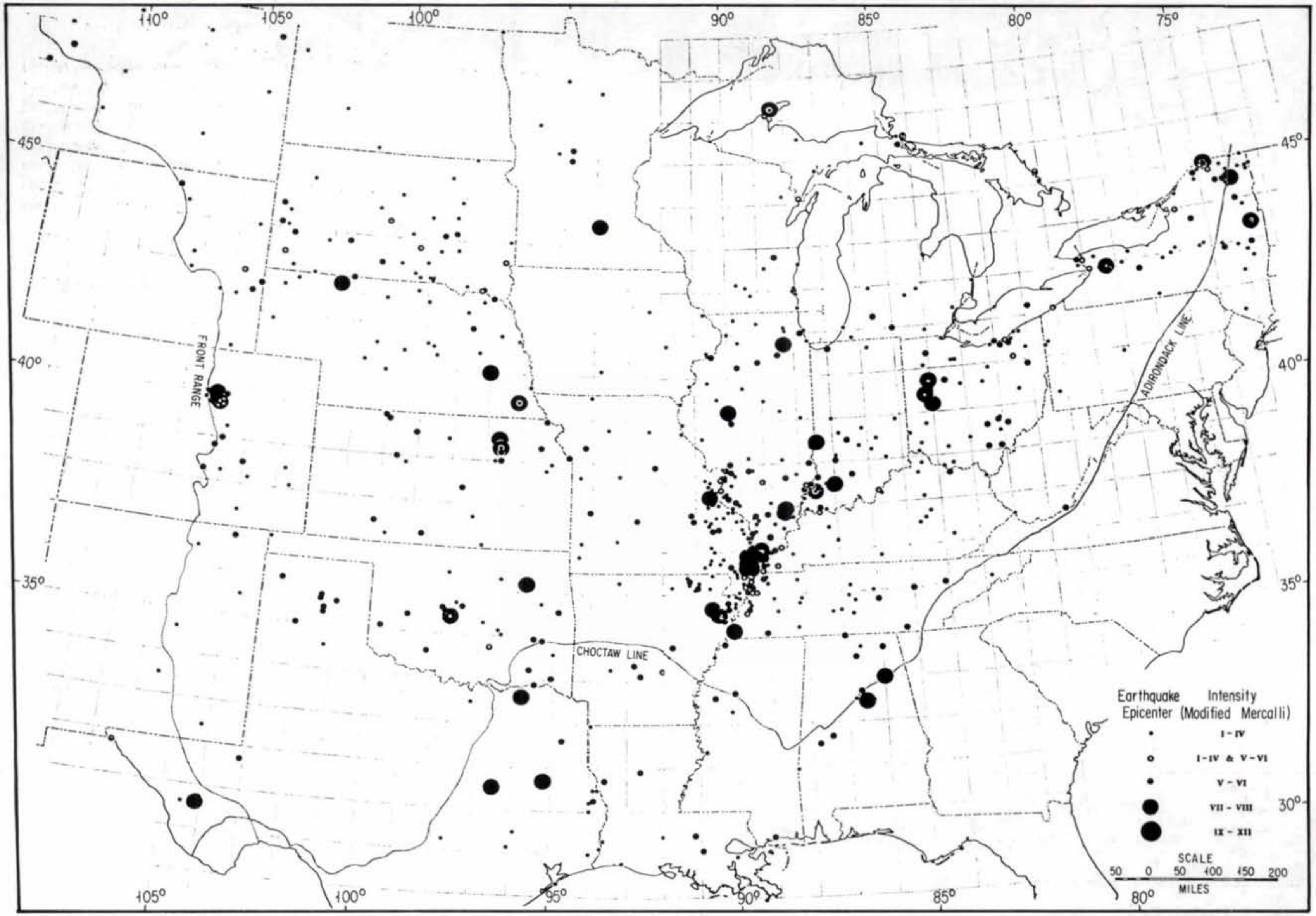

Figure 1--Distribution of earthquake epicenters in the central United States (reproduced with permission from Docekal, 1970).

Table 1--Parameters of Minnesota earthquakes.

Location	Year	Day	Central Standard Time (a)	North Latitude	West Longitude	Felt area square km (square miles)	Maximum Intensity	Magnitude (h)					
								$m_{b,G\&R}$	$m_{b,H1}$	$m_{b,AGG}$	m_b (average of preceding)	m_b (teleseismic)	m_b (composite) (j)
1. Long Prairie	1860-1861	- - -	- - -	46°06.0'	94°52.0' (b)	- - -	VI-VII (f) V+(g)	4.9-5.5 (f) 4.3 (g)	4.5-5.0 (f) 4.0 (g)	4.3-5.0 (f) 3.6 (g)	4.6-5.2 (f) 4.0 (g)	- -	4.6
2. Le Sueur	1865-1870	- - -	- - -	44°27.5'	93°54.0' (c)	- - -	VI-VII (f) V+(j)	4.9-5.5 (f) 4.3 (j)	4.5-5.0 (f) 4.0 (j)	4.3-5.0 (f) 3.6 (j)	4.6-5.2 (f) 4.0 (j)	- -	4.3
3. Red Lake	1917	6 Feb	11h26m	47°55'	95°00' (c)	- - -	- - -	- - -	- - -	- - -	- - -	- -	- -
4. Staples (Motley)	1917	3 Sep	15h30m	46°20.2'	94°38.0' (b)	48,000 (f) (18,500)	VI-VII (f) V-VI (g)	4.9-5.5 (f) 4.3-4.9 (g)	4.5-5.0 (f) 4.0-4.5 (g)	4.3-5.0 (f) 3.6-4.3 (g)	4.6-5.2 (f) 4.0-4.6 (g)	- -	4.8
5. Bowstring	1928	23 Dec	00h10m	47°32.5'	93°47.6' (c)	- - -	III (g)	3.1 (g)	3.0 (g)	2.1 (g)	2.7 (g)	- -	3.1
6. Detroit Lakes (Audubon)	1939	28 Jan	11h55m	46°52.0'	95°59.0' (b)	8,000 (j) (3,000)	IV (f,g)	3.7 (f,g)	3.5 (f,g)	2.8 (f,g)	3.3 (f,g)	- -	3.7
7. Alexandria	1950	15 Feb	04h05m	45°58'	95°22' (b)	- - -	V-VI (g)	4.3-4.9 (g)	4.0-4.5 (g)	3.6-4.3 (g)	4.0-4.6 (g)	- -	3.8
8. Pipestone	1964	28 Sep	- - -	44.0°	96.4° (d)	- - -	- - -	- - -	- - -	- - -	- - -	3.4	3.4
9. Morris	1975	9 Jul	8h54m15.1s	45°39.0'	96°05.0' (b)	82,000 (e) (31,500)	VI (e)	4.9 (c)	4.5 (c)	4.3 (c)	4.6 (c)	4.6	4.6
10. Sauk Centre (West Union)	1979	5 Mar	6h27m56.1s	45°47'	95°08'	- - -	- - -	- - -	- - -	- - -	- - -	2.6	2.6

(a) For Coordinated Universal Time, add 6 hours.
(b) Relocation as described in text.
(c) Location refers to designated town.
(d) Teleseismic location.
(e) Source: U.S. Geological Survey (Stover and others, 1977).
(f) Source: Docekal (1970)
(g) Source: Leeds (1970)
(h) See Appendix A for explanation of magnitude calculations.
(j) My estimate based upon all available data.

Figure 2--Location map for Minnesota earthquakes. Diamonds represent earthquake epicenters.

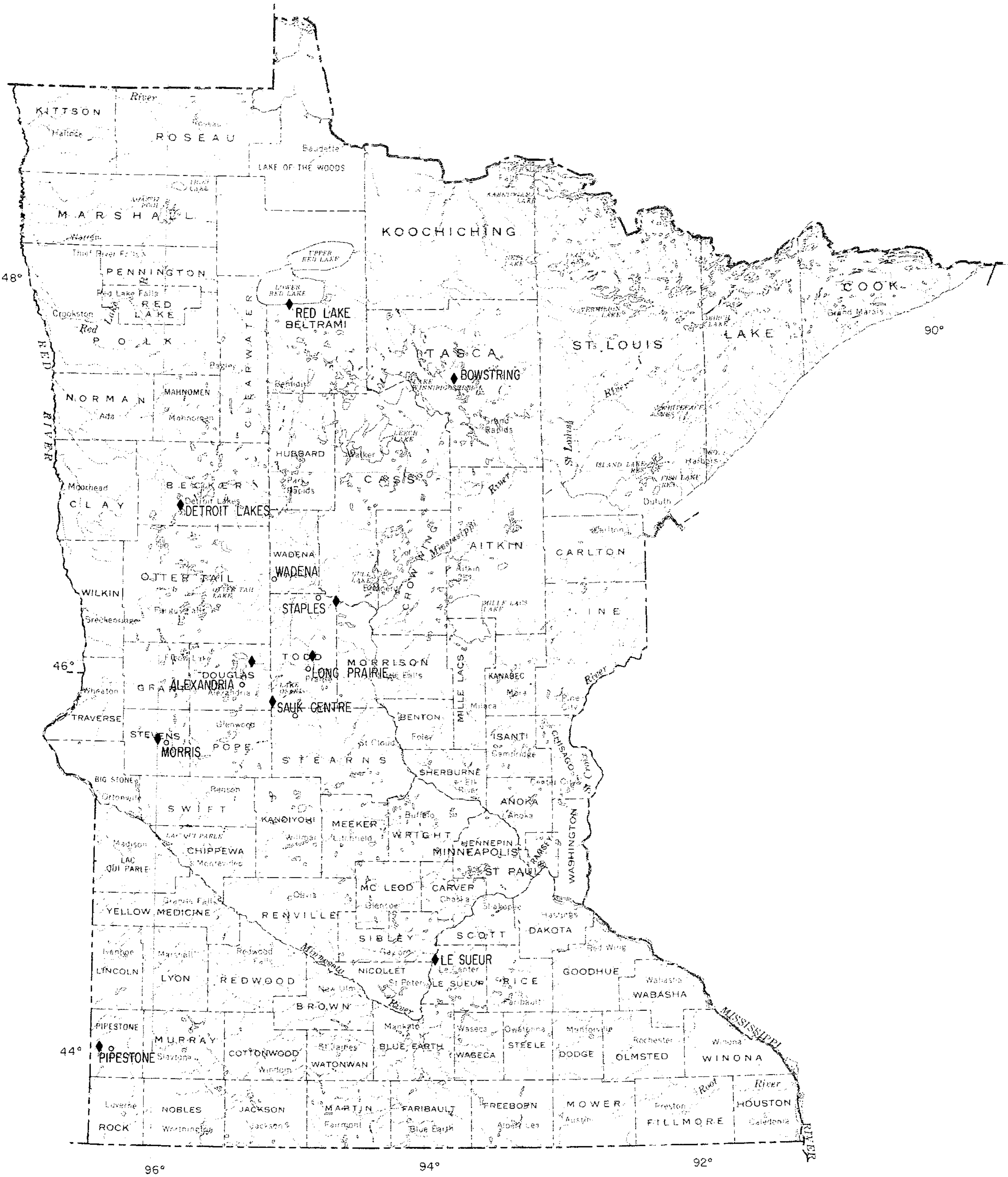

Figure 2--Location map for Minnesota earthquakes. Diamonds represent earthquake epicenters.

INDIVIDUAL EARTHQUAKES

Long Prairie, 1860-1861

Documentation for the Long Prairie earthquake first appeared at the time of the 1917 Staples (Motley) event, and is based principally upon the testimony of an old settler, Hon. William E. Lee. Lee is referred to by Warren Upham (1917), archaeologist of the Minnesota Historical Society, as the "most prominent citizen of Long Prairie." Lee is quoted by the St. Paul Pioneer Press of 9 September 1917 as writing to Upham: "I lived at Long Prairie before the Civil War and we had an earthquake shock at that time. I was a small boy but remember it very distinctly; it was either in 1860 or 1861. It was the subject of general talk in this locality at the time and I have no doubt there are other old settlers who may recall it."

Lee is further quoted by the Long Prairie Leader of 6 September 1917 as saying with reference to the 1917 event that "the vicinity experienced a harder shock in 1860, one that would have done damage had the country been more thickly settled at that time."

Long Prairie is 45 km (28 miles) south-southwest of Motley, the epicenter of the 3 September 1917 event, and registered an intensity of IV for that earthquake. I have moved the epicenter of the Long Prairie event one third of the distance from Long Prairie toward Motley (15 km or 9 miles) on the basis of the following considerations: (1) Low population density in 1860 leaves considerable uncertainty as to the epicenter. (2) The shaking at Long Prairie was reported to have been stronger in 1860 than in 1917, which if true implies that the 1860 event was closer to Long Prairie, or larger, or both. (3) If we move the epicenter away from Long Prairie at all, then a plausible direction is toward the 1917 event.

Le Sueur, 1865-1870

Upham (1917) reports a letter from Ora J. Parker, "a well known attorney of Le Sueur," occasioned by the 1917 Staples (Motley) earthquake. As quoted in the St. Paul Pioneer Press of 9 September 1917: "A definite earthquake shock did occur in Minnesota prior to the year 1870 and it was distinctly felt by myself and others at Le Sueur. I do not remember the date exactly, except that it was between 1865 and 1870. It was on Sunday in the afternoon and I remember that a man who was lying on the floor in the house at the time sprang to his feet in astonishment when he felt the shock. There was talk generally the next day of the shock."

Docekal (1970) argues that because the earthquake "furnished a topic of conversation for many days," it must have had an intensity of at least V. He considers the possibility that this event was so large (intensity VI-VII) that it could have been the same earthquake as the 1860 Long Prairie event, as the years for both are uncertain but approximately the same. I regard this as improbable because Long Prairie is 180 km (112 miles) north-northwest of Le Sueur, and any event severe enough to be felt at both places should have been felt at many locations between. Posey (1917) reached the same conclusion. I therefore question Docekal's conclusion that "the Le Sueur earthquake would rank as perhaps one of the strongest earthquakes in the northern extension of the Midcontinent Seismic Trend."

Red Lake, 6 February 1917

Information for this event comes from U.S. Weather Bureau (1917a, 1917b, 1917c, 1918). One shock with a duration of about 1 minute was reported, accompanied by a rumbling sound. A Rossi-Forel intensity of 4 was assigned to it.

The location of the felt report is not given and the two Red Lakes are 32 km (20 miles) across. I have placed the epicenter along the more populated south shore.

Staples (Motley), 3 September 1917

This event is generally referred to as the Staples earthquake, but I have relocated the epicenter 11 km (7 miles) farther east and prefer to associate it with the town of Motley.

Upham (1917) reported on 19 October 1917 to the Seismological Society of America:

> "On September 3 (1917) at 3:30 p.m. a quake was felt upon a considerable area of central Minnesota, probably perceptibly affecting fully 10,000 or even 20,000 square miles, that is, about an eighth or a quarter of the whole state. It was most severe at Staples, a railway village and junction in the north edge of Todd county, where the shocks lasted more than 20 seconds; goods on shelves in stores were knocked down, and many windows were broken, chimneys toppled over, and concrete walks were cracked. At very closely the same time it was sensibly felt in Little Falls, Brainerd,

and St. Cloud, but with little damage. In Minneapolis, 120 miles southeast from Staples, a few people noticed the shock; also about 3:30 p.m., houses trembled, pictures on the wall shook, curtains moved, and the windows rattled, and boys playing in a park 'felt the ground wiggle.'"

Felt reports are provided in Table 2. Figure 3 shows an isoseismal contour map constructed from these data. The epicentral relocation noted above is based upon this figure. Up to Intensity VI, Rossi-Forel intensities are equal to or slightly greater than the standard Modified Mercalli intensities.

Docekal (1970) argues that the intensity value of VI preferred by other authors is too low, and that the lower range of VII was reached. I find this hard to reconcile with the Modified Mercalli Intensity scale reproduced in Appendix B, and prefer to retain the value of VI. Docekal notes that the magnitude may be lower than is normally associated with this intensity value, because the highest intensities occur for unconsolidated materials in the preglacial valleys of the Mississippi and Crow Wing Rivers.

Posey (1917) estimates a felt area of 26,000 square km (10,000 square miles). Docekal (1970) increases this to 48,000 square km (18,500 square miles) but bases the revision on a single felt report near Minneapolis, 182 km (114 miles) southeast. The Staples World of 4 September 1917 cites a felt report at International Falls, 265 km (165 miles) north-northeast. Felt areas of 26,000 and 48,000 square km would correspond to radii of 91 km (57 miles) and 124 km (77 miles), respectively. I feel that Docekal's estimate is plausible, considering the lack of population in northern Minnesota in 1917.

Earthquake effects included cracked walls, broken windows, and falling chimneys. The Minneapolis Tribune of 4 September 1917 notes that "many windows and chimneys were broken at Staples as well as at Brainerd, Little Falls, and other places." A crack appeared in the concrete floor of the vault of the city clerk's office in Staples. As reported in Table 2, windows, stoves, and dishes rattled, and goods were shaken off the shelves.

Table 2--Felt reports for Staples (Motley) earthquake, 3 September 1917 (U.S. Weather Bureau, 1917b).

SECTION V.—SEISMOLOGY.

SEISMOLOGICAL REPORTS FOR SEPTMBER, 1917.

W. J. HUMPHREYS, Professor in Charge.

[Dated: Weather Bureau, Washington, D. C., Nov. 2, 1917.]

TABLE 1.—*Noninstrumental earthquake reports, September, 1917.*

Day.	Approximate time, Greenwich Civil.	Station.	Approximate latitude.	Approximate longitude.	Intensity Rossi-Forel.	Number of shocks.	Duration.	Sounds.	Remarks.	Observer.
		MINNESOTA.								
3	21 28	Aldrich	46 23	94 53	5	1	1	Rumbling		Nettie Hansen.
		Alexandria	45 53	95 20	3	1				P. O. Unumb.
		Brainerd	46 21	94 08	5-6	3	7	Rumbling	Bricks fell from chimneys	J. A. Hoffman.
		Crosby	46 30	93 51	4	1	5	do		E. B. Brown.
		Crow Wing	46 17	94 15		1		do		Martin Berggreen.
		Eagle Bend	46 10	95 00	4-5	1	20	do		W. J. Sorff.
		Fort Ripley	46 09	94 17		1		do		C. A. Tucker.
		Henning	46 20	95 23	3-4			Faint	Dishes jarred	Louise von Ohlen.
		Grant	46 37	94 33	5	1	20	Rumbling		E. M. Hinch.
		Gull Lake Dam	46 27	94 16	4-5	1	10	do		A. L. Wampel.
		Jenkins	46 38	94 17	4-5	1			Shook buildings	O. B. Whitney.
		Leader	46 30	94 36	5	1	5	Rumbling	Windows and stoves rattled	O. A. Olsen.
		Lincoln	46 13	94 37	6	1		do	Plaster cracked	H. H. Craighead.
		Long Prairie	45 58	94 50	3	1		None		L. E. Stalicop.
		McGregor	46 37	93 16	3	1	2	Rumbling		Elmer Hallberg.
		Merrifield	46 30	94 06	3	1	6	do		Quin Parker.
		Milaca	45 44	93 38	3				Dishes rattled	Esther Riesland.
		Minneapolis	44 59	93 18	2-3	1	10	None		A. E. Houstario.
		Motley	46 20	94 36	5	1	25	Rumbling		E. G. Haymaker.
		Onamia	46 04	93 38	3			do		Henry Gonlet.
		Parkers Prairie	46 10	95 16	5	1	20	do		Aaron Lundblad.
		Philbrook	46 18	94 40	5	2		do		J. W. Winsot.
		Pierz	45 58	94 02	3	1		do		C. E. Gravel.
		Pillager	46 20	94 24	5	2	20	do		J. C. Peterson.
		Pine River Dam	46 42	94 23						H. F. Leider.
		Pequot	46 37	94 16	4-5	3	6	Rumbling	Goods shaken off shelf	A. R. Holman.
		Sauk Center	45 47	94 57	3	1	6			Dr. A. L. Blix.
		Staples	46 22	94 45	6	1	10	Rumbling	Walls cracked	R. Arundel.
		Sylvan	46 21	94 22	5			do		
		Verndale	46 24	94 59		1		do		Lewis Bradford.
		Wadena	46 27	95 06				do		Postmaster.

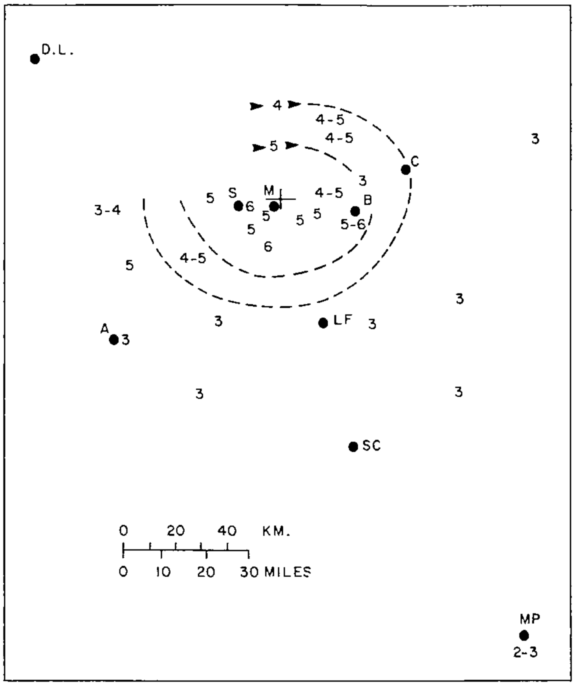

Figure 3--Isoseismal map for Staples earthquake, 3 September 1917, constructed from data of Table 2. City abbreviations: A - Alexandria, B - Brainerd, C - Crosby, DL - Detroit Lakes, LF - Little Falls, M - Motley, MP - Minneapolis, SC - St. Cloud, S - Staples.

Table 2 indicates nearly universal observation of rumbling sounds. The newspaper clipping in Figure 4 likens this to the roar of a passing heavy truck. It notes also that the shock was felt by people in boats on a lake. Durations up to 20 seconds were reported.

Bowstring, 23 December 1928

A small shock was reported (Heck and Bodle, 1930) in which a house seemed to sway in an east-west direction. They place the epicenter at 47.4° N., 94.0° W., but if the felt report originated in Bowstring, the correct coordinates will be those given in Table 1.

Detroit Lakes (Audubon), 28 January 1939

Bodle (1941) reports that a shock with maximum intensity of IV occurred near Detroit Lakes and was felt over an "area with radius of 80 km" (50 miles).

The event received front page newspaper coverage for the 2 February 1939 issues of the Detroit Lakes Record, the Detroit Lakes Tribune, the Frazee Press, and the Lake Park Journal. Many felt reports were received from Detroit Lakes, Frazee (15 km ESE), Audubon (15 km WNW), Lake Park (25 km WNW), Lake Eunice (15 km WSW), and Vergas (18 km S). The strongest felt reports appear to have been in Audubon, where the telephone exchange was "swamped" with calls. I have therefore placed the epicenter at Audubon. These towns define a circle with radius of about 30 km. If we add isolated felt reports from outlying areas, a radius of 50 km (30 miles) seems more likely than Bodle's figure noted above.

The newspaper reports agreed that the sensation consisted of a deep rumble (like a "truck collision" or "a train going over a bridge") followed by a weak tremor which lasted for 5-15 seconds. Dishes and windows rattled, a wood pile collapsed, and large cracks in the lake ice reportedly opened. According to the superintendent of the Sand Beach sanatorium near Lake Park, "the entire building shook violently and dietitians in the kitchen reported that dishes rattled in the pans and they feared the floors would crack."

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 Ft. 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 4--Newspaper report from Little Falls Daily Transcript, 4 September 1917.

Alexandria, 15 February 1950

Murphy and Cloud (1952) report that "a sharp shock accompanied by a muffled boom awakened residents (of Alexandria) and startled night workers. Two 136-foot wells at the Land o' Lakes Creamery were damaged."

The most extensive newspaper item appeared in the Park Region Echo for 15 February 1950. It reports "At 4:05 a.m. Wednesday buildings in an area from Alexandria to Wadena shook under the impact of a mysterious force. Simultaneously, a muffled boom woke light sleepers of the community and startled the night workers on duty at that time." Numerous felt reports described sensations like a heavy truck passing by, "only more violent," a loud low-frequency noise, and the rocking of buildings.

Placement of the epicenter is complicated due to conflicting reports with respect to Wadena, which lies 65 km (40 miles) north-northeast of Alexandria. The principal felt reports come from Alexandria. The evidence for Wadena appears to derive from the Wadena telephone operator who, when queried by the Alexandria operator "about 5 o'clock," said that "a tremor had occurred there about 15 minutes before." This would conflict with the reported time of 4:05. Further, a search of the weekly Wadena Pioneer Journal for 16 and 23 February found no mention of an earthquake. Murphy and Cloud (op. cit.) do not mention Wadena. The newspaper report cited above does mention that an individual living 5 km north of Alexandria was awakened from sleep, and the Park Region Echo for 21 February 1950 mentions that felt reports were received "from Alexandria north to Wadena".

On the basis of this evidence, I have placed the epicenter slightly north of Alexandria toward Wadena, say 10 km, but much closer to Alexandria. This differs slightly from Docekal's (1970) epicenter 30 km north and 10 km east of Alexandria, based upon evidence which is not clear from his text.

Pipestone, 28 September 1964

The original reference for this event has been lost and cannot be reconfirmed. The event was located instrumentally. The location (44.0° N., 96.4° W.) places the epicenter 6 km (4 miles) due west of Pipestone, Minnesota, and 4 km (2-1/2 miles) east of the Minnesota-South Dakota border. No felt reports exist.

Morris, 9 July 1975

This earthquake occurred about 17 km (10 miles) west-northwest of Morris at a depth of 5-10 km (3-6 miles). It is by far the best documented earthquake in Minnesota history, and possibly the largest. Thousands of people in at least four states felt vibrations from it. Dozens of seismic stations throughout North America, from the Pacific to the Atlantic Ocean and from the Arctic Ocean to the Gulf of Mexico, recorded seismic waves produced by it. A portable array of six seismometers was deployed at the epicenter within 36 hours by the U.S. Geological Survey, but no aftershocks were detected over a two-week recording interval. Nearly 200 written or oral felt reports were received by the University of Minnesota in response to newspaper advertisements. Table 3 is a summary of these felt reports.

A maximum intensity value of VI has been assigned to several locations in and near Morris. The reported damage (tbl. 3) included cracked building and basement walls, falling objects, damaged chimneys, and at least one cracked window. An investigating team observed small earth cracks, but these could not with certainty be attributed to the shock. A dominant theme in the 200 felt reports was rumbling, as of heavy trucks passing or of construction machinery. Two reports were received of slight injury, but these were self-inflicted (one man fell off a hayrack in his excitement).

The Morris earthquake was well recorded by earthquake seismographs throughout the United States and Canada, from at least as far as California and British Columbia on the west, Yellowknife on the north, Newfoundland on the east, and Alabama on the south. Seventy records were collected and read, and many more exist. The closest usable stations were Thunder Bay, Ontario (5.51°; 612 km; 383 miles) and Milwaukee (6.45°; 716 km; 448 miles). The most distant usable stations were St. John's, Newfoundland (29.64°; 3293 km; 2058 miles), Resolute, Northwest Territories (29.21°; 3243 km; 2026 miles), and Alert, Northwest Territories (38.51°; 4275 km; 2672 miles).

Three hypocentral locations for the Morris earthquake are given in Table 4. A composite value would place the epicenter at 45°39' N., 96°05' W., about 17 km (10 miles) from Morris in a west-northwest direction.

Table 3--Felt reports for Morris earthquake, 9 July 1975.

INT. VI IN MINNESOTA

Alberta.--Felt by all; frightened many. KMRS Radio Station reported cracks in church basement and parsonage of Church of the Nazarene; inside foundation damage 8 km south of Alberta. Damage slight.

Chokio.--Felt by and awakened many. KMRS Radio Station reported chimney damage, widening of basement cracks, and cracks in wall of new building. Loud earth noises. Small objects fell. Damage slight.

Glenwood.--Felt by many; frightened few. "Four basements cracked."

Kent.--Felt by many; frightened few. "Two basements cracked." Small objects moved on cupboard shelves.

Morris.--Felt by many. KMRS Radio Station reported cracks in basement walls, crack in foundation, and minor plaster cracks. "About 11 km south of Morris on Highway 59, several cracks appeared on north end of the Apostolic Christian Church."

Wheaton.--Felt by many; frightened few. Basements and foundations cracked; window and chimney cracked.

INT. V IN MINNESOTA

Appleton, Barnesville, Barrett, Barry, Beardsley, Benson, Brandon, Brooten, Browns Valley, Campbell, Canby, Clara City, Clinton, Clontarf, Collegeville, Cottonwood, Cyrus, Danvers, Dawson, De Graff, Donnelly, Dumont, Elbow Lake, Fergus Falls, Graceville, Grey Eagle, Hancock, Herman, Hoffman, Holdingford, Holloway, Holmes City, Johnson, Little Falls, Louisburg, Madison, Maynard, Milan, Montevideo, Murdock (well-water muddied), Nassau, Nelson, Norcross, Odessa, Ortonville, Paynesville, Perham, Rothsay, Sartell, Tenney, Tintah, Upsala, and Watson.

INT. V IN NORTH DAKOTA

Abercrombie, Cayuga, Christine, Cogswell, Geneseo, Hankinson, Lidgerwood, and Mantador.

INT. V IN SOUTH DAKOTA

Big Stone City, Bryant, Claire City, Corona, Langford, Milbank, Revillo, Rosholt, Sisseton, South Shore, Stockholm, Twin Brooks, and Wilmot.

INT. IV IN IOWA

Sioux City.

INT. IV IN MINNESOTA

Albany, Alexandria, Ashby, Audubon, Avon, Battle Lake, Bellingham, Bluffton, Brainerd, Carlos, Clitherall, Comstock, Corona, Correll, Danube, Deer Creek, Doran, Elrosa, Erhard, Farwell, Foxhome, Freeport, Garfield, Grove City, Hanley Falls, Hawley, Hazel Run, Henning, Hewitt, Kensington, Kerkhoven, Lake Lillian, Litchfield, Lowry, Long Prairie, Marietta, Marshall, Melrose, Motley, New London, New Munich, New York Mills, North Redwood, Olivia, Ottertail, Pillager, Porter, Raymond, Richwood, Sabin, Sacred Heart, Sebeka, Sedan, Staples, Starbuck, Vining, Wabasso, Wadena, Wendell, and Willmar.

INT. IV IN NORTH DAKOTA

Absaraka, Chaffee, Colfax, De Lamere, Dwight, Fairmount, Fingal, Gwinner, Havana, Horace, Leonard, Lisbon, Mapleton, McLeod, Mooreton, Oriska, Wahpeton, and Wyndmere.

INT. IV IN SOUTH DAKOTA

Aberdeen, Bancroft, Eden, Gary, Hazel, Iroquois, New Effington, Ortley, Peever, Strandburg, Stratford, Summit, Tulare, Turton, Veblen, and White Rock.

INT. III IN MINNESOTA

Baker, Bertha, Browerville, Eagle Bend, Georgetown, Hector, Hitterdal, Mankato, Melby, Menahga, Minneapolis, Moorhead, Morton, Prinsburg, St. Cloud, Sunburg, Svea, Swanville, Ulen, Vergas, Villard, and Wood Lake.

INT. III IN NORTH DAKOTA

Barney Gardner, Harwood, Rutland, Sheldon, Stirum, and West Fargo.

INT. III IN SOUTH DAKOTA

Albee, Amherst, Conde, Elkpoint, Erwin, Florence, Garden City, La Bolt, Lake Norden, Lily, Mansfield, Pierpont, Verdon, and Watertown.

INT. II IN MINNESOTA

Battle Lake, Belgrade, Belview, Boyd, Callaway, Clarissa, Dent, Detroit Lakes, Dilworth, Evansville, Frazee, Garrison, Greenbush, Little Sauk, Milroy, Miltona, Morgan, Parkers Prairie, St. Paul, Vesta, and Walnut Grove.

Table 3--continued.

INT. II IN NORTH DAKOTA

Davenport, Fargo (press), Forbes, Great Bend, Hickson, Milnor, Page, Valley City, and Verona.

INT. II IN SOUTH DAKOTA

Aberdeen, Athol, Bradley, Davis, De Smet, Frankfort, Marvin, Millbank (press), Oldham, and Sioux Falls (press).

Table 4--Hypocenters for Morris earthquake, 9 July 1975.

	U.S.G.S.[1]	Zollweg[2]	Herrmann[3]
Latitude, north	45°39.8'	45°34.8[1]	45°42'
Longitude, west	96°05.7'	96°10.2'	96°00'
Distance north of Morris	8.6 km (5.4 miles)	-0.5 km (-0.3 miles)	12.8 km (8.0 miles)
Distance west of Morris	14.0 km (8.7 miles)	19.9 km (12.3 miles)	6.7 km (4.2 miles)
Distance from Morris	16.4 km (10.3 miles)	19.9 km (12.3 miles)	14.4 km (9.0 miles)
Hypocentral depth, assumed	10 km	5 km	7.5 km

1 Stover and others (1977).
2 J. Zollweg, written communication, 3 February, 1977.
3 Herrmann (1979).

Herrmann (1979) cites the following source parameters for the earthquake, based upon an analysis of surface waves:

Tension axis: trend 283°, plunge 14°
Pressure axis: trend 17°, plunge 14°
Seismic moment: $M_o = 3.2 \times 10^{22}$ dyne-cm

These correspond to two possible focal planes:

1) Strike 60°E., Dip 70° SE.
2) Strike 150°E., Dip vertical

The seismic data do not permit choosing between them, but P.K. Sims (1978, oral communication) strongly supports solution 1 from geologic considerations.

The felt area was reported by the U.S. Geological Survey (Stover and others, 1977) to cover approximately 82,000 square km (31,500 square miles). This includes portions of northern Iowa, western Minnesota, eastern South Dakota, and southeastern North Dakota.

Figure 5 shows an isoseismal map for the earthquake. The details of Figure 5 should be reliable, as the population in the region is well distributed and the data base in terms of number of reports is quite large. In broad outline the contours are circular, but in detail trends can be noted in directions north-northwest and east-northeast. The latter is particularly strong, with an outlier of intensity V and a lobe of intensity IV near Brainerd, the epicenter of the 3 September 1917 earthquake. The east-northeast direction coincides with a major tectonic hinge line (fig. 6).

Sauk Centre (West Union), 5 March 1979

A very small earthquake was well recorded by the Central Minnesota Seismic Array (CMSA) with origin time 6h27m56.1s CST. Azimuthal direction from CMSA was very well determined (at 267.5±2°), and distance was fairly well determined at 151.0±10 km. This places it between Alexandria and Sauk Centre, near the town of West Union. Epicentral coordinates are given in Table 1. Magnitude is estimated at 2.6. No felt reports exist.

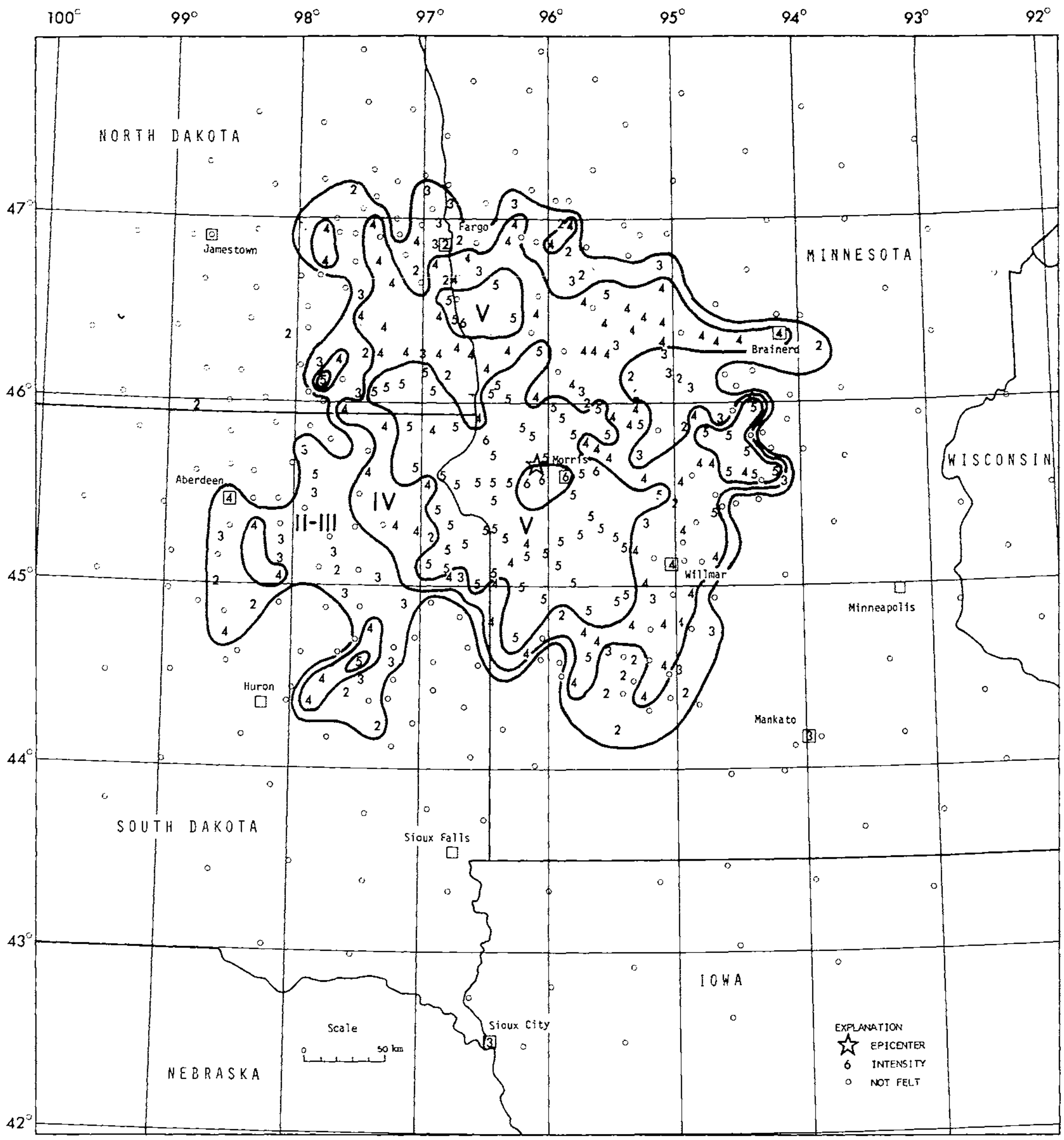

Figure 5--Isoseismal map for Morris earthquake, 9 July 1975 (reproduced with permission from Stover and others, 1977).

GEOLOGIC SETTING

Figure 6 shows the earthquake epicenters on a map of bedrock geology for Minnesota. A striking correlation appears between the locations of the events at Long Prairie, Staples, Alexandria, Morris, and Sauk Centre and a hypothesized northeast-trending boundary between two contrasting Early Precambrian terranes. This boundary is believed to be marked by a major fault in central Minnesota for which the name Morris fault is being proposed by the Minnesota Geological Survey.

North of the boundary all of the Precambrian rocks belong to the so-called greenstone-granite terrane (Morey and Sims, 1976). This terrane is characterized by northeast-trending belts of complexly folded, steeply dipping greenstone pillow lavas and other low-grade metamorphic rocks of volcanic derivation invaded by elongated granitic plutons. A large number of isotopic ages on a variety of these rocks all fall in the range of 2.7±0.5 billion years.

South of the boundary all of the Precambrian rocks are assigned to the so-called gneiss terrane (Morey and Sims, 1976). This terrane is characterized by high-grade feldspathic to amphibolitic gneiss that shows evidence of repeated strong deformation and metamorphism over a long period of time. The oldest components of the gneiss give isotopic ages of 3.5 to

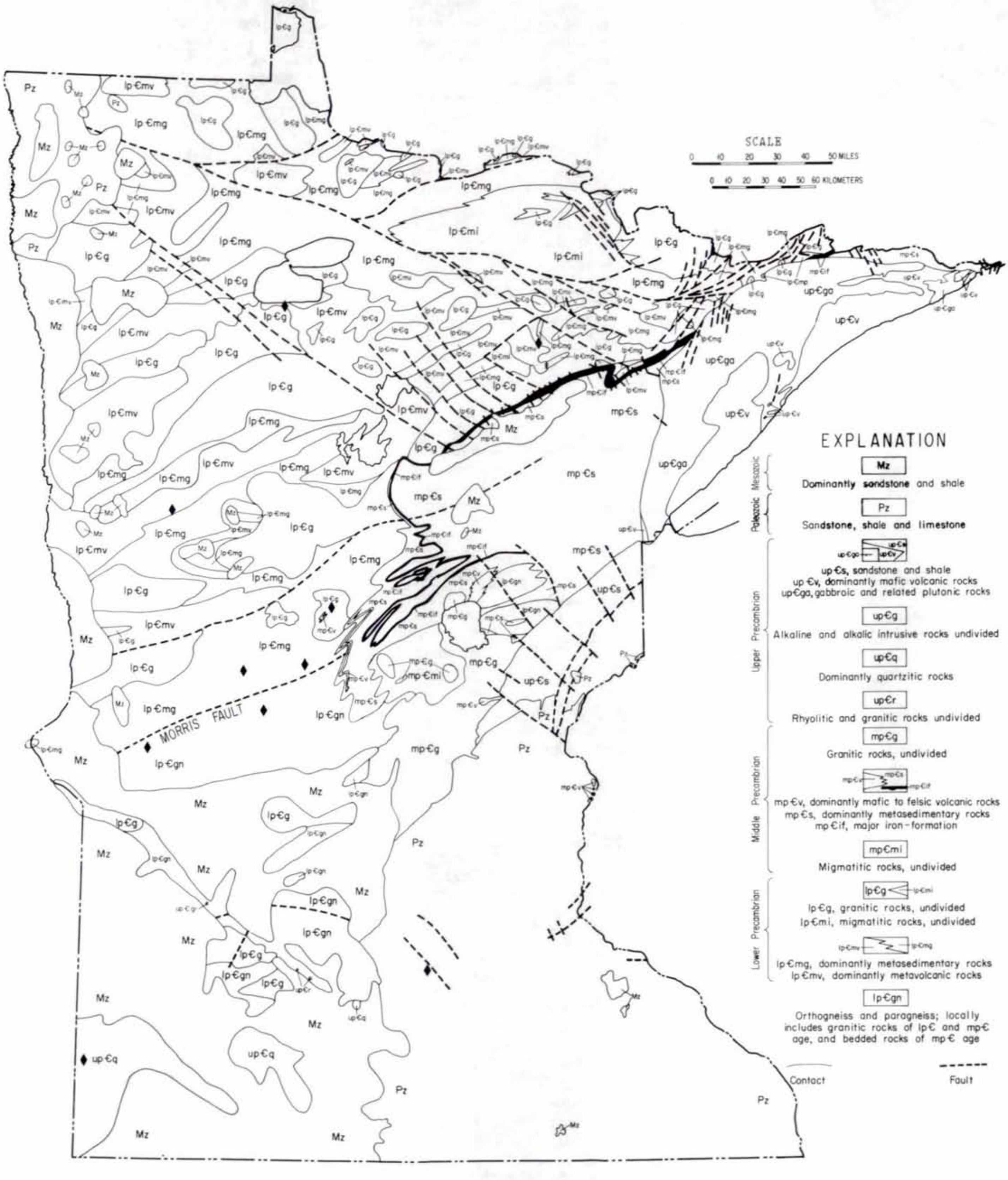

Figure 6--Bedrock geologic map of Minnesota showing earthquake locations. Diamonds represent earthquake epicenters. Modified from Morey (1978).

3.6 billion years. The gneiss was invaded by granitic plutons at about 2.5 billion years, 1.8 billion years and 1.7 billion years.

To the east, the boundary between the two terranes disappears under Middle Precambrian supracrustal rocks that lie unconformably on the older rocks. To the west the boundary disappears under Cretaceous sediments, which according to new evidence may be tectonically disturbed near the boundary (Schurr, 1979). It is believed that the boundary is part of a major tectonic feature that extends as far east as the Grenville Front in Ontario. This feature of obvious continental significance is informally referred to as the Great Lakes tectonic zone (Sims and others, 1979).

The suggested correlation depends in part upon the reliability of the earthquake epicenter locations. Two of the epicentral locations (Staples and Morris) are tightly constrained within 5-10 km (3-6 miles). The Alexandria event is less tightly constrained, although the specific damage reports plus sufficient population density in 1950 should limit the uncertainty to 10-20 km (6-12 miles). The Sauk Centre event has about the same uncertainty. The Long Prairie event has greater uncertainty because only a single felt report exists and the population in 1860 was sparse. Nevertheless, it is reasonable to place the epicenter slightly north of Long Prairie with an uncertainty that should not exceed 30 km (18 miles).

Although the epicentral location of the Le Sueur earthquake is poorly constrained, it lies suggestively close to one of several transform faults that define the southwest edge of the St. Croix horst, a northeast-trending block of uplifted basalt in the Midcontinent Rift System of Keweenawan age. The fault lies 18-23 km (11-15 miles) east of the city of Le Sueur. The location for the fault is based upon three test wells between longitudes 93°33' and 93°36' which penetrated basalt at depths between 225 and 258 meters (740 and 846 feet). They thus lie over the St. Croix horst and east of the boundary fault. Seismic lines 75 and 76 of Mooney and others (1970b, fig. 8) showed depth to basalt to exceed 3,000 meters (10,000 feet) at longitudes 93°40' and 93°47', which thus must be west of the boundary fault. Despite this geographic coincidence, however, the Le Sueur earthquake cannot be firmly related to structures associated with the Midcontinent Rift System.

The Bowstring and Red Lake earthquakes both lie on or near northwest-trending faults which cut rocks of Lower and Middle Precambrian age. These faults may project southeastward to a major offset in the Keweenawan Rift System and its associated geophysical anomalies just south of Duluth. Sims (1976) has speculated that this is the location of a major Keweenawan transform fault.

The Detroit Lakes and Pipestone events have no association with known faults, although Detroit Lakes lies on a fairly steep magnetic gradient that may be fault related.

EARTHQUAKE RISK

Risk assessment relies largely on earthquake history. The absence of major earthquakes, together with the infrequency of earthquakes in general, implies a low risk level for Minnesota. This statement must be tempered in light of the brief span of the historical record.

Algermissen and Perkins (1976) assigned damage probability for the United States in terms of severity of ground shaking and frequency of occurrence of damaging earthquakes. Minnesota lies outside their lowest contour interval, 0.04g, on their map of "horizontal acceleration in rock with 90 percent probability of not being exceeded in 50 years." It is clear from the map, however, that they relied principally on large events with large felt areas.

The Uniform Building Code of the International Conference of Building Officials rates Minnesota in Seismic Risk Zone 1 (0 = minimum risk, 3 = maximum risk). The State Building Code has amended this to Seismic Risk Zone 0.

Dames and Moore (Leeds, 1970) applied statistical methods to evaluate risk for the Prairie Island (Red Wing) nuclear power plant. They predict Intensity V ground shaking every 2,000 years and Intensity VI shaking every 3,000 years.

The geographic relationship of selected earthquake epicenters to the operating nuclear power plants is given in Table 5. The Monticello plant lies within the probable felt areas of three Minnesota earthquakes. The Prairie Island plant probably lies within the felt area of one Minnesota earthquake, as well as within the felt areas of several earthquakes with epicenters outside of Minnesota, as listed earlier.

We may inquire finally as to the statistical probability of a larger Minnesota earthquake than has occurred over the short

Table 5--Distances from selected events to operating nuclear power plants.

Event (see Table 1)	Magnitude (see Table 1)	Monticello	Prairie Island
Long Prairie, 1860	4.6 (est)	117 km (73 miles)	240 km (150 miles)
Le Sueur, 1870	4.3 (est)	95 km (59 miles)	110 km (69 miles)
Staples, 1917	4.8 (est)	134 km (84 miles)	253 km (158 miles)
Morris, 1975	4.6	184 km (115 miles)	301 km (188 miles)

(120 years) historical record. A useful guide is provided by Chinnery (1979). For three regions in the eastern United States, he investigated the relationship between maximum intensity, I, and the frequency of earthquake occurrence. He found a remarkably constant value of 0.57 for the parameter b in the relationship,

$$\log_{10}N = a - bI.$$

N is the cumulative number of events per year whose intensity equals or exceeds I; a is a parameter describing the level of seismic activity in the region. Chinnery notes that, subject to some plausible assumptions, this value for b is consistent with a widely observed value of b' = 0.95 in the relationship,

$$\log_{10}N' = a' - b'M.$$

N' is the cumulative number of events per year with magnitude between M-1/2 and M+1/2; a' is a parameter describing the level of seismic activity in the region.

The data for Minnesota from Table 1 can be applied to these results. We focus our attention on an east-west band across the central third of Minnesota, where all of the larger earthquakes have occurred. During 120 years, five events produced intensities of VI or greater, yielding

$$a = \log_{10}(5/120) + (0.57)6 = 2.04.$$

Similarly, four events produced magnitudes between 4 and 5, yielding

$$a' = \log_{10}(4/120) + (0.95)(4.5) = 2.80.$$

The equations can be used to make the following very rough estimates:

Maximum intensity	Years between successive earthquakes with this intensity
V	7
VI	25
VII	90
VIII	330

Magnitude	Years between successive earthquakes with this magnitude
4-1/2	30
5	90
5-1/2	265

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ADDENDUM

Subsequent to publication a detailed analysis of seismic records from the Central Minnesota Seismic Array (CMSA) has detected an 11th seismic event which occurred on April 16, 1979. The parameters for this event are as follows:

Origin time:	6h40m16.7s CUT, 16, April 1979
Epicenter:	46°41'48.5" north latitude 95°23'08.4" west longitude 30 km NW of Wadena, Minnesota 40 km ESE of Detroit Lakes, Minnesota near Butler, Ottertail County, Minnesota
Depth:	Presumed shallow
Magnitude	3.0
Distance from CMSA6:	190.0± 5 km
Azimuth from CMSA6:	300.0° ± 5°

ERRATUM

On figure 6, page 13, the location of the Bowstring earthquake, 1928, in northeastern Minnesota is shown approximately 60 kilometers east and 20 kilometers north of the correct location. The correct location, which is near the center of Itasca County, is shown on figure 2, page 5, and also listed as item 5, table 1.

APPENDIX A

EARTHQUAKE MAGNITUDE, EARTHQUAKE INTENSITY, AND SEVERITY OF SHAKING

Two scales are in common use to describe the severity of an earthquake--the Intensity scale and the Magnitude scale.

The Intensity scale measures surface effects in terms of damage to buildings, loss of life, ground breakage, etc. The scale is expressed in Roman numerals from I to XII. Since surface effects will differ from one location to another, any particular earthquake will display several values of intensity. These may be contoured to produce an isoseismal map. A listing of observational criteria for the Intensity scale is provided in Appendix B.

The Magnitude scale provides an indirect measure of energy release from an earthquake as inferred from amplitudes of the observed seismic waves. Any particular earthquake has only one magnitude value. The Magnitude scale is open-ended, but most earthquakes fall within the range of 0 to 8-1/2. The Magnitude scale is often referred to as the Richter scale, in honor of Emeritus Professor Charles F. Richter of the California Institute of Technology.

The Magnitude scale is based upon a logarithmic progression, such that each unit step in the scale represents a tenfold increase in the measured seismic amplitudes and a 31-fold ($10^{1.5}$) increase in energy release. Thus a magnitude-7 earthquake releases 1000 times as much energy as a magnitude-5 earthquake. Magnitude-3 shocks are barely perceptible, magnitude-5 shocks will be disturbing to nearby observers but will not do much damage, and magnitude-7 and above shocks are considered major earthquakes. The largest recorded shocks have magnitude of 8-1/2 to 8-3/4 and occur only once a decade or so worldwide.

Magnitude cannot be related directly to intensity because intensity depends upon depth of the earthquake, density of reporting population, occurrence over land versus over water, etc. Nevertheless, *if* the earthquake is shallow and occurs in a populated area, we might expect general relationships as follows:

Magnitude	Maximum intensity at epicenter
1-2	I
3-4	II-III
4-5	IV-V
6-7	VII-VIII
7-8	IX-X
8+	XI-XII

Several magnitude scales are in more or less common use. These include body-wave magnitude, m_b, surface-wave magnitude, M_S, and a scale used in eastern North America based upon the seismic phase Lg, m_{bL_g} (Nuttli, 1973b). In principle these should all converge to the same magnitude value for a given earthquake, but in practice they may not do so exactly. Results given here will be for m_b unless indicated otherwise.

The estimation of magnitude becomes difficult and imprecise under any of the following conditions: (1) the event is so small as to be outside the recording capabilities of even nearby seismic observatories, (2) the event is relatively small and located at a large distance from most or all observatories, or (3) the event took place prior to the development of modern seismic instrumentation. Except for the events of 28 September 1964, 9 July 1975, and 5 March 1979, one or more of these conditions applies to all of the earthquakes listed in Minnesota. When instrumental data are not available, we are reduced to inferring magnitudes from maximum intensities and/or felt areas. Several formulas have been proposed, as follows:

1. Gutenberg and Richter (1942)
   $m_{b,G\&R} = 1.3 + 0.6\ I_{max}$

2. Hadsell (1968)
   $m_{b,H1} = \frac{1}{2}(I_{max} + 3) \pm 0.6$

3. Hadsell (1968)
   $m_{b,H2} = \log_{10} F + 4 \pm 0.6$
   with F = felt area in 10^3 square miles

4. Aggarwal (1978)
   $m_{b,AGG} = (-0.20 \pm 0.05) + (0.75 \pm 0.03)\ I_{max}$

For specified maximum intensity, the various formulas yield

I_{max}	$M_{b,G\&R}$	$M_{b,H1}$	$M_{b,AGG}$
III	3.10	3.00±0.6	2.05±.14
IV	3.70	3.50±0.6	2.80±.17
V	4.30	4.00±0.6	3.55±.20
VI	4.90	4.50±0.6	4.30±.23
VII	5.50	5.00±0.6	5.05±.26

Aggarwal's formulation would merit preference here because, unlike the others, it is based upon data from eastern North America. He included 42 events ranging from 2.3-7.0 in magnitude, III-X in intensity, and 1-20 km in focal depth. However, his formula yields relatively poor agreement for that one Minnesota event (9 July 1975) for which excellent isoseismal and teleseismic magnitudes are available. The event is assigned m_b = 4.6. With maximum intensity = 6, the three magnitude formulas based upon intensity yield 4.9, 4.5, and 4.3. Closest agreement is provided by the Hadsell formula or else by an average of the three.

Docekal (1970, v. 2, p. vii) rechecked and in many cases recomputed felt areas for earthquakes in his list. A variety of methods have been used for this purpose. Branner and Hansell (1933) determined areas by measuring a circle whose radius extended to the most distant intensity reports. Hadsell (1968) measured the area of the smallest circle which would enclose all of the felt reports.

APPENDIX B

MODIFIED MERCALLI INTENSITY SCALE, 1956 VERSION
(Richter, 1958)

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle--CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments--CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations--CFR.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Line of sight and level distorted. Objects thrown into the air.

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with the conventional Class A, B, C construction).

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.