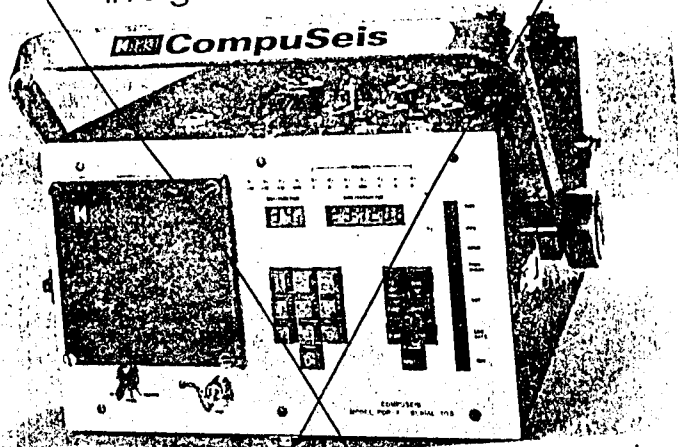


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THE DENVER EARTHQUAKE SEQUENCE OF MARCH-APRIL 1981

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ABSTRACT: The Denver earthquake sequence of March-April 1981 was monitored by a network of four permanent and eight portable seismographs. In addition to the main shock ($m_s = 4.3$) on 2 April, six microaftershocks ($M < 2$) during the subsequent two-week period were recorded and located. Five of those six events had epicenters within the most active area of the 1967-1968 Rocky Mountain Arsenal (RMA) sequence. A composite focal mechanism solution for the main shock and the six aftershocks showed a combination of reverse and strike-slip faulting (14% inconsistency in the 29 P-wave polarities) that is different from the predominantly normal faulting reported for the 1967-1968 RMA sequence. These different focal mechanisms, plus variable water-level response at the RMA well during the earthquake sequence in the 1960's, may suggest the presence of a multiple fracture system in the source volume.

INTRODUCTION

The upper 10-12 km of the crust just north of Denver, Colorado, is a unique seismogenic environment. It is the first site where earthquake activity associated with high-pressure fluid injection into a deep borehole received widespread public and scientific attention. Fluid disposal into the Rocky Mountain Arsenal (RMA) well (3671 m deep) early in 1962 resulted in the triggering of earthquakes shortly thereafter. The seismic activity continued into at least 1968 even though fluid injection into the well had ceased in February 1966. Two recent papers (Herrmann et al., 1981; Hsieh and Bredehoeft, 1981) have reviewed these earlier studies. We note that the seismicity in the RMA locale had decreased to virtually zero energy release by 1974, with a quiescent interval from 1974 to 1978. Next, felt events (magnitudes about 3) occurred in 1978 and 1979 (Stover et al., 1982). Then another quiescent interval lasted until the spring 1981 sequence we discuss herein.

The aforementioned two 1981 studies of the "Denver Earthquakes", as the RMA seismicity came to be termed, attest to the continuing interest in this unique seismogenic zone. Herrmann and his collaborators (1981) conducted several seismological studies. New surface-wave

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data and P-wave first-motion data were interpreted to define northwest-striking, predominantly normal faulting in the focal region. Joint hypocenter relocation of a selected set (103 events) of near-earthquakes was calculated along with theoretical modeling of near-field seismoscope observations. Results from both of those latter two studies were interpreted to support their focal mechanism. Hsieh and Bredehoeft (1981) reported on a modeling analysis of the reservoir characteristics at the RMA. They compared the horizontal distribution of fluid pressure buildup within the reservoir with the spatial distribution of the earthquake epicenters (1962 to 1972). That comparison showed the earthquakes were confined to the portion of the reservoir where the pressure buildup exceeded a critical pressure level of 32 bars. The authors found that the evidence for induced seismicity was "rather conclusive".

The 1981 sequence began with a single foreshock on 24 March ($M_s = 2.8$; U.S. Geological Survey, 1981a) that was felt in the north Denver suburbs (Commerce City, Northglenn, Thornton, Westminster). Portable seismographs were sited in the epicentral area immediately following that event. They showed no additional seismic activity until the main shock ($m_b = 4.3$; U.S. Geological Survey, 1981b) occurred on 2 April. That event was felt (Modified Mercalli intensity VI) throughout the Denver metropolitan area--Boulder, Golden, Castle Rock, Greeley and environs (see U.S. Geological Survey, 1981b, for additional intensity information). Between 2 April and 16 April, several aftershocks were recorded by a network of portable seismographs. The following sections report on that survey.

INSTRUMENTATION AND FIELD PROCEDURE

Following the felt foreshock on 24 March at 13:03:40.0 UTC (6:04am MST), two portable, analog, smoked-paper recording seismographs were installed (stations GAR and URA; see Table 1) and became operational

Table 1. Location and Operation Parameters for the Seismograph Stations Used in the March-April 1981 Earthquake Sequence Study.

Operator	Station	Latitude (deg S)	Longitude (deg W)	Elevation (m)	Period of Operation
USGS	GAR	39°54.48'	104°56.63'	1604	3/24-4/14
USGS	URA	39°52.90'	105°00.75'	1688	3/24-4/05
USGS	BAR	39°54.93'	104°46.15'	1564	4/03-4/16
USGS	THO	39°54.93'	104°55.06'	1585	4/03-4/16
USGS	ARS	39°48.36'	104°52.93'	1586	4/03-4/16
USGS	RAD	39°51.65'	104°45.14'	1632	4/04-4/16
USGS	H2O	39°55.43'	105°00.05'	1606	4/05-4/16
USGS	RIV	39°47.58'	104°57.80'	1566	4/05-4/06
CO School of Mines	GLD	39°45.04'	105°13.28'	1762	Permanent
NEIS(USGS)	GOL	39°42.02'	105°22.27'	2359	Permanent
CIRES(U. of CO)	CIR	40°00.78'	105°15.18'	1650	Permanent
Regis College	DEN	39°47.50'	105°02.00'	1655	Permanent

prior to noon on the same day. Seismograms for those instruments documented that there was no subsequent foreshock activity (station GAR was only about 1.5 km from the eventual epicenter for the main shock on 2 April and URA was approximately 5 km distant). At 16:10:06.3 UTC, the magnitude $m_b = 4.3$ main shock (U.S. Geological Survey, 1981b) occurred (see Figures 1, 2, 3). Three additional portable seismographs were installed on 3 April. On the following day, 4 April, a strong spring blizzard occurred allowing but one additional station (RAD) to be installed. Then, stations H2O and RIV were made operational on 5 April. Thus, the eight smoked-paper seismographs along with four permanent stations (GLD, GOL, CIR, and DEN; see Table 1) provided data for this study (see Figures 1 and 2).

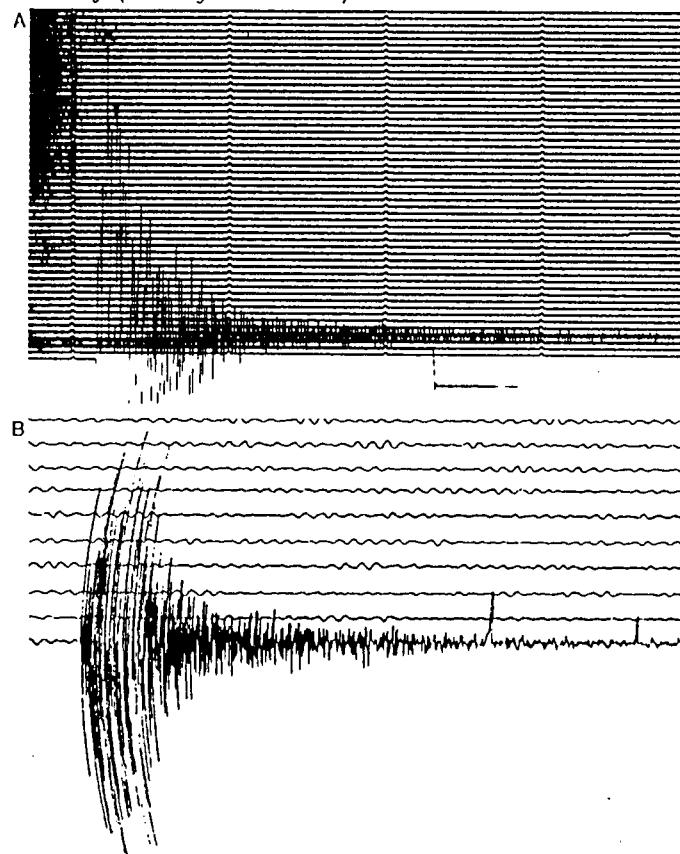


Figure 1. Seismograms for the main shock (2 April 1981; $m_b = 4.3$) from the permanent stations: (A) DEN (trace interruptions = 60 mm = 1 minute on original seismogram; $\Delta = 15.1$ km) and (B) CIR (chronometer malfunction--no time marks; spacing between traces = 5 mm and 1 minute = 30 mm on original seismogram; $\Delta = 27.7$ km). See Table 1 for station coordinates.

DATA REDUCTION AND ANALYSIS

The general criteria used to guide the analysis procedure was that a shock be recorded at a minimum of four stations. Event arrival times were determined with a low-power magnifier and then corrected for small variations in the length between minute marks. S-phases were identified by abrupt changes in amplitude and/or period of seismic signal.

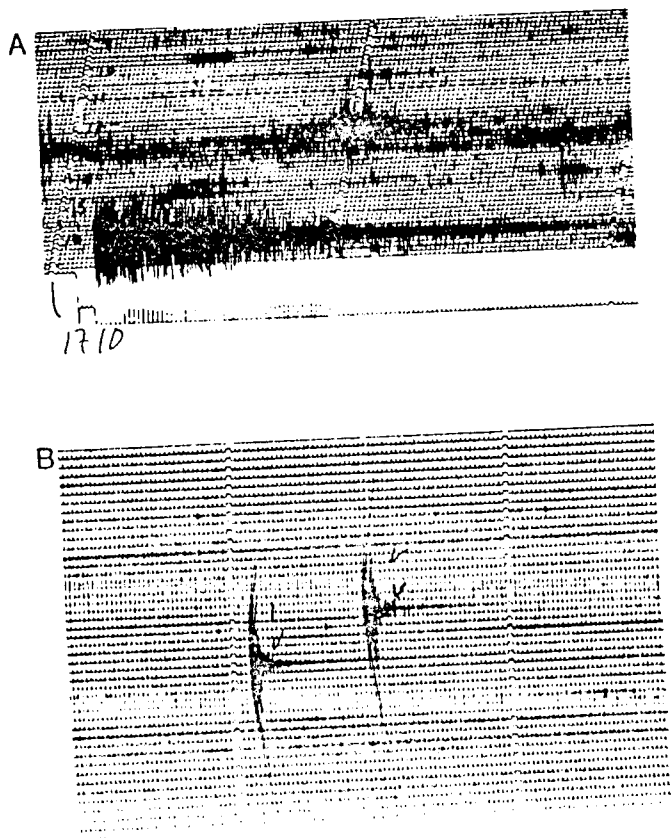


Figure 2. Smoked-paper seismograms for (A) the main shock at station GAR (trace interruptions = 60 mm = 1 minute on original seismogram; $\Delta = 1.1$ km) and (B) two aftershocks (No. 1 (lower) and 2 (upper); see Table 3) with duration magnitudes 1.7 and $\Delta = 7.8$ km and 9.7 km, respectively, at station URA.

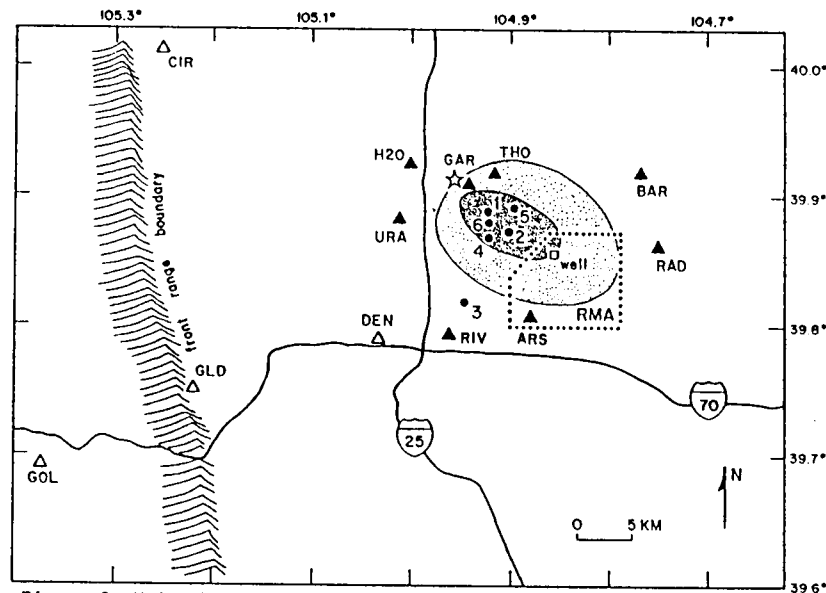


Figure 3. Main shock-aftershock epicenter map. Symbols: star - main shock epicenter; solid dot with number - aftershock epicenter (refer to Table 3); solid triangle with 3-character code - portable (smoked-paper station location (refer to Table 1)); open triangle with 3-letter code - permanent station location; RMA - Rocky Mountain Arsenal, boundary shown with dotted line; open square - injection well at RMA; dark-shaded elliptical area - area containing 70% of the 103 relocated epicenters from the 1967-1968 sequence (Herrmann et al., 1981). Interstate highways 25 and 70 also shown.

Because the peak-to-peak signal amplitudes were electronically clipped, network duration magnitudes, M_{cl} , were estimated from the aftershock coda lengths (Lee et al., 1972). While the formula used does not apply specifically to the area of the aftershocks, it does provide a uniform size classification for the events studied.

For our location of the main shock (Table 3; cf. Table 2), arrival time data from the initial two temporary stations (GAR, URA) and the four permanent stations (GOL, GLD, DEN, CIR) were used. However, because of the aftershocks' low energy levels, only data derived from the six-station temporary network were used in conjunction with the program HYPOELLIPSE (Lahr, 1980). Table 3 lists the aftershock location parameters obtained. Two crustal velocity models were used as necessary. The first was an Arsenal model from Herrmann et al. (1981). That model specified the velocity structure down to a depth of only 15 km (see Table 4). When a more complete (to a depth of 40 km) velocity model was required to locate the main shock, a combination of the Arsenal model and Bucher and Smith's (1971) Colorado Plateau model was employed (see Table 5).

Table 2. National Earthquake Information Service (NEIS) Parameters for the Foreshock and Main Shock of the Denver Earthquake Sequence of March-April 1981.

Day/Month	Origin Time (UTC)	Location (Deg N-Deg W)	Depth (km)	Mag	No. of Stations	Standard Dev (sec)
24 March	13:03:40.0	39.751-104.936	5 ¹	2.8 ²	5	1.1
02 April	16:10:06.3	39.910-104.964	8 ¹	4.3 ³	41	*

¹ Depths fixed ² M_L ³ m_b * Not listed

RESULTS

Figures 3 and 4 and Table 3 present the principal results of this study. In addition to the main shock, we were able to locate six microaftershocks (duration magnitudes less than 2). Figure 3 shows that the five high quality (A and B) epicenters occur in the area where Herrmann *et al.* (1981) found the most dense concentration (70%) of the 1967-1968 activity. The depth range of these five recent events was 3 to 9 km, which also agrees with depths from Herrmann *et al.*'s (1981) relocated results. The other aftershock of the recent series (event number 3) was located outside of the zone described by Herrmann *et al.* (1981). However, it is the smallest locatable event (duration magnitude = 0) and has the poorest location quality (C).

Herrmann *et al.* (1981) also presented focal-mechanism solutions (predominantly normal faulting) for three of the 1967 earthquakes (10 April, 9 August, 27 November). Their solutions for the 9 August and 27 November events were rated very good (A) quality, while the 10 April solution was judged to be of lesser (C) quality. For this study, combining the first motion data from the main shock and the six aftershocks (Figures 3 and 4) yielded a total of 29 P-wave polarities. The graphical focal mechanism solution obtained for that data set was not similar to the normal faulting found for the 1967 earthquake mechanisms. Rather, a combination of strike-slip and reverse fault movements was indicated (Figure 4). The agreement between the polarity data and that solution is good (14% inconsistency; four inconsistencies among the 29 first motions).

Such differences in mechanism imply a rather substantial change in principal stress orientations between the 1967 (near vertical P-axis) and 1981 (near vertical T-axis) earthquake sequences. Three possible explanations for such changes are as follows:

- 1) The 1981 sequence was anomalous and therefore atypical of the in situ stress regime at the RMA,
- 2) The 1981 sequence was not anomalous and represents a return to ambient stress conditions that are perhaps similar to those existing at the RMA prior to the injection of fluids there, or

- 3) There is more than one fracture system present in the source volume and different elements can become active at different times. Interaction between previous seismic energy release episodes and the regional stress patterns would occur in such a situation.

Table 3. Main Shock and Aftershock Parameters for the Denver Earthquake Sequence of March-April 1981. Calculations Used Data from Permanent and Portable Seismograph Stations in the Hypocenter Location Program, HYPOELLIPSE (Lahr, 1980).

Event	Origin Time (UTC) (Mo-Day-Hr:Min:Sec)	Latitude (deg N)	Longitude (deg W)	Depth (km)	M _D	RMS (sec)	QF
Main	04-02-16:10:06.3	39.9135	104.9548	8.7	4.3*	0.14	A
1	04-04-05:38:02.0	39.8737	104.9222	6.7	1.7	0.13	B
2	04-04-04:38:27.4	39.8713	104.9003	2.7	1.7	0.20	B
3	04-05-20:44:47.6	39.8160	104.9495	2.3	0.0	0.16	C
4	04-06-23:14:33.8	39.8678	104.9232	6.1	1.3	0.09	A
5	04-07-06:02:26.7	39.8962	104.8962	6.6	0.6	0.10	A
6	04-07-06:05:10.8	39.8793	104.9197	9.0	1.2	0.10	B

Event	Horizontal (km, deg)	Semi-Axes (km, deg)	Vertical (km)	Semi-Axis (km)	No. Obs.	Gap (deg)
Main	1.2, -5	1.8, -95	1.9		11	190
1	1.0, -108	1.8, -18	3.6		9	121
2	0.8, -32	1.2, -122	2.8		10	109
3	1.1, -57	7.0, 33	6.0		9	135
4	0.5, -46	0.8, 44	2.1		10	160
5	0.8, -85	1.6, 5	2.4		8	119
6	1.2, -71	2.0, 19	3.0		7	147

M_D = Duration magnitude according to Lee *et al.* (1972).

RMS = Root-mean-square error of time residuals in seconds.

QF = Solution quality of error ellipsoid based on length of largest semi-axis (HYPOELLIPSE).

Horizontal Semi-Axes = Lengths (km) and azimuths (deg) of principal axes (horizontal projection) of error ellipsoid (HYPOELLIPSE).

Vertical Semi-Axis = Length (km) of the principal vertical axis of error ellipsoid (HYPOELLIPSE).

No. Obs. = Number of phase arrival times used in the hypocenter determination.

Gap = The largest sector, in degrees, where there were no observing stations (HYPOELLIPSE).

* = m_b Magnitude (U.S. Geological Survey, 1981b).

Table 4. Crustal Velocity Model Used for Locating Aftershocks of the April 2, 1981, Denver Earthquake.

Layer	Velocity (km/sec)	Depth (km)	Thickness (km)
1	2.170	0.000	0.380
2	3.050	0.380	0.820
3	3.220	1.200	1.150
4	4.100	2.350	0.450
5	4.600	2.800	0.150
6	4.870	2.950	0.690
7	5.800	3.640	1.060
8	5.900	4.700	10.300
9	6.000	15.000	1000.000

Table 5. Crustal Velocity Model Used for Locating the Denver Earthquake of April 2, 1981.

Layer	Velocity (km/sec)	Depth (km)	Thickness (km)
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6	4.870	2.950	0.690
7	5.800	3.640	1.060
8	5.900	4.700	10.300
9	6.000	15.000	13.000
10	6.800	27.000	1000.000
11	7.800	40.000	

Obviously, our single focal mechanism does not allow us to choose between these various possibilities or even to know if we have the correct one. However, the presence of a multiple-fracture system (No. 3) is perhaps the more likely because of the variable water-level response of the RMA well observed by R. T. Hurr (USGS, Water Resources Division, Denver, Colorado) and his co-workers. During the earthquake sequence in the late 1960's, Hurr reports (oral communication, 1982) that at least two modes of water-level behavior were noted during various individual shocks of the sequences. Those modes consisted either of the presence or of the absence of an interruption (plateauing) of the general decline in the water level that has followed the cessation of pumping in 1966. Prior to a seismic event, the water-level would plateau. Immediately following the event, the water-level would oscillate rapidly and then return to the ambient decline. The presence of multiple-fracture systems in the reservoir volume was postulated by Hurr and his colleagues to explain these variations. Thus, it may be that the predominantly normal faulting mechanisms in the 1967-1968 sequence were on one set of fractures, while the predominantly reverse fault mechanism of the 1981 sequence was on a different set of fractures.

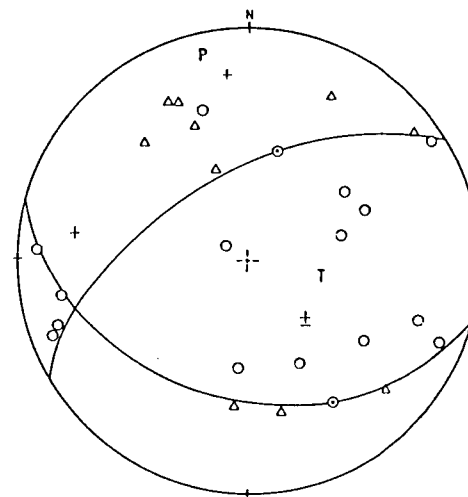


Figure 4. Composite focal mechanism solution (lower hemisphere, equal area) for main shock and the six aftershocks (Table 3). Symbols: open circle - compressions; open triangle - dilatations; (+, -) - plus and minus signs for poor-quality (low signal-to-noise ratio) compressional and dilatational first motions, respectively; open circle with center dot - nodal plane poles; (P, T) - pressure and tension axes; solid-line nodal planes - nodal planes with the following strikes and dips: N58°E, 60°NW and N76°W, 40°SW.

CONCLUSIONS

This study arose because of a rare opportunity. Even though only limited manpower and resources were available during the time of this earthquake sequence, its importance, based on the previous seismic history of the region and the proximity to a highly developed area, warranted the investigation. Our results could have been much more extensive, except for the unfortunate occurrence of a spring blizzard; even so, we feel our results allow the following conclusions:

- 1) The NEIS location for the 2 April main shock has been corroborated (compare Tables 2 and 3).
- 2) The main shock occurred some 10-12 km northwest of the Arsenal well and near the northwestern terminus of a relocated subset of the 1967-1968 cluster of seismic activity.
- 3) The aftershocks occurred principally in the most dense portion of that 1967-1968 cluster of epicenters.

- 4) The mode of faulting was dissimilar (mixed reverse and strike-slip) to that observed during the 1967-1968 activity (predominantly normal) and probably indicates the presence in the source volume of multiple-fracture systems.

REFERENCES

- Bucher, R. L., and R. B. Smith (1971). Crustal structure of the eastern basin and range province and in the northern Colorado Plateau from phase velocities of Rayleigh waves, in The Structure and Physical Properties of the Earth's Crust, Geophysical Monograph Series, 14, J. C. Heacock, ed., American Geophysical Union, Washington, DC, 59-70.
- Herrmann, R. B., Sam-Kuen Park, and Chien-Ying Wang (1981). The Denver earthquakes of 1967-1968, Bull. Seism. Soc. Am., 71, 731-745.
- Hsieh, P. A., and J. D. Bredehoeft (1981). A reservoir analysis of the Denver earthquakes: A case of induced seismicity, J. Geophys. Res., 86, 903-920.
- Lahr, J. C. (1980). HYPOELLIPSE/MULTICS: A computer program for determining local earthquake hypocentral parameters, magnitude, and first-motion pattern, U.S. Geol. Surv. Open-File Rept. 80-59, 59 p.
- Lee, W. H. K., R. E. Bennett, and K. L. Meagher (1972). A method of estimating magnitude of local earthquakes from signal duration, U.S. Geol. Surv. Open-File Rept., 28 p.
- Stover, C. W., G. Reagor, and S. T. Algermissen (1982). Seismicity data for the state of Colorado, unpublished.
- U.S. Geological Survey (1981a). Preliminary determination of epicenters monthly listing, March 1981, National Earthquake Information Service, U.S. Geol. Surv., Golden, Colorado, 10.
- U.S. Geological Survey (1981b). Preliminary determination of epicenters monthly listing, April 1981, National Earthquake Information Service, U.S. Geol. Surv., Golden, Colorado, 2.

SENSITIVITY OF KANSAS MICROEARTHQUAKE NETWORK

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ABSTRACT: This study explores the magnitude-versus-distance sensitivity of the Kansas Geological Survey (KGS) microearthquake network. The ability of each seismograph station to record earthquakes of various magnitudes as a function of epicentral distance is investigated, and a series of magnitude-versus-distance graphs results. The ability of the network to monitor seismic activity in eastern Kansas is excellent to magnitude 1.5 and is sufficient to detect events greater than magnitude 2.3 in western Kansas. Station detection radii for magnitude 1.5 events range from 145 km for the Emporia seismograph station (EMK) to 225 km at Tuttle Creek (TCK); and for a magnitude 2 event, from 245 km at EMK to 385 km at TCK. The sensitivities of the nine seismographs of the network are similar despite their widespread locations across eastern Kansas.

INTRODUCTION

In 1977 and 1978, a network of nine seismograph stations was established in eastern Kansas by the Kansas Geological Survey (KGS) as a means of exploring earthquake activity within the state (Figure 1) and evaluating earthquake risk at existing and proposed sites for dams and nuclear power plants (Steeple, 1978). The funding for this network was provided by the U.S. Nuclear Regulatory Commission (NRC) and by the U.S. Army Corps of Engineers. The station configuration was designed to provide location capability for earthquakes in eastern Kansas of magnitude 1.6 and greater. This paper summarizes the detection and location capability achieved.

GEOLOGICAL SETTING

The KGS seismic network is located in a region of stable tectonic behavior that has a low rate of seismic activity and a presumed low to moderate seismic risk (Steeple et al., 1979). Despite being in the Central Stable Region, several features of geological and geophysical significance are located in Kansas (Figure 1). Nearly 50 percent of the microearthquakes and historical earthquakes in Kansas have occurred along the Nemaha Ridge (a buried Precambrian granitic uplift) and the Humboldt Fault Zone, which forms the eastern boundary of the Nemaha Ridge. Another important structural feature is the Midcontinent Geophysical Anomaly (MGA) which extends from the Lake Superior region southwest to central Kansas and into Oklahoma, and is the largest positive gravity anomaly in North America. The MGA marks a sequence of mafic igneous rocks emplaced along a zone of major late Precambrian