CIRCULAR 143

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Allan R. Sanford
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SOCORRO 1974

First printing, 1974

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63–1–4
Printed by University of New Mexico Printing Plant, April, 1974

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801 Price $1.50

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ABSTRACT

Seismicity was determined for the area within a 300-km radius from the proposed nuclear waste disposal site in southeastern New Mexico. The primary data used to establish seismic risk were: reports of felt shocks prior to 1961; instrumental epicenters and magnitudes from 1961 through 1972; and lengths, displacements, and ages of fault scarps cutting Quaternary geomorphic surfaces. The prinicpal results of this study were: 1) earthquakes exceeding local magnitude 3.5 have not occurred within 40 km of the site in the past 12 years; probably not in the past 50 years, 2) on the average of once every 50,000 years major earthquakes (magnitude 7.8) are possible within 115 km of the site, but these events will produce accelerations of only about 0.07 g at the site; and 3) some evidence indicates that earthquakes located on the Central Basin Platform, 80 to 100 km southeast of the site, could be related to water injection for secondary recovery of oil.

INTRODUCTION

This study was undertaken to determine the seismicity at the proposed radioactive waste disposal site in southeastern New Mexico. The site is centered at lat. 32.41° N. and long. 103.76° W. about 42 km (25 mi) east of Carlsbad. Algermissen's (1969) seismic risk map of the United States, fig. la, indicates that the region around the site has a relatively low Zone 1 seismicity classification. The maximum expected seismic intensities from local or distant shocks in a Zone 1 region is V-VI (modified Mercalli Intensity Scale of 1931, see Appendix 1). On an earlier seismic risk map (fig. lb) Richter (1959) places the Carlsbad region within a seismic zone where the probable maximum intensity is expected to be VIII.

Both of these seismic risk maps are based on essentially the same data. The differences are due to varying interpretations. Most of these data are non-instrumental, simply reports of felt or damaging shocks. Our evaluation of the seismic risk of the region is based not only on the non-instrumental data, but on a substantial amount of instrumental data not available to Richter or Algermissen. In addition, they did not attempt to incorporate geologic evidence of recent crustal movements into their estimates of seismicity. This type of data, accounting for geologic features, especially fault scarps offsetting Quaternary geomorphic surfaces, is essential to accurate estimates of seismic risk over the planned lifetime of the disposal facility

ACKNOWLEDGMENTS

The authors are indebted to the following people and organizations for providing data used in this report: Stuart A. Northrop, Professor Emeritus of the University of New Mexico; Lt. Col. H. E. Wakitsch of AFTAC/VELA Seismological Center; D. H. Shurbet of Texas Tech University; Jerald McIntyre of University of Texas at El Paso;. John Kosovich of Trinidad Junior College; Kenneth Olsen of Los Alamos Scientific Laboratory; and John Hoffman of the Albuquerque Seismological Center (USGS). Omer Alptekin and Mark Dee, graduate assistants at New Mexico Institute of Mining and Technology, assisted the authors on some phases of the research.

This study of the seismicity of the proposed nuclear waste disposal site in southeastern New Mexico was requested and supported by the Oak Ridge National Laboratories under Contract No. AT-(40-1)-4423.

DATA

The seismicity study was restricted to an area within 300 km (180 mi) of the proposed site (fig. 2 on page vi). The basic data collected were: reports of felt shocks prior to January 1, 1961; instrumental locations and magnitudes of earthquakes from January 1, 1961 through December 31, 1972; and locations of fault scarps offsetting Quaternary

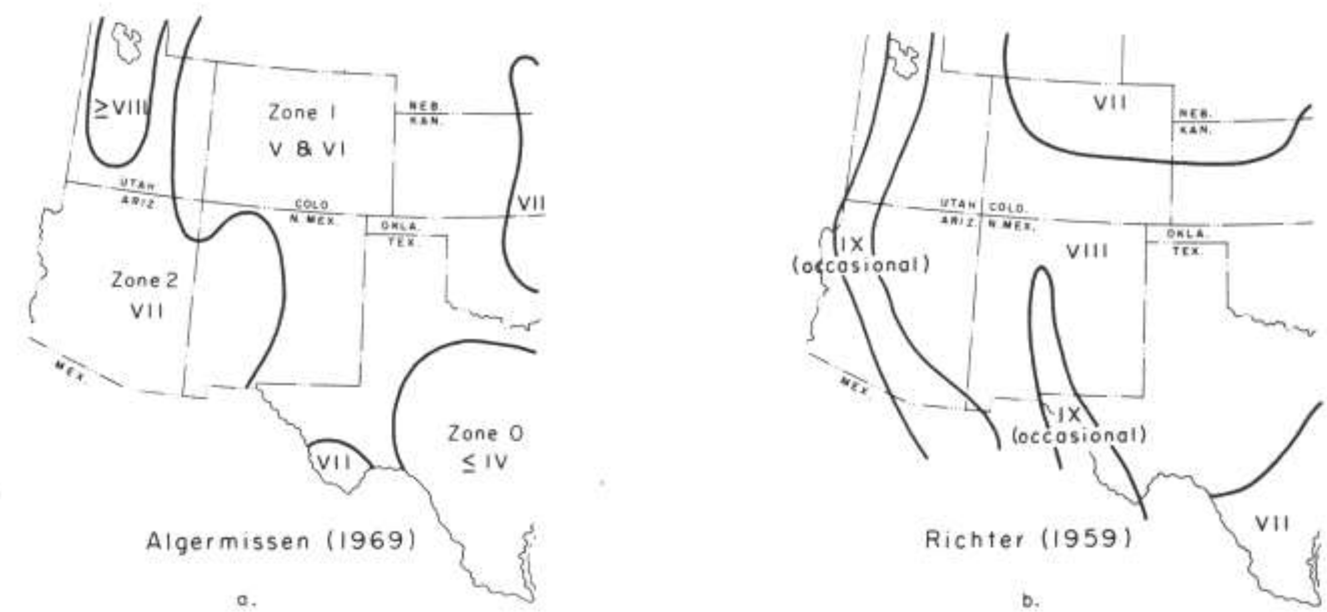

FIGURE 1–*Seismic risk maps for southwestern U.S. (map "a" by Algermissen, 1969, and map "b" by Richter, 1959).*

TABLE 1 – *Reports of felt earthquakes within 300 km of disposal site prior to 1961*

No.	Date Yr/Mo/Day	Time GMT	Location of Max. Reported Intensity	Distance(km) & Direction from Site	Maximum Reported Intensity[1]	References[2]	Remarks
1	1923 Mar 7	04:03	El Paso, Tex.	260, S75W	V	(1), (2), (3)	Felt in Sierra Blanca (166 km to SE), Columbus (130 km to W), Alamogordo (135 km to N). Newspaper accounts suggest epicenter in northern Chihuahua.
2	1926 July 17	22:00	Hope and Lake Arthur, N. M.	90, N54W	III	(4)	Earth sounds heard in NE direction at Hope; windows rattled at Lake Arthur.
3	1930 Oct 4	03:25	Duran, N. M.	280, N32W	(IV)	(5)	Moderate shock felt by many. Rolling motion, rumbling sound, rattled windows. No damage.
4	1931 Aug 16	11:40	Valentine, Tex.	210, S20W	VIII	(5), (6), (7)	Strong damaging earthquake. Felt over 1,250,000 sq. km. See discussion in text.
5	1931 Aug 16	19:33	Valentine, Tex.	210, S20W	(V)	(5)	Strong aftershock.
6	1931 Aug 18	19:36	Valentine, Tex.	210, S20W	V	(5)	Strong aftershock.
7	1931 Aug 19	01:36	Valentine, Tex.	210, S20W	(V)	(5)	Strong aftershock.
8	1931 Oct 2	?	El Paso, Tex.	260, S75W	(III)	(5)	Feeble shock.
9	1931 Nov 3	14:50	Valentine, Tex.	210, S20W	(V)	(5)	Strong aftershock of Aug. 16, 1931 earthquake.
10	1935 Dec 20	05:30	Clovis, N. M.	230, N13E	III-IV	(8)	Two shocks. Tile wall in creamery cracked.
11	1936 Jan 8	06:46	Carlsbad, N. M. ?	40, N89W	(IV)	(3), (5)	Newspaper account indicates this earthquake was probably centered near Ruidoso, N. M.
12	1936 Aug 8	01:40	El Paso, Tex.	260, S75W	(III)	(3), (5)	Weak shock not felt elsewhere.
13	1936 Oct 15	~18:	El Paso, Tex.	260, S75W	(III)	(5)	Slight shock.
14	1937 Mar 31	22:45	El Paso, Tex.	260, S75W	(IV)	(3), (5)	Felt by many.
15	1937 Sept 30	06:15	Ft. Stanton, N. M.	200, N53W	(V)	(5)	Awakened many.
16	1943 Dec 27	04:00	Tularosa, N. M.	220, N70W	IV	(9)	Rattled windows.
17	1949 Feb 2	23:00	Carlsbad, N. M.	40, N89W	(IV)	(5), (9)	Press reported two distinct shocks which were felt by several, and a few frightened. Windows, doors, dishes rattled.
18	1949 May 23	07:22	East Vaughn, N. M.	280, N28W	VI	(5), (9)	Felt area 33 km strip connecting East Vaughn and Pastura. At E. Vaughn few things fell from shelves, loose objects rattled.
19	1952 May 22	04:20	Dog Canyon, N.M.	158, N79W	IV	(5), (9)	Felt by two in ranch house. Windows, doors, dishes rattled.
20	1955 Jan 27	00:37	Valentine, Tex.	210, S20W	IV	(5), (9)	Felt by many. Houses shaken.

[1] Based on Modified Mercalli Intensity Scale of 1931 (see Appendix I). Intensities given in parentheses were assigned by the authors of this paper.

[2] The numbers in this column are for the references listed below.
(1) Woollard (1968)
(2) Bull. Seismol. Soc. Amer. (1923)
(3) Newspaper account
(4) Northrop (1973)
(5) U. S. Earthquakes
(6) Sellards (1933)
(7) Byerly (1934)
(8) Northrop and Sanford (1972)
(9) Abstracts of Earthquake Reports for the Pacific Coast and Western Mountain Region.

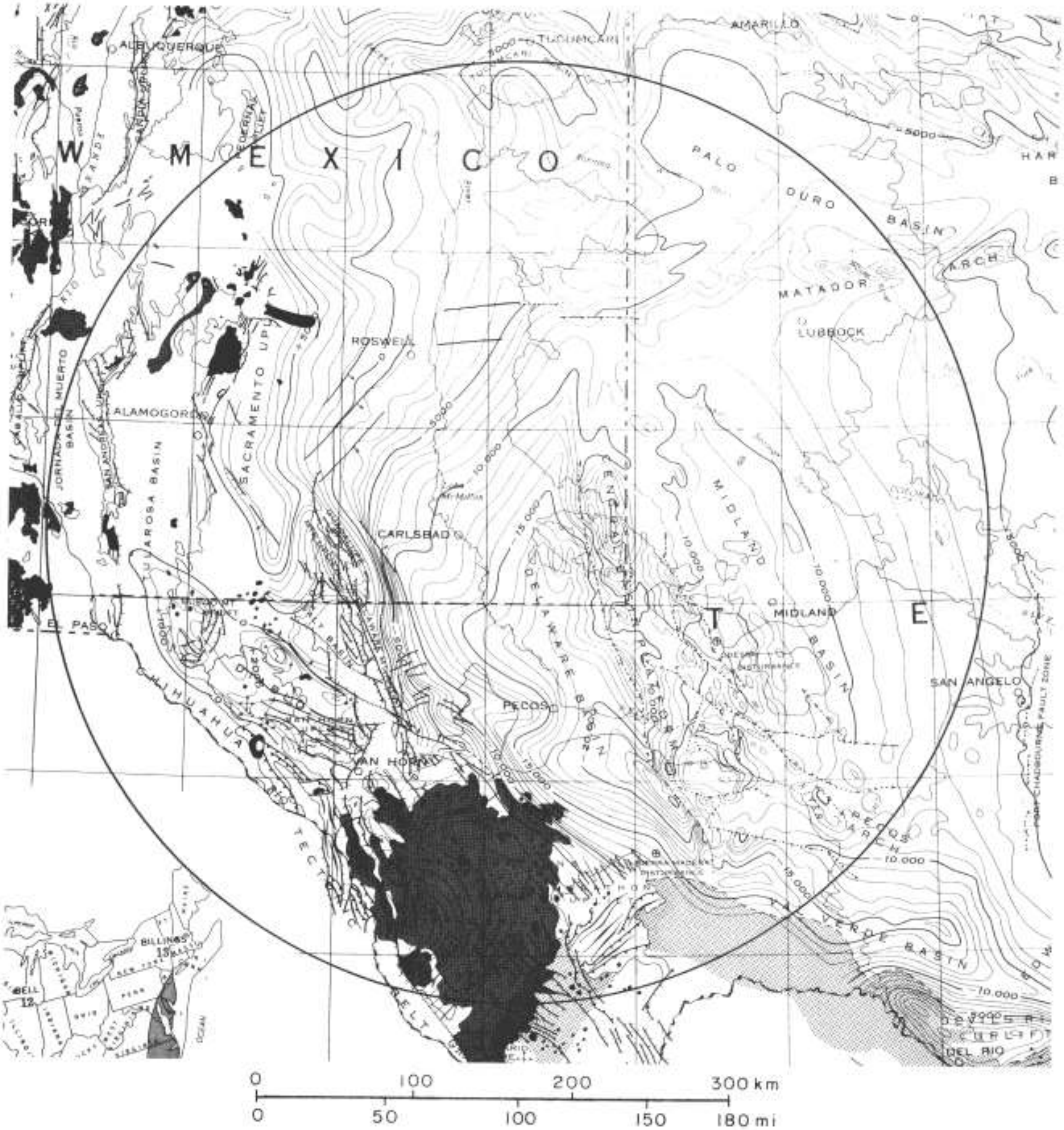

FIGURE 2—*Tectonic map of the region surrounding the proposed disposal site. The radius of the circle centered on the site is 300 km (180 mi) (from U.S. Geological Survey and American Association of Petroleum Geologists).*

geomorphic surfaces. These data are presented in tables 1 and 2 and in figs. 3 and 6.

Felt Earthquakes Prior to Jan. 1, 1961

Table 1 lists earthquakes within 300 km of the site prior to 1961. Information on locations and strengths of earthquakes listed in table 1 is based on values of earthquake intensity. Intensity values (Appendix 1) are assigned on the basis of reactions and observations of people during a shock and the degree of damage to structures. Given many intensity observations, the maximum intensity and limit of perceptibility can be established. Both quantities can be related approximately to the earthquake magnitude (Richter, 1958; Slemmons and others 1965; Wiegel, 1970).

In addition to sources listed in table 1, we contacted a number of historical societies, museums, and longtime residents in southeastern New Mexico and West Texas to determine if some shocks had been overlooked. This effort did not reveal any earthquakes not already in our listings (tables 1 and 2).

TABLE 2 – *Instrumentally located earthquakes within 300 km of disposal site from 1961 through 1972*

No.	Date Yr/Mo/Day	Origin Time GMT	Location Lat°N/Long°W		Distance from Site in Km.	Azimuth from Site	Magnitude[1] M_B	M_L	Reference[2]	Area
21	62 Mar 3	18:16:48.1	33.8	106.4	288	N57W		1.7	(1)	Bingham, N. M.
22	62 Mar 6	09:59:09.7	31.2	104.8	166	S36W		3.5	(2)	Van Horn, Tex.
23	64 Jun 18	20:20:18.4	33.1	106.1	230	N70W		1.8	(1)	Tularosa, N. M.
24	64 June 19	05:28:39.4	33.1	106.1	230	N70W		2.1	(1)	Tularosa, N. M.
25	64 Nov 8	09:25:59.0	31.9	103.1	82	S48E		~3.0	(2)	Kermit, Tex.
26	64 Nov 21	11:21:22.5	31.9	103.1	82	S48E		~3.3	(2)	Kermit, Tex.
27	65 Feb 3	19:59:31.5	31.9	103.1	82	S48E		3.9	(3)	Kermit, Tex.
28	65 Apr 13	09:35:46.0	30.3	105.1	265	S29W	4.2	3.2	(4)	Chihuahua, Mex.
29	65 Aug 30	05:17:37.9	32.1	102.3	140	S76E	3.5	3.3	(4)	Midland, Tex.
30	66 Aug 14	15:25:44.1	31.7	103.1	98	S40E	3.4	4.1	(3)	Wink, Tex.
31	66 Aug 17	18:47:13	30.5	105.6	272	S40W		3.2	(2)	Chihuahua, Mex.
32	66 Aug 19	04:15:44.6	30.3	105.6	292	S37W	4.1	5.3	(4)	Chihuahua, Mex.
33	66 Aug 19	08:38:21.9	30.3	105.6	292	S37W	4.0	4.3	(4)	Chihuahua, Mex.
34	66 Sept 17	21:30:14.0	34.9	103.9	278	N3W		2.7	(3)	Quay, N. M.
35	66 Nov 26	20:05:41	30.8	105.5	240	S43W		3.3	(2)	Chihuahua, Mex.
36	66 Nov 28	02:20:57.3	30.4	105.4	270	S35W	3.8	4.0	(4)	Chihuahua, Mex.
37	66 Dec 5	10:10:37.8	30.4	105.4	270	S35W	4.2	4.0	(4)	Chihuahua, Mex.
38	67 Sept 29	05:49:39.0	32.1	106.9	296	S84W		3.2	(3)	La Mesa, N. M.
39	68 Mar 9	21:54:23.3	32.5	106.0	208	N86W		3.2	(4)	Orogrande, N. M.
40	68 Mar 23	11:53:37.1	32.5	106.0	208	N86W		2.4	(2)	Orogrande, N. M.
41	68 May 2	02:56:43.8	33.1	105.2	154	N60W		3.0	(5)	Elk, N. M.
42	68 Aug 22	02:22.25.5	34.3	105.8	282	N42W		2.1	(2)	Cedarvale, N. M.
43	69 May 12	08:26:18.7	31.9	106.4	254	S78W		3.8	(6)	El Paso, Tex.
44	69 May 12	08:49:16.3	31.8	106.4	255	S75W	4.3	3.5	(6)	El Paso, Tex.
45	69 June 1	17:18:24.8	34.2	105.2	238	N33W		2.3	(2)	Corona, N. M.
46	69 June 8	11:36:02.3	34.2	105.2	238	N33W		2.7	(5)	Corona, N. M.
47	69 Oct 19	11:51:34.4	30.8	105.7	254	S47W	3.8	3.9	(6)	Chihuahua, Mex.
48	71 July 30	01:45:50.9	31.7	103.1	98	S40E	3.0	4.5	(2), (6)	Wink, Tex.
49	71 July 31	14:53:48.6	31.7	103.1	98	S40E	3.4	4.2	(2), (6)	Wink, Tex.
50	71 Sep 24	01:01:53.6	31.7	103.1	98	S40E		3.8	(2)	Wink, Tex.
51	72 Feb 27	15:50:01.9	32.9	105.8	198	N74W		2.3	(2)	Cloudcroft, N. M.
52	72 Dec 9	05:58:00.7	31.8	106.4	254	S75W		3.0	(2)	El Paso, Tex.
53	72 Dec 10	14:37:49.8	31.8	106.4	254	S75W		3.0	(2)	El Paso, Tex.
54	72 Dec 10	14:58:01.6	31.8	106.4	254	S75W		2.7	(2)	El Paso, Tex.

[1] M_B is reported by CGS, M_L is calculated by NMIMT from ALQ and SNM seismograms.

[2] Numbers in this column are for the references listed below.

(1) Sanford (1965)
(2) New location by NMIMT, not previously published.
(3) Sanford and Cash (1969)
(4) U.S. Dept. of Commerce, Seismological Bulletin
(5) Toppozada and Sanford (1972)
(6) U.S. Dept. of Commerce, Earthquake Data Report

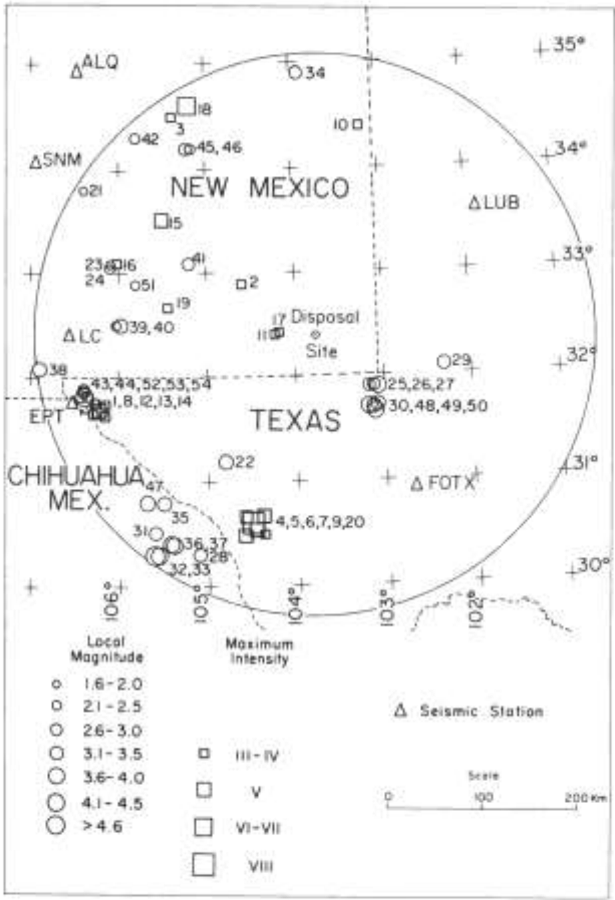

FIGURE 3–*Locations of earthquakes within 300 km of the disposal site. Locations shown with square symbols are based on reports of felt earthquakes prior to 1961. Epicenters shown with circles were determined instrumentally and cover the period 1961 through 1972. Opposite the squares and circles are the numbers of shocks in tables 1 and 2.*

The principal weakness of the seismic data prior to 1961 is that they are partly a function of population density. In sparsely settled areas like the mountainous regions of southeastern New Mexico and southwestern Texas (population density of about 1 person per sq. mi), moderate shocks could have gone completely unreported, or, at best, reported at low intensity levels not indicating true strengths of the earthquakes. With few exceptions, shocks listed in table 1 are moderate and only reported felt at one locality. Converting this intensity into a magnitude results in values too low in most cases. Only for the earthquake of August 16, 1931 are intensity observations sufficient to estimate magnitude with reasonable accuracy.

Imperfect noninstrumental data were incorporated into this study because they are available for a much longer period of time than the instrumental data. Strong earthquakes are rare events. Therefore the longer the earthquake history available, the more probable the report of an earthquake that may be the largest the region is likely to experience.

The apparent epicenters of the shocks listed in table 1 appear as squares on the map in fig. 3. With the exception of the weak shock at Hope, New Mexico (no. 2 in table 1) and the 2 reported earthquakes at Carlsbad (numbers 11 and 17 in table 1), all shocks prior to 1961 occurred to the west of the site and at distances greater than 160 km. The shock of January 8, 1936, almost certainly did not occur at Carlsbad as reported by *U. S. Earthquakes.* A story in a Carlsbad newspaper *The Daily Current-Argus,* January 8, 1936, p. 1, states that the shock was centered near Ruidoso 170 km northwest. The earthquake was felt by only a few persons in Carlsbad. We have not been able to confirm the location of the January 8, 1936 earthquake, but if Ruidoso is the true location, the shock must have been quite strong to have been felt in Carlsbad. The second shock, February 2, 1949, occurred near the city of Carlsbad (Appendix 2).

Locations and Magnitudes after Jan. 1, 1961

After 1961, the number of seismic stations in southwestern U. S. became sufficient for the National Earthquake Information Center of NOAA (formerly U. S. Coast and Geodetic Survey) to locate most of the moderately strong earthquakes ($M_L > 3.5$) in the region of study. Weak as well as moderately strong earthquakes also have been located by New Mexico Institute of Mining and Technology (Sanford, 1965; Sanford and Cash, 1969; Toppozada and Sanford, 1972).

Table 2 lists all instrumentally located shocks within 300 km of the site from January 1, 1961 through December 31, 1972. Epicenters for these earthquakes appear as circles on the map in fig. 3. The greatest number of shocks in the 12-year period of instrumental data occurred in the SW quadrant (fig. 2) from the site-15 shocks with magnitudes (M_L) exceeding 3.0. The number of shocks with $M_L > 3.0$ in the other quadrants in fig. 2 was 8 in the SE quadrant, 2 in the NW quadrant, and none in the NE quadrant. The large number of weak shocks ($M_L < 3.0$) in the NW quadrant is the result of the geographic locations and periods of operations of the seismic stations from 1961 through 1972 (table 3). Because seismic stations north and west of the site were more numerous and in operation longer periods of time than elsewhere, location of weak shocks near these stations was possible. If stations had been in operation south of the site during the entire 12-year period, many shocks with $M_L < 3.0$ would have been located in the SW and SE quadrants from the site.

With the exception of the activity southeast of the site, the distribution of instrumental epicenters from 1961 through 1972 differed little from the distribution of felt shocks prior to 1961. Both distributions indicate seismic activity has been most intense southwest of the site.

The 8 earthquakes located instrumentally to the southeast of the site are important because of their strengths (M_L as great as 4.5) and nearness to the site (as little as 82 kin). These shocks are associated with the Central Basin Platform, a highly faulted Early Permian structure (Meyer, 1966), in recent years the site of many major oil fields.

TABLE 3 — *Locations and periods of operation of seismic stations within 750 km of proposed disposal site*

Station	Nearest Population Center	Location Lat°N Long°W	Elevation Meters	Period of Operation
ALQ	Albuquerque, N.M.	34.94 106.46	1853	Oct. 1961 to Present
EPT	El Paso, Tex.	31.77 106.51	1186	1963 to Present
FOTX	Ft. Stockton, Tex.	30.90 102.70	880	June 21, 1964 to April 12, 1965
JCT	Junction, Tex.	30.48 99.80	591	March 1965 to Present
LC	Las Cruces, N.M.	32.40 106.60	1550	Jan. 1962 to Nov. 1965 Aug. 1967 to Dec. 1967
LUB	Lubbock, Tex.	33.58 101.87	979	Dec. 1961 to Present
SNM	Socorro, N.M.	34.07 106.94	1511	July 1961 to Present
TFO	Payson, Ariz.	34.27 111.27	1402	1963 to Present
TJC	Trinidad, Colo.	37.22 104.69	2103	1966 to Present
TUC	Tucson, Ariz.	32.31 110.78	985	Pre-1961 to Present
WMO	Ft. Sill, Okla.	34.72 98.59	505	1962 to 1969

Before the present study, earthquakes prior to February 3, 1965 were not known to have occurred on the Central Basin Platform area. Queries of local historical societies and newspapers confirmed an absence of any reports prior to 1965. However, this region of low population at the present time was sparsely populated prior to the beginning of oil development in 1920.

To learn more about earthquakes on the Central Basin Platform, a 10-month seismogram from a temporary LRSM (Long Range Seismic Measurements) station near Ft. Stockton, Texas was examined. Apparently, this is the only high-magnification station (350-400 K at 1 Hz) to have operated for any substantial period of time within 120 km of the Central Basin Platform activity. Fortunately, the period of operation of the Ft. Stockton station (FOTX), from June 21, 1964 to April 12, 1965, included the date of the then earliest known earthquake on the Central Basin Platform—February 3, 1965.

Table 4 lists earthquakes (observed on FOTX seismograms) we believe originated in the same region of the Central Basin Platform as shocks 25, 26, 27, 30, 48, 49, and 50 in table 2 and fig. 3. Table 4 includes shocks 25, 26, and 27 listed in table 2. Prior to the examination of the FOTX records, the strong and locatable earthquakes of November 8, 1964 (25) and November 21, 1964 (26) in the Central Basin Platform were unknown.

All of the measured S-P intervals on the FOTX seismograms yield an epicentral distance corresponding to the distance between the FOTX station and the area of activity on the Central Basin Platform. For some of the stronger shocks in table 4, P arrival times were available from the Las Cruces station (LC). The difference between P arrival times at stations LC and FOTX in table 4 is the same (34.7±0.5 seconds) for the unlocated shocks as for the located shocks on November 8 and November 21, 1964 and February 3, 1965.

The FOTX records indicate the Central Basin Platform was seismically active during mid-1964. The fact that the rate of activity at the beginning of the 10-month period equalled the rate of activity at the end of the period suggests earthquakes occurred prior to June, 1964. Unfortunately, the date of onset of seismic activity on the Central Basin Platform cannot be determined from available seismological data. Thus, the question of whether shocks in this region are natural or related to water injection for secondary recovery of oil, can probably be resolved only by determining depths of focus for earthquakes. Central Basin Platform earthquakes are discussed in more detail later.

Strongest Reported Earthquake in Region

The strongest reported earthquake to occur within 300 km of the disposal site was the "Valentine, Texas" earthquake on August 16, 1931 (event no. 4 in table 1). Valentine, Texas reported the maximum intensity for this shock—VIII on the Modified Mercalli Scale of 1931 (Appendix 1). Reports of earthquake intensity were gathered from a large number of localities by the USCGS (U.S. Earthquakes, 1931 and Sellards, 1933). Intensities at the time of this shock were based on the Rossi-Forel Intensity Scale, subsequently abandoned in favor of the Modified Mercalli (M.M.) Intensity Scale of 1931. We have assigned M.M. intensities on the basis of descriptions of earthquake effects (primarily damage to structures) given by Sellards (1933), and plotted the isoseismal map shown in fig. 4. Close to the source, the isoseismals are elongated northwest-southeast conforming to the structural grain of the region (fig. 2). Further from the epicenter, the earthquake had higher intensities to the east than west due to lower topographic relief to the east.

TABLE 4 – *Central Basin Platform earthquakes recorded at Ft. Stockton station (FOTX) from June 21, 1964 through April 12, 1965*[1]

Date Yr/Mo/Day	FOTX-P Arrival Time GMT	FOTX-S-P Interval Secs.	LC-P Arrival Time GMT	Other Stations Recording Shock
64 June 22	07:07:47	14	07:08:22	
64 Jul 13	12:20:03	14		
64 Jul 13	16:18:17	14		
64 Jul 19	02:34:16	13		
64 Aug 14	14:56:37	14	14:57:11	
64 Sep 7	13:42:36	14	13:43:10	
64 Sep 8	22:06:20	15		
64 Sep 11	12:33:08	14		
64 Nov 8	09:26:19	S[2]	09:26:53	SNM
64 Nov 16	02:06:05	15		
64 Nov 17	08:05:14	14		
64 Nov 18	10:20:30	14		
64 Nov 19	11:39:59	14		
64 Nov 19	11:40:30	14		
64 Nov 21	11:21:42	S[2]	11:22:17	SNM, ALQ
64 Nov 23	03:30:18	14		
64 Nov 25	23:18:43	14		
64 Nov 26	00:03:13	14		
64 Nov 27	16:29:53	14	16:30:28	
64 Nov 28	23:46:55	14		
64 Dec 1	20:59:50	13		
64 Dec 1	06:49:47	13		
64 Dec 5	23:09:43	14		
64 Dec 7	06:24:12	14		
64 Dec 7	06:31:40	14		
64 Dec 8	17:16:02	14		
64 Dec 13	19:19:19	13		
64 Dec 14	15:20:26	14		
64 Dec 26	00:08:29	14		
65 Jan 8	14:01:13	14		
65 Jan 12	20:35:19	14		
65 Jan 12	20:49:38	14		
65 Jan 21	11:51:51	14		
65 Feb 2	09:59:19	13		
65 Feb 3	19:59:52	S[2]	20:00:27	SNM, ALQ, WMO, UBO
65 Mar 8	21:00:01	14		
65 Mar 9	03:46:18	14		
65 Apr 2	07:30:58	14		

1 Listing of shocks restricted to events whose maximum peak to peak amplitudes exceeded 20 mm.

2 Earthquake too strong on the seismogram to read S-P interval

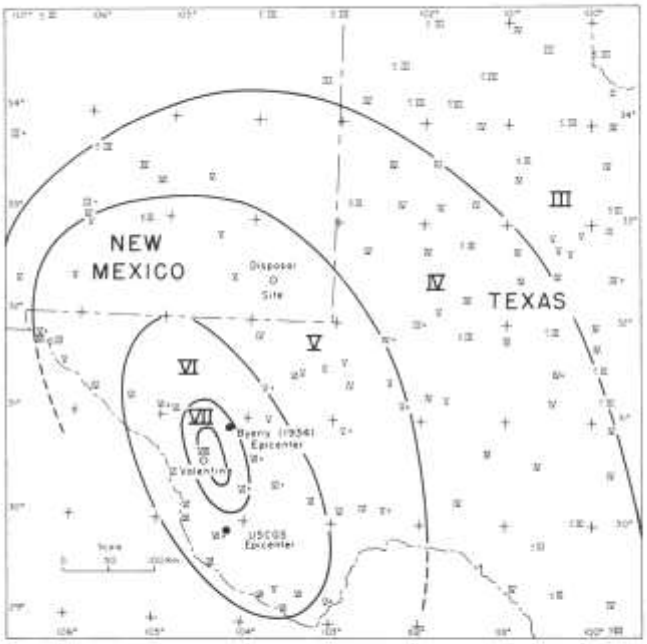

FIGURE 4—*Isoseismal map for the Valentine, Texas earthquake on August 16, 1931.*

Two instrumental locations and origin times have been published for this earthquake. USCGS places the epicenter at 29.9° N. and 104.2° W. and the origin time at 11:40:15 GMT. On the other hand, Byerly (1934), who made a detailed instrumental investigation of this earthquake, found the epicenter to be 30.9° N. and 104.2° W. and the origin time 11:40:21 GMT. Byerly's epicenter, 110 km (66 mi) north of the USCGS epicenter, is closer to the region of highest reported intensities, thus, probably the most accurate of the two locations.

Byerly listed the direction of first motions on seismograms of the Valentine earthquake recorded at distances ranging from 5.8° (550 km) to 104.8° (11,500 km). Applying the recent techniques of first motion analysis, we obtained a surprisingly good fault-plane solution (fig. 5) considering the doubtful quality of the seismograms in 1931. The solution indicates predominantly dip-slip motion along a normal fault striking N. 40° W. and dipping 74° southwest. This type of fault motion is consistent with the known structure in the epicentral region.

The area over which an earthquake is perceptible can be used to estimate its magnitude (Slemmons and others, 1965; Wiegel, 1970). The area of perceptibility for a shock of prescribed strength varies considerably with location. For example, the extent of the felt region is much greater for a shock of given magnitude in the eastern conterminous U. S. than the western. Equations applicable to certain regions of the country are listed below:

Region	Equation	No.
Western (Wiegel, 1970)	$M = 2.3 \log_{10}(A + 3{,}000) - 5.1$	(1)
Rocky Mountain and Central (Wiegel, 1970)	$M = 2.3 \log_{10}(A + 14{,}000) - 6.6$	(2)
Eastern (Wiegel, 1970)	$M = 2.3 \log_{10}(A + 34{,}000) - 7.5$	(3)
Nevada (Slemmons and others, 1965)	$M = 1.4 \log_{10}(A/2)$	(4)

In all of the equations, A is the area of perceptibility in square miles. The main problem in determining the magnitude of the Valentine quake is deciding which equation applies. The epicenter lies near the boundary of two physiographic provinces, the Basin and Range to the west, and the High Plains to the east. The area affected by this shock is much greater to the east than the west.

The equation for the Rocky Mountain and central region appears most applicable. Substituting the felt area reported by USCGS, 450,000 square miles, yields a magnitude of 6.4. This result appears reasonable and is compatible with the maximum intensity reported for the shock (VIII at Valentine).

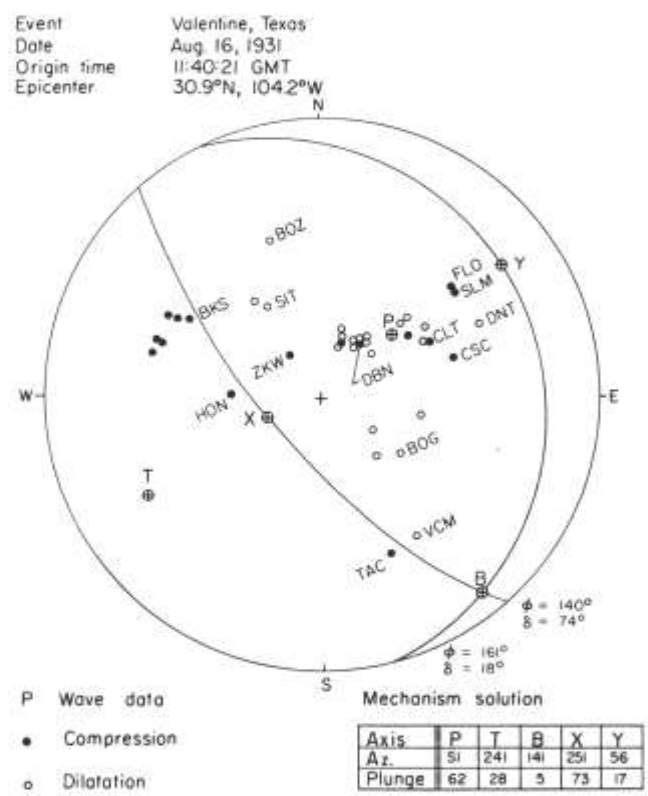

FIGURE 5—*Fault-plane solution for the Valentine, Texas earthquake on August 16, 1931.*

FIGURE 6 – *Map showing location of fault scarps cutting Quaternary alluvial surfaces. After Talmage (1934), Reiche (1938), Kelley (1971), Dake and Nelson (1933), King (1948), King (1965), Kottlowski (1960), Kottlowski and Foster (1960), and Pray (1961).*

Quaternary Fault Scarps

An estimate of the seismicity of the region can be obtained from the lengths, displacements, and ages of faults offsetting Quaternary geomorphic surfaces (Sanford and others, 1972). The principal advantage of this method is that it incorporates a much longer span of seismic history than other techniques. However, this advantage is offset by difficulties in applying the method, in particular, obtaining reliable ages for the fault scarps.

Investigation of fault scarps was confined to the region within 300 km of the disposal site exclusive of the Permian basin (fig. 6). (Bachman, 1973, has completed a detailed investigation of surface features of the Permian basin which indicates recent fault scarps do not exist in that area.) The study was restricted to fault scarps that offset Quaternary alluvial surfaces because these are the only fault displacements whose age can be estimated with any degree of certainty. Some Quaternary tectonic movements in the area may have occurred along faults cutting older rocks, but detection of recent offsets along these faults is nearly impossible.

The first phase of the investigation was a search of the literature for references to fault scarps of recent age. The literature as well as an earlier detailed investigation of fault scarps along the Rio Grande rift (Sanford and others, 1972) indicated nearly all scarps are located in the basins near the escarpments of the tilted fault-block mountains. For this reason, the second phase of the investigation, an examination of aerial photographs, was restricted to the boundaries between the basins and the mountain escarpments. Photographs covering a total area of 10,000 sq. km in New Mexico were examined. The study of aerial photographs did not reveal any major fault scarps not already reported in the literature. On the other hand, details of the known faulting were obtained as well as an indication of a recent age from the general youthful appearance of the scarps.

All of the fault scarps shown in Texas were taken from geologic maps but were not confirmed by an examination of aerial photographs. Because the New Mexico study indicated areas of recent faulting had been identified on published geologic maps, we believe that few scarps were missed in Texas. The fault scarp on the east side of the Salt Basin graben, 55 km south of the New Mexico border, was visited. Judging from its sharpness, this feature originated recently.

The fault scarps, particularly along the margins of the San Andres and Sacramento Mountains, indicate major earthquakes have occurred in the region within the past 500,000 years. The length of the faulting in these two areas (about 60 to 100 km) and the maximum displacements (up to 30 m) suggest earthquakes comparable in strength to the Sonoran earthquake of 1887 (Aguilera, 1920). This major earthquake (probable magnitude of about 7.8) produced 80 km of fault scarp with a maximum displacement of about 8.5 m extending southward from the United States-Mexico border at about long. 109° W.

SEISMIC RISK MAP

Earthquake and fault-scarp data (figs. 3 and 6), indicate that damaging shocks probably will not occur at or within 40 km of the disposal site during the lifetime of the installation. The disposal site, however, will be subjected to ground motions generated by major earthquakes located in the mountainous regions to the west and possibly by moderate earthquakes with epicenters on the Central Basin Platform.

In fig. 7, the region surrounding the disposal site has been zoned on the basis of the severest seismic conditions likely to occur in 500,000 years, the approximate lifetime of the installation. The primary data used to generate the seismic risk map in fig. 7 were the lengths, displacements, and ages of the fault scarps.

All fault scarps shown in fig. 6 offset Quaternary surfaces that are less than 500,000 years in age. The lengths and displacements of the scarps are indicative of major earthquakes comparable in size to the 1887 Sonoran earthquake (magnitude of about 7.8). Inasmuch as the evidence points to major earthquakes in the past 500,000 years, a reasonable expectation is that they will occur in the next 500,000 years.

The positions of existing scarps as well as the general tectonic framework of the region suggest that a major earthquake is not likely to occur any closer than the Salt Basin graben, a distance of about 115 km. For

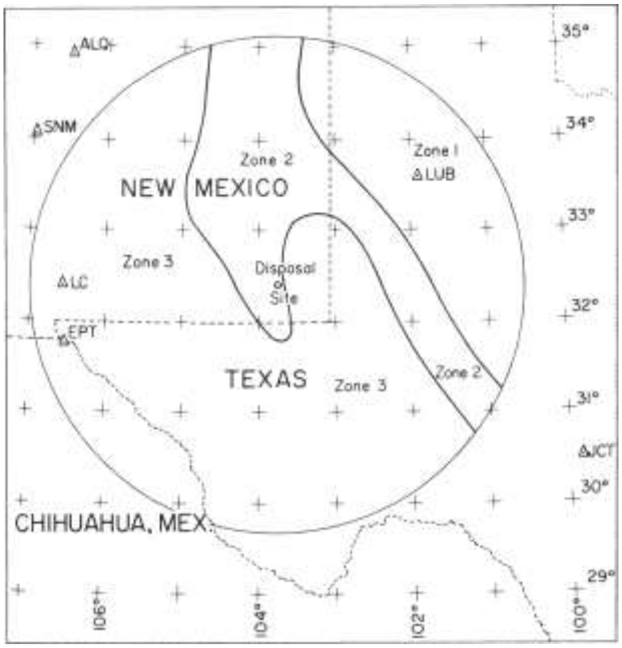

FIGURE 7—*Seismic risk map for the region surrounding the proposed waste disposal site (time period 500,000 years).*

the seismic risk map in fig. 7, magnitude 7.8 shocks were assumed to be possible in a 500,000-year period west of the eastern margins of the Tularosa Basin and Salt Basin graben. Zoning was determined in the following manner. First, maximum accelerations as a function of distance from the epicenter were found from the work of Schnabel and Seed (1973). Second, accelerations were converted to intensities using Richter's (1958) empirical relation. Third, the map was subdivided into the following risk zones, corresponding closely to those used by Algermissen (fig. la):

Zone	Accelerations cm/sec^2	Intensities M.M.
3	>150	>VIII
2	35 to 150	VI to VIII
1	<35	<VI

If only major shocks west of the site had to be considered, the seismic risk map would be relatively simple—three zones running roughly northwest-southeast through the region with the disposal site toward the center of Zone 2. However, if moderate earthquakes are considered possible anywhere along the Central Basin Platform, the seismic risk map becomes more complex. In fig. 7, a magnitude 6 earthquake was considered possible along this structure, and zoning was determined in the same manner as described above. The siesmic risk map in fig. 7 is the result of combining the zoning for major earthquakes west of the site with zoning for moderate earthquakes on the Central Basin Platform. The site can be affected more by moderate earthquakes on the Central Basin Platform than by major earthquakes in the Tularosa Basin or Salt Basin graben. The assumption that shocks can be as large as magnitude 6 on the Central Basin Platform may not be correct, particularly if these shocks are associated with water injection for secondary recovery of oil.

RECURRENCE RATES

The number of times in a 500,000-year period the disposal site will be subjected to the degree of shaking indicated on the seismic risk map can be found from the earthquake data in tables 1 and 2. Recurrence rates can be calculated from the empirically determined relation between number of shocks and magnitude (Richter, 1958)

$$\log_{10} åN = a - b M_L, \qquad (5)$$

where EN is the number of shocks having magnitudes of M_L or greater, and "a" is the logarithm to the base 10 of the number of shocks with $M_L > 0$. If the values for "a" and "b" are known for a seismic region, then equation (5) can be used to estimate the strongest earthquake anticipated in that region during a specified period of time, or the time interval between shocks of prescribed strength.

Fig. 8 is a graph of magnitude versus $\log_{10}$ åN for the earthquakes listed in tables 1 and 2, exclusive of shocks from the Central Basin Platform and aftershocks of the 1934 Valentine earthquake. Curve AB is based on instrumental data only from table 2, and curve CD is based on data from both tables. Maximum reported intensities in table 1 were converted to magnitudes using the relations established for California by Richter (1958). Recent studies (Sanford and others, 1972) indicate these relations are applicable to New Mexico earthquakes.

The sharp break in curves AB and CD indicates that data are incomplete for magnitudes less than 3.2 to 3.4. The linear portion of the curves for $M_L > 3.4$ can be extrapolated to estimate the strongest earthquake to expect in a 100-year period. For AB, this shock is magnitude 6.8; and for curve CD, the shock is magnitude 6.3.

The slope of both curves, 0.6, is substantially smaller than previously observed in the region. For the Rio Grande rift near Socorro, Sanford and Holmes (1962) obtained a value for "b" of 0.99. Algermissen (1969) reports a "b" value of 1.02 for the central and southern Rocky Mountains. Because the number of shocks used to establish the linear portions of curves AB and CD is small (16 and 25, respectively) an error in "b" is quite possible. An alternate computation of the strongest earthquake in a 100-year period can be made by assuming a line with a slope of 1.0 passing through the ML equal to 5.3 point (curves EF and GH in fig. 8). For line EF, the strongest earthquake will have a magnitude of 6.2, and for line GH, the magnitude will be 5.9.

The recurrence rate for the strongest earthquake the region is ever likely to experience (magnitude 7.8) can also

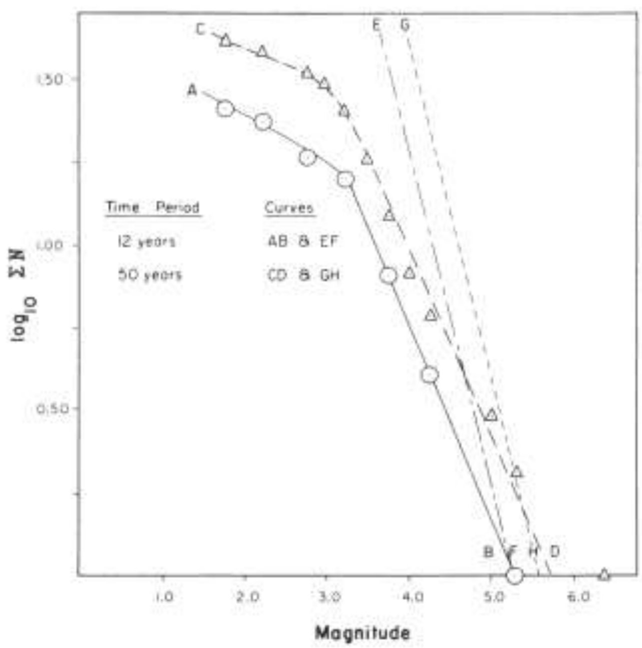

FIGURE 8 — A graph of the logarithm of the cumulative number of earthquakes versus the magnitude. Curve AB is based on shocks listed in table 2 exclusive of earthquakes located on the Central Basin Platform. Curve CD is based on curve AB data plus earthquakes listed in table 1 exclusive of the aftershocks of the Valentine, Texas earthquake.

be estimated by extrapolation of the curves in fig. 8. For curves AB, CD, EF, and GH, a 7.8 earthquake will occur once every 400, 900, 4,000, and 8,000 years, respectively. Data on fault scarps in the region do not indicate major earthquakes are occurring as frequently as once every 400 to 1,000 years. This observation suggests that the slopes of the linear portions of curves AB and CD in fig. 8 may be incorrect; consequently, many shocks with $M_L < 4.5$ (maximum intensity < VI) in the region may have gone un-reported or undetected. An alternate explanation is that the actual relation between the $\log_{10}$åN and ML becomes nonlinear for large values of ML. Therefore, an extrapola-tion of equation (5) based on smaller earthquakes cannot be used to estimate recurrence rates for major earthquakes.

Nevertheless, magnitude 7.8 earthquakes could be occurring in the western half of the study region at a rate of once every 5,000 years. Major earthquakes that could affect the disposal site at the level shown on the seismic risk map (fig. 7) would occur less frequently. These shocks must have epicenters in the Salt Basin graben, a structure that covers only about 10 percent of the area considered in calculating the recurrence intervals. Therefore, major earth-quakes to the west could produce Zone 2 effects (maximum intensity VI-VIII) at the disposal site only about once every 50,000 years. Calculation of recurrence rates for moderate earthquakes on the Central Basin Platform is not meaningful until the question of their origin is settled.

CENTRAL BASIN PLATFORM EARTHQUAKES

Shurbet (1969) was the first to suggest that seismic activity on the Central Basin Platform is related to water injection for secondary recovery of oil. His suggestion was based on the clearly established association between earth-quakes and waste injection into crystalline bedrock at the Rocky Mountain Arsenal near Denver (Healy and others, 1968). Subsequently, a direct association between earth-quakes and fluid injection for secondary recovery of oil was established at the Rangely field in northwestern Colo-rado (Healy and others, 1972). As the fluid pressure builds up during injection, the effective stress across pre-existing fractures diminishes. Frictional resistance to sliding is directly proportional to the effective stress.

The principal observations supporting an association between earthquakes and water injection on the Central Basin Platform are:

Felt earthquakes on the Central Basin Platform were not reported prior to August 14, 1966.

The Central Basin Platform is an old structure (Early Permian) with no evidence at the surface of being rejuvenated.

All but one of the known Central Basin Platform shocks occurred near, or in, a major oil field being subjected to massive water injection.

The oil field referred to above is the Ward-Estes North, operated by the Gulf Oil Corporation. The center of the field is 31.57° N. and 102.98° W. and it is 28 km long and 5 km wide with a N. 10° W. trend (the structural trend of the Central Basin Platform). The locations of shocks 25, 26, and 27 in table 2 are 22 km north of the field and shocks 30, 48, 49, and 50 are on its northern boundary. Considering the uncertainties in the instrumental epicenters, all of these shocks could have occurred within the boundaries of the field.

The Ward-Estes North field is a prime candidate for earthquakes because of the enormous quantities of water injected. The cumulative total of water injected to 1970 was 1,158,550,000 barrels. Water injection began in 1944 but more than three-quarters has occurred since 1955. This field alone accounts for 42 percent of all the water injected in Ward and Winkler Counties, Texas. These two counties straddle the western margin of the Central Basin Platform just south of the New Mexico border. The water injected in the Ward-Estes North field is about 3 times the total amount injected in all the oil fields in the southeastern corner of New Mexico (Tps. 18 to 26 S.; Rs. 27 to 38 E.; 10,000 sq. km).

Central Basin Platform earthquakes may be related to water injection, but the evidence certainly is not conclusive. Natural earthquake activity could have been occurring long before injection commenced, but not reported because of the low population density of the region. Rejuvenation of the Central Basin Platform structure could be so recent that surface manifestations are slight or absent. Old buried structures in northeastern New Mexico, where there is no oil production, are seismically active. The apparent association of the seismic activity with the Ward-Estes North field may be coincidence; perhaps a degree of certainty could be established by determining depths of focus of current seismic events.

SUMMARY

Reports of felt shocks prior to 1961 indicate the region near the proposed disposal site is not seismically active.

Instrumental data since 1961 do not give any evidence for earthquakes with $M_L > 3.5$ in the immediate vicinity of the site.

Fault scarps west of the disposal site indicate major earthquakes, M_L — 7.8, have occurred in the past 500,000 years.

The location of known fault scarps and the general tectonic framework of the region suggest that a major earthquake is not likely to occur any closer than 115 km west of the site. Major earthquakes ($M_L = 7.8$) at this distance will produce ground accelerations of about 0.07 g.

An analysis of earthquake statistics since 1923 indicates the site will be subjected to shaking at the 0.07-g level about once every 50,000 years from earthquakes located west of the site, particularly along the Salt Basin graben.

The earthquakes on the Central Basin Platform south-east of the site have epicenters in, or near, an oil field undergoing massive water injection for secondary recovery. Also the Central Basin Platform is an old structure, lacking surface evidence of rejuvenation; and earthquakes were not reported felt prior to August 14, 1966. These points suggest a direct link between earthquakes and water injection, but the evidence is not conclusive.

If the Central Basin Platform shocks are natural and can attain a magnitude of 6.0 anywhere on the structure, then the maximum acceleration from these shocks at the site will be about 0.1 g.

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APPENDICES

Appendix 1 — Modified Mercalli Intensity Scale of 1931 (Abridged)

From Abstracts of Earthquake Reports for the Pacific Coast and Western Mountain Region

I Not felt except by a very few under especially favorable circumstances. (Rossi-Forel Scale.)

II Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to III Rossi-Forel Scale.)

III Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel Scale.)

IV During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V Rossi-Forel Scale.)

V Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel Scale.)

VI Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale.)

VII Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motorcars. (VIII Rossi-Forel Scale.)

VIII Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed. (VIII+ to IX Rossi-Forel Scale.)

IX Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX + Rossi-Forel Scale.)

X Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel Scale.)

XI Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Appendix 2 — Field Report of Carlsbad Earthquake Feb. 2, 1949

From Abstracts of Earthquake Reports for the Pacific Coast and Western Mountain Region, 1949, MSA 61, USCGS, p. 29.

2 February, 16:00. State of New Mexico.

Following up press reports that an earthquake had been felt in Carlsbad, a coverage was made by Prof. Stuart A. Northrop, Collaborator in Seismology for New Mexico. The press reported two distinct shocks; woman and several neighbors alarmed; thought something had run into house; several ran outside. Comment by Prof. Northrop: Probably a slight subsidence.

Carlsbad. IV. Motion rapid, lasted a few seconds. Felt.in several homes; frightened few people. Rattled windows, doors, dishes; house creaked.

Carlsbad. IV. Lasted 30 seconds. Rattled windows, doors, dishes. Frightened observer. Ground: Soil, level.

Carlsbad. III. Lasted about 1 or 2 seconds. Felt by several in home. House seemed to shudder momentarily. Ground: Soil, compact, level.

Reported not felt: Artesia, Carlsbad Caverns Nat'l Park, Lakewood.

Type Faces: Camera-ready copy composed at
N.M. Bureau Mines on IBM MT
Text in 10 pt. Press Roman leaded
two points
Subheads in II pt. Press Roman

Presswork: Text printed on 38" single color Miehle and 22
1/2" MGD
Cover printed on 29" single color Harris

Paper: Cover on 65# white Antique
Body on-60# white offset