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New Mexico Geology, v. 28, n. 4 pp. 99-109, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v28n4.99

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This latest report on earthquake activity in New Mexico and bordering areas by New Mexico Institute of Mining and Technology (NMT) investigators covers the 6-yr period 1999–2004[1]. It is a continuation of catalogs for 1962 through 1998 published as Circular 210 by the New Mexico Bureau of Geology and Mineral Resources in 2002. (Data are available online at http://geoinfo.nmt.edu/publications/circulars/210/.) Earthquake research centered at NMT is appropriate because a small region surrounding Socorro produces a disproportionate share of the state's activity and has generated the strongest historical earthquakes. A primary goal of the research at NMT has been to establish an accurate earthquake database for the Socorro area and all of New Mexico from which reliable estimates of earthquake hazard can be obtained. To this end, it has been important to eliminate quakes arising from explosions and those that have been induced by human activity, for example, collapse of underground mines and disposal of large volumes of waste water generated in development of energy resources.

Abstract

Earthquakes in New Mexico and bordering areas have been instrumentally located since 1962 at New Mexico Institute of Mining and Technology. Catalogs of these earthquakes for the period 1962 through 1998 were published in 2002. This report extends the cataloging of earthquakes for the region through 2004. For this 6-yr period 198 earthquakes with magnitudes of 2.0 or greater were located. An unusual feature of the seismicity 1999 through 2004 is that 63% of the earthquakes were concentrated in two swarms, one near water disposal wells on the western edge of the Dagger Draw oil field in southeastern New Mexico, and the other within and bordering the coalbed methane fields of the Raton Basin in northeastern New Mexico. We suggest that the proximity of these swarms to oil and gas fields may indicate that the earthquakes are induced by destabilization of the crust through production and waste disposal practices. The remaining 37% of the earthquakes 1999 through 2004 were concentrated near Socorro and west Texas. Except for the Socorro area, activity along the Rio Grande rift was low.

Introduction

The earthquake catalogs presented here for New Mexico and bordering areas are for the 6-yr period 1999 through 2004. They are a continuation of catalogs published for the same region over a 37-yr period 1962 through 1998 (Sanford et al. 2002). Procedures followed in generating the catalogs here are identical to those used by Sanford et al. (2002); however, they are restricted to shocks of magnitude 2.0 or greater. The earlier catalogs listed events with magnitudes as low as 1.3. Another difference for the 1999–2004 listings of quakes is the addition of epicenter error and maximum station azimuthal gap to the parameters date, origin time, epicenter location, and magnitude.

For 1999 through 2004, 198 earthquakes of magnitude 2.0 or greater were located in New Mexico and bordering areas, a region extending from 31.0° to 38.0° N latitude and from 101.0° to 111.0° W longitude (Fig. 1). In the preceding 6-yr interval, 123 quakes of magnitude 2.0 or greater occurred in the same region. This suggests a near doubling of activity in 1999 through 2004. However, an unusual feature of this latest 6-yr period is the onset of two vigorous earthquake swarms located in small areas of New Mexico. Some observations suggest the two swarms are induced: (1) in the Delaware Basin of southeast New Mexico by disposal of large quantities of water produced along with oil, and (2) in the Raton Basin of northeast New Mexico by the removal and/or injection of water associated with production of coalbed methane. Because these two tight clusters of earthquakes account for 123 of the quakes from 1999 through 2004, each will be described separately in this paper. Following Sanford et al. (2002), the remaining 75 earthquakes are divided between two areas: a 5,000-km^2 region surrounding Socorro that is designated the Socorro Seismic Anomaly (SSA; Balch et al. 1997), and the other, the remainder of New Mexico and bordering areas designated RNM. The justification for the separation into two areas is that the SSA occupies only 0.7% of the area covered in the study but contributes a disproportionally large fraction of the total activity, 23% in the 37-yr period 1962 through 1998 (Sanford et al. 2002) and 15% in the 6-yr period covered by this study.

Procedures

Earthquake data

Most of the data used to determine origin times, epicenters, and magnitudes came from two networks operated by New Mexico Institute of Mining and Technology (NMT): (1) nine stations surrounding Socorro (Fig. 2) and (2) nine stations surrounding the Waste Isolation Pilot Project (WIPP) near Carlsbad (Fig. 3). Data from these NMT networks were augmented by arrival times from stations operated by the U.S. Geological Survey, the U.S. Bureau of Reclamation, the University of Texas–El Paso, and the University of Texas–Dallas. The appendix has a table of coordinates for stations used to locate earthquakes from 1999 through 2004 and a map of the station locations.

Earthquake magnitudes

All magnitudes in this study were determined from the New Mexico duration magnitude scale:

$$M_d = 2.79 \log \tau_d - 3.63,$$

where τ_d is the duration of recorded ground motion in seconds (Newton et al. 1976; Ake et al. 1983). This relation was first developed by Dan Cash of Los Alamos National Laboratory (LANL) for quakes in northern New Mexico. Later an essentially identical relation was obtained by a group at NMT for earthquakes throughout New Mexico. Both the NMT and LANL duration magnitude scales are tied to local magnitudes obtained from Wood-Anderson seismograms (Richter 1958) of New Mexico earthquakes. Hanks and Kanamori (1979) showed that local magnitude is equivalent to moment magnitude.

Earthquake locations

Earthquake origin times and epicenters were obtained from the inverse method computer program SEISMOS (Hartse 1991). Slightly different versions of the program were used to locate earthquakes within the SSA and those in RNM and the Raton Basin and Delaware Basin swarms.

The velocity model used with SEISMOS to locate earthquakes outside the SSA was a simple half-space with a velocity of 6.15 km/sec and a Poisson's ratio of 0.25. (An exception was the Raton Basin swarm when a Poisson's ratio of 0.235 produced smaller epicenter errors.) Because of the model adopted, only P_g and S_g arrival times were used in the location procedure. For earthquakes within the SSA, a relatively complex and tightly constrained crustal velocity model obtained from inversion of reflection data was used (Hartse et al. 1992)[2].

Focal depths were not calculated for any of the earthquakes listed in the catalogs of this paper. Even in the case of SSA events, where readings from several relatively close stations were available (see Fig. 2), attempts to obtain reliable focal depths failed because focal depth errors were exceedingly large. Better estimates of

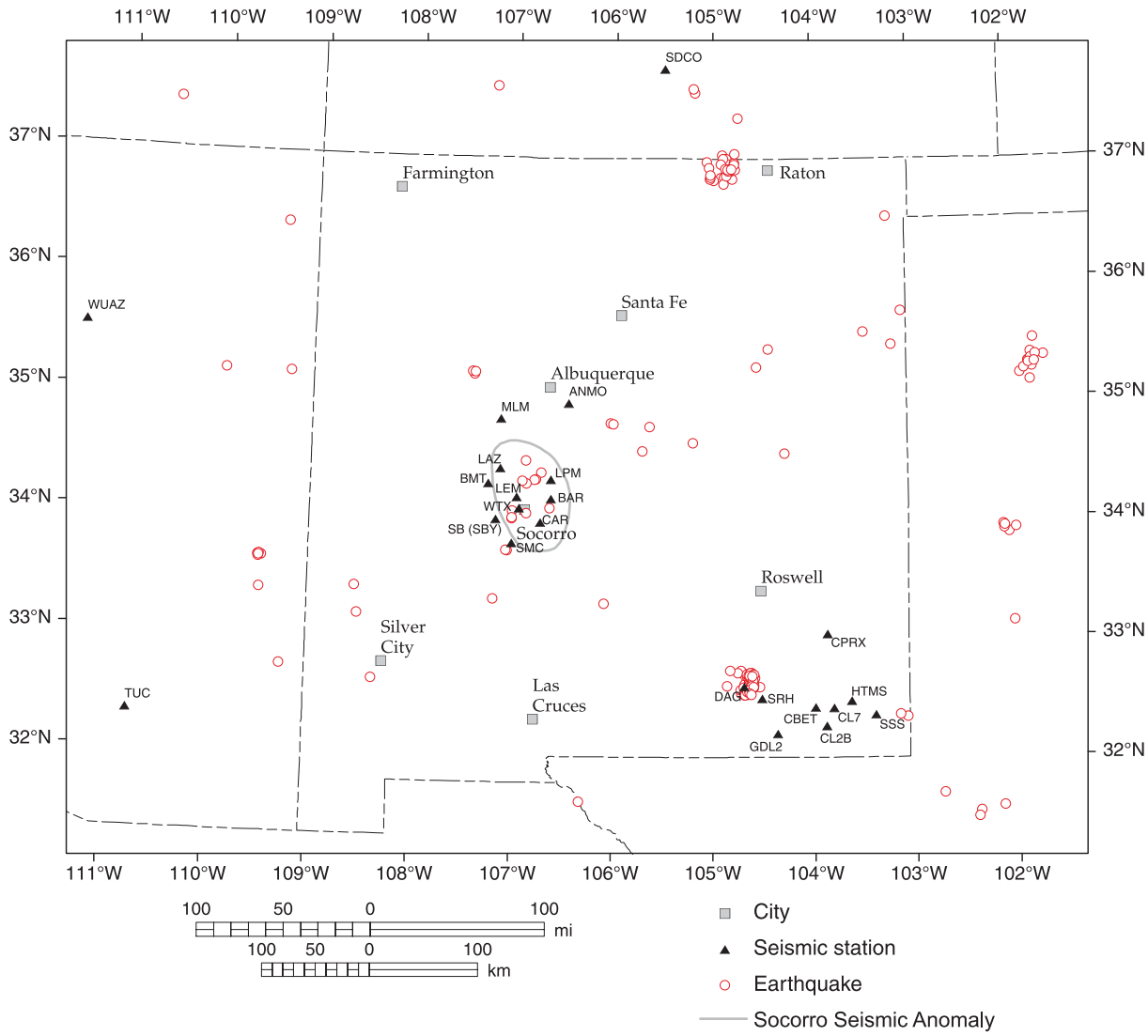

FIGURE 1—Earthquakes in New Mexico and bordering areas, 1999–2004 with magnitudes of 2.0 or greater. A total of 198 earthquake epicenters are plotted, 123 of which occurred in two tight clusters of activity, one in northeastern New Mexico and the other in the southeastern corner of the state. The remaining 75 earthquakes are located throughout the region, including 11 within the Socorro Seismic Anomaly (the elliptical area outlined (Balch et al. 1997)), a small region that contributes a disproportionate fraction of the activity.

epicenter locations and origin times were obtained by fixing the focal depth at 5 km, the approximate middle of the seismogenic zone.

For events occurring outside the SSA, calculation of focal depths was impossible because of the large distances to the recording stations and the half-space crustal structure used in the SEISMOS location program. The result of these two conditions is that the location program is unable to determine any difference in focal depths that occur within a reasonable depth range of 1.0–10.0 km. Therefore, although we fixed focal depths at 5 km for most of the earthquakes in the study, the use of other fixed depths between 1.0 and 10.0 km for individual events produced locations well within one standard deviation of each other.

Accuracy of epicenters

Epicenter accuracy is defined as how close the locations calculated by SEISMOS are to the true epicenters. A primary factor influencing accuracy is how near the adopted crustal velocity model matches the true velocity structure. For the SSA, the match is close (Hartse 1991) and the recording distances short. For the remainder of New Mexico and bordering areas, the adopted half-space crustal model has a velocity that is an average for the entire study area. Some cataloged epicenters may be less accurate because paths to the recording stations were long and passed through crust that has a velocity different from the average. Except for earthquakes in the SSA, the epicenter error listed in the catalogs may not adequately reflect deviations from the true locations arising from crustal velocity variations from the average.

Other factors influencing accuracy of epicenters are: (1) number of stations, (2) distance of stations, (3) azimuthal distribution of stations, (4) quality of P and S arrivals, and (5) number of paired P and S arrivals. The program SEISMOS estimates a one standard deviation epicenter error in kilometers, but this estimate can be affected by either overestimating or underestimating the timing errors of the P and S arrivals. Also, the estimated error does not appear to incorporate the effect of large gaps (the maximum azimuthal separation between adjacent stations). Calculated locations with gaps of 270°or more that have estimated epicenter errors as low as 2.5–7.0 km are listed in the catalogs. Inasmuch as this appears unrealistic, gap has been included in the catalogs so that it can be used as a parameter in assessing the most accurate epicenters.

Socorro Seismic Anomaly (SSA)

Earthquakes of magnitude 2.0 or greater that occurred in the 5,000-km^2 SSA surrounding Socorro in 1999 through 2004

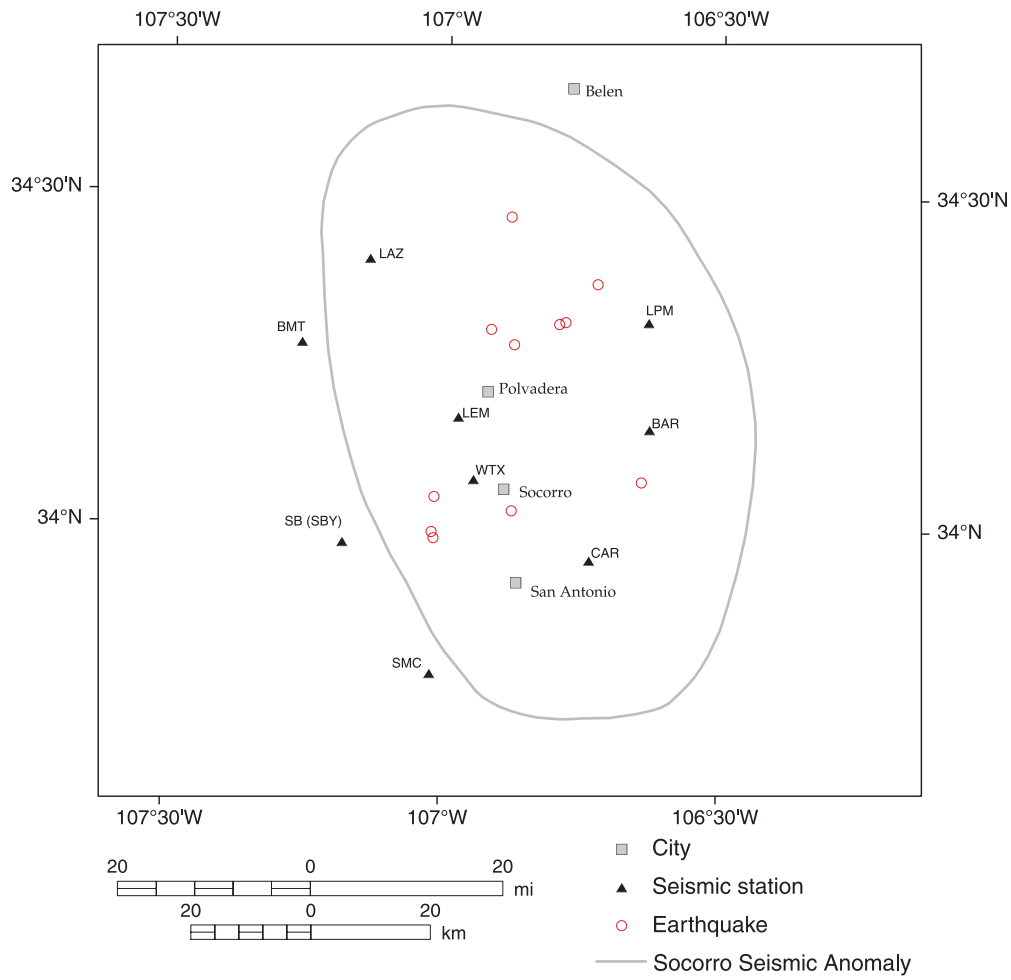

FIGURE 2—Socorro, New Mexico, seismograph network stations. Epicenters for 11 earthquakes of magnitude 2.0 or greater for the period 1999–2004 are shown within the Socorro Seismic Anomaly (the outlined elliptical area; Balch et al. 1997).

TABLE 1—Socorro Seismic Anomaly earthquakes with magnitudes of 2.0 or greater: 1999–2004.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1std (km)	Gap (degrees)	Magnitude
1	1999	8	1	12	12	41.48	34	22.07	106	43.55	0.50	138	2.1
2	1999	12	9	12	39	12.09	34	2.71	107	0.94	0.45	76	2.6
3	1999	12	13	4	17	46.13	34	18.62	106	46.99	0.79	214	2.1
4	1999	12	13	10	58	46.36	34	18.41	106	47.64	0.42	95	2.0
5	1999	12	13	23	24	16.43	34	4.23	106	38.50	0.62	205	2.3
6	2001	5	5	6	29	10.19	33	58.97	107	1.00	0.53	104	2.1
7	2001	5	7	17	38	3.10	33	59.52	107	1.20	0.54	110	2.8
8	2001	11	18	14	22	59.87	34	16.52	106	52.53	0.30	87	2.2
9	2001	12	12	16	44	17.82	34	17.90	106	55.07	0.58	110	2.1
10	2003	11	2	11	58	8.94	34	1.53	106	52.57	0.45	84	2.0
11	2004	5	24	21	36	28.42	34	28.06	106	53.03	0.48	90	2.9

are listed in Table 1, and epicenters are mapped in Figure 2. Earthquake activity in this region is attributed to crustal extension arising from inflation of a mid-crustal magma body—the Socorro Magma Body (Fialko and Simons 2001). This thin (~150 m), extensive (~3,400 km^2) magma body is at a depth of ~19 km (Ake and Sanford 1988; Hartse et al. 1992; Balch et al. 1997; Schlue et al. 1996).

The 11 quakes in 1999 through 2004 are scattered throughout the SSA region (Fig. 2). The number each year ranged from zero in 2000 and 2002 to five in 1999. The average yearly rate of 1.8 is just slightly higher than the previous 6-yr period 1993 through 1998. However, the annual rate for the 12-yr interval before 1993 was 11.5, which illustrates the highly irregular nature of the SSA seismicity. Despite the relatively low level of seismic activity from 1999 through 2004, SSA earthquakes contributed 15% of the earthquakes of magnitude 2.0 or greater, exclusive of shocks in the Raton Basin and Delaware Basin swarms.

Remainder of New Mexico and bordering areas (RNM)

Earthquakes of magnitude 2.0 or greater that occurred in the RNM from 1999 through 2004 are listed in Table 2 except for those in the Raton Basin and Delaware Basin swarms. Epicenter locations are mapped in Figure 1. The number of earthquakes is only one-half the total for the previous 6-yr period. An analysis of the number of quakes versus magnitude indicates that the 64-event data set for RNM is com-

TABLE 2—Remainder of New Mexico and bordering areas earthquakes with magnitudes of 2.0 or greater: 1999–2004. Asterisks indicate locations by the U.S. Geological Survey.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1std (km)	Gap (degrees)	Magnitude
1	1999	2	9	20	28	18.18	35	43.43	103	5.37	5.49	133	2.0
2	1999	2	25	0	32	11.72	36	50.05	104	55.12	8.08	178	2.0
3	1999	8	6	7	0	1.02	34	32.17	104	16.75	6.97	244	2.0
4	1999	9	1	16	35	15.18	33	42.81	107	3.78	1.17	306	2.3
5	1999	9	4	3	35	43.91	33	43.14	107	4.51	0.92	294	2.2
6	1999	10	9	12	9	39.31	31	32.66	102	22.68	10.71	332	2.0
7	2000	1	23	16	27	53.94	35	24.19	104	26.58	9.57	338	2.0
8	2000	4	6	18	39	4.26	35	26.46	103	11.55	4.75	126	2.1
9	2000	4	24	9	41	30.26	33	7.73	102	0.29	3.93	141	2.0
10	2000	8	2	12	21	30.24	35	21.59	101	46.61	4.44	140	2.1
11	2000	8	7	17	19	6.55	35	17.01	101	48.05	4.78	137	2.8
12	2000	8	7	18	34	7.48	35	16.85	101	48.24	7.57	197	2.4
13	2000	8	7	21	36	19.84	35	18.44	101	46.43	5.02	138	2.5
14	2000	8	10	13	39	48.78	35	14.27	101	45.84	13.45	309	2.3
15	2000	8	17	1	8	5.55	35	7.76	101	47.27	4.76	192	3.6
16	2000	10	31	13	19	16.98	33	18.68	107	11.68	4.17	260	2.1
17	2000	11	4	13	13	30.29	35	28.85	101	44.85	6.70	183	2.1
18	2000	12	7	9	38	51.68	34	45.42	105	38.62	3.52	213	2.0
19	2000	12	16	22	8	54.51	35	20.04	101	38.56	10.44	306	3.3
20	2000	12	27	12	51	37.31	33	23.86	108	34.51	7.14	178	2.2
21	2001	1	2	10	21	34.42	34	33.30	105	42.73	2.55	192	2.1
22	2001	1	20	10	4	22.81	33	10.11	108	32.53	11.44	181	2.0
23	2001	6	1	20	29	43.16	32	20.30	103	4.83	4.26	307	2.0
24	2001	6	2	1	56	54.39	32	21.50	103	9.02	3.31	205	3.0
25	2001	9	3	21	54	22.26	31	0.36	107	19.83	9.89	298	2.1
26	2001	11	22	0	7	9.60	31	41.96	102	43.70	8.67	331	2.5
27	2001	11	23	13	47	10.57	31	29.78	102	23.68	9.69	338	2.4
28	2002	1	11	12	32	20.80	36	24.58	109	21.50	7.32	285	2.4
29	2002	1	16	15	25	32.21	35	11.39	101	53.39	10.11	308	2.6
30	2002	1	19	11	51	14.13	35	13.50	101	50.66	11.10	303	2.2
31	2002	3	31	2	54	6.01	35	16.21	101	48.06	10.73	304	2.8
32	2002	4	30	4	37	15.89	35	10.19	109	16.70	4.69	174	2.3
*33	2002	6	18	11	4	47.78	37	35.40	107	14.40			2.9
34	2002	6	19	12	14	22.26	36	30.69	103	13.90	4.83	217	3.3
*35	2002	9	26	10	32	10.00	37	24.60	110	31.80			3.0
36	2002	10	4	8	36	14.62	33	51.98	102	2.35	6.06	159	2.3
37	2002	10	4	9	23	26.63	33	55.95	102	5.61	5.29	160	2.5
38	2002	10	4	9	31	13.15	33	53.90	102	5.19	8.75	193	2.1
39	2002	10	18	15	46	14.83	33	55.27	102	4.74	4.55	160	2.4
40	2002	11	12	13	37	19.57	34	37.52	105	12.15	4.11	217	2.0
41	2002	11	17	12	47	39.45	33	54.44	101	57.97	5.09	159	2.5
42	2003	2	22	7	40	52.02	32	37.73	108	23.04	3.09	164	2.3
43	2003	5	22	22	24	52.77	34	47.10	106	2.12	1.73	126	2.0
44	2003	5	23	12	59	22.76	34	46.67	106	0.51	1.80	83	2.2
45	2003	8	5	5	42	24.11	35	15.21	104	33.95	2.96	107	2.6
46	2003	8	12	6	43	59.20	31	35.06	102	8.71	6.58	255	2.4
47	2003	9	5	20	21	4.28	35	11.07	107	25.02	3.10	295	2.4
48	2003	9	24	15	2	7.43	35	20.39	101	43.60	4.04	140	3.0
49	2003	10	20	0	15	54.08	35	32.85	103	28.47	7.12	205	2.7
*50	2003	10	28	23	20	13.00	35	16.80	101	44.40			2.4
51	2003	12	13	9	16	3.13	31	37.53	106	19.27	3.51	210	2.2
52	2003	12	21	16	1	39.69	33	37.54	109	32.55	3.42	133	2.6
53	2003	12	21	16	8	54.96	33	37.51	109	30.48	2.73	134	2.6
54	2003	12	21	16	12	56.66	33	38.08	109	31.89	2.93	133	2.5
55	2003	12	21	16	19	36.77	33	36.56	109	32.48	3.64	134	2.0
56	2003	12	21	19	32	55.53	33	37.27	109	32.19	2.94	133	2.2
57	2003	12	28	2	55	1.99	37	32.48	105	11.25	4.34	103	3.5
58	2003	12	28	3	57	2.17	37	34.56	105	12.14	5.03	83	3.0
59	2004	3	5	18	28	20.75	35	10.42	109	56.18	4.94	111	2.4
60	2004	3	12	8	37	26.51	33	21.50	109	31.41	10.17	193	2.3
61	2004	4	15	1	16	48.47	32	43.75	109	17.52	12.63	78	2.1
62	2004	11	14	21	27	50.35	33	16.83	106	5.26	2.43	130	3.2
63	2004	11	24	10	16	38.94	35	12.24	107	26.17	3.57	296	2.0
64	2004	12	13	9	43	7.30	35	12.06	107	24.70	3.30	295	2.2

plete down to magnitude 2.0. A surprisingly large fraction of the 64 earthquakes are located in the Great Plains of west Texas with a prominent concentration near Amarillo. These events as well as others outside the boundaries of New Mexico generally have large epicenter errors, frequently on the order of 10 km. Similar to the results of the 1962–1998 study (Sanford et al. 2002), some epicenters in 1999–2004 extend in a diffuse band northeastward from the SSA to the New Mexico–Texas border, and like the earlier study, the Rio Grande rift is not defined by the earthquake activity.

Delaware Basin earthquake sequence

The Delaware Basin earthquake sequence is located on the western margin of the Dagger Draw oil field 40 km northwest of Carlsbad. Because of its location, this

earthquake sequence has been designated the Dagger Draw swarm. Magnitude 2.0 or greater earthquakes in the Dagger Draw swarm began as early as 20 March 1998. (Weaker shocks occurred earlier, certainly by July 1997, and perhaps as early as December 1996.) The latter earthquake and three others in 1998 (Sanford et al. 2002) are included in the Table 3 listing of Dagger Draw swarm events to the end of 2004. An analysis of the 94 Dagger Draw swarm earthquakes in Table 3 indicates the data are complete down to magnitude 2.0.

For most of the 6.75 yrs of Dagger Draw swarm activity in Table 3, locations were poorly constrained. Although the original seven stations of the WIPP network were located 50–120 km distance from the Dagger Draw swarm, the azimuthal distribution of stations was poor. Even with the addition of readings from the Socorro network, gaps remained large. Locations improved greatly in the summer of 2003 with the installation of station DAG located 6–10 km west to southwest of the Dagger Draw swarm events. Further improvement occurred with the installation in March 2004 of another close station (SRH) at a distance of 12–22 km southeast of the Dagger Draw swarm.

Despite the addition of stations DAG and SRH, direct calculation by SEISMOS of focal depths yielded very unrealistic values. Selection of reasonable fixed depths between 1.0 and 10.0 km yielded epicenters very near a tight cluster of disposal wells (Fig. 3). As a result, we elected to use the depth of injection at the disposal wells, 3.4 km, as the fixed focal depth for the location of all Dagger Draw swarm events. This choice appeared to produce epicenters with the smallest errors.

The map of epicenters for the Dagger Draw swarm (Fig. 3) is restricted to 15 events in Table 3 with epicenter errors of 3.0 km or less and gaps of 140° or less. All but one of these 15 quakes occurred after station DAG went into operation. Nine of the epicenters define a rectangular area 3.4 km east-west and 2.4 km north-south. From this 8-km^2 region, the other six epicenters extend northward for a distance of ~10 km.

An analysis of time differences between station arrivals indicates the epicenter distribution in Figure 3 applies throughout the 6.75 yrs of the Dagger Draw swarm, at least for the strong quakes. The magnitude 3.9 earthquake on 14 March 1999 is one of the 15 events in Figure 3 that is located in the 8-km^2 area of highest activity. Time differences between stations recording the 14 March 1999 earthquake were compared with the same differences for strong earthquakes on 17 March 1999 (3.5), 30 May 1999 (3.9), 17 September 2002 (3.5), and 23 May 2004 (3.9). The comparison showed that these four strong shocks also had epicenters within the area of highest activity in Figure 3.

Additional evidence supporting the epicenter distribution in Figure 3 are clearly defined S-P intervals observed on ~50 seismograms of weak Dagger Draw swarm quakes recorded at station DAG. The S-P intervals yield distances of 6–10 km, distances that are in agreement with the distribution of epicenters in Figure 3.

The eastern margin of the most active region in Figure 3 lies within a tight cluster (radius ~500 m) of three disposal wells located in sec. 4 T20S R24E and centered at 32.599° N latitude and 104.590° W longitude. The volume of water disposed of by injection in the three wells is very large. At the end of April 2003, the monthly disposal rate was 150,000 m^3. The cumulative disposal on the same date for the three wells was ~11,500,000 m^3. The cumulative volume by the end of 2004 is estimated to have been 14,500,000 m^3, equivalent to a cube of water ~245 m on a side.

The proximity of the earthquake epicenters to three wells that have injected very large amounts of water at a depth of ~3.4 km suggests that the earthquakes are induced. The classic example of earthquakes produced by injection of fluid occurred in the Denver area (Healy et al. 1968). From 8 March 1962 to 20 February 1966 ~550,000 m^3 of fluid was injected in a well at the Rocky Mountain Arsenal, an amount only ~3.8% of the estimated quantity of fluid injected into the three Dagger Draw oil field disposal wells by the end of 2004. Earthquakes in the Denver swarm ranged up to magnitude 5.5, and epicenters extended over a distance of ~10 km.

Healy et al. (1968) were able to establish that the Denver swarm was triggered by the fluid injection by using a careful analysis of daily fluid pressure variations and the temporal behavior of the earthquakes. For the Dagger Draw swarm, short-term comparisons between well-head pressures, fluid injected, and earthquake numbers and strengths have not been made for lack of the necessary data. For this reason, an absolutely conclusive connection between the Dagger Draw swarm and the very large volumes of injected water cannot be established.

Raton Basin earthquake sequence

The Raton Basin earthquake sequence is a tight cluster of shocks that straddles the New Mexico–Colorado border from approximately 36.75° to 37.25° N latitude (Fig. 1). From the beginning of the Raton Basin earthquake sequence on 28 August 2001 to 15 October 2001, the earthquakes were located north of the 37.00° N latitude border. On or shortly before 15 December 2001, epicenters for nearly all quakes shifted south of the border. Table 4 lists earthquakes that occurred in the Raton Basin earthquake sequence from 15 December 2001 to the end of 2004. Earthquake activity that preceded 15 December 2001 is described in an excellent and detailed U.S. Geological Survey investigation (Meremonte et al. 2002).

The New Mexico Tech Raton Basin earthquake sequence catalog (Table 4) lists 33 earthquakes, not a particularly impressive number of events. However, an analysis of number of earthquakes versus magnitude for the 33 earthquakes indicates many earthquakes below magnitude 3.0 were not detected because stations close to the activity did not exist (Fig. 4 or Appendix). An analysis of the 15 earthquakes with magnitudes of 3.0 or greater indicates that the number of earthquakes is increasing by about a factor of 10 for each unit decrease in magnitude. Extrapolation of this rate of increase to shocks with magnitudes less than 3.0 shows the data would be complete for earthquakes of magnitude 2.0 or greater if ~160 earthquakes had been detected and located in the approximately 36-month period. By comparison, this is two times the activity for any 36-month interval in the SSA (Sanford et al. 2002). By New Mexico standards, the Raton Basin earthquake sequence after 15 December 2001 is a remarkable seismic event.

Many locations of Raton Basin earthquakes are poorly constrained because the station nearest to the swarm events was in Albuquerque (ANMO), ~260 km to the southwest. A new U.S. Geological Survey station was installed in June 2003, station SDCO located ~110 km to the northwest of the Raton Basin earthquake sequence. When readings from this station were available, epicenter error decreased significantly.

The map of Raton Basin earthquake sequence epicenters (Fig. 4) after 15 December 2001 is restricted to the 18 events in Table 4 that have epicenter errors of 5 km or less and gaps of 140° or less. Most of these best-constrained locations are for earthquakes that occurred after station SDCO went into operation. However, even with readings from SDCO, distances from the Raton Basin earthquakes to seismograph stations ranged from approximately 100 to 600 km. Because of these very long paths, deviations of crustal structure from the 6.15 km/sec half-space model in SEISMOS can have a significant effect on epicenter locations. Therefore, the calculated locations can differ from the true locations in a manner dependent on the mix of stations used. Despite the uncertainty in epicenter locations, their distribution in Figure 4 indicates a very small geographic area is generating an exceptionally large number of earthquakes. Proving conclusively that this very unusual Raton Basin swarm has a natural origin may be as difficult as proving conclusively that its events are induced.

The major observation suggesting Raton Basin earthquake activity may be induced is the large quantity of water removed and disposed of by injection in the devel-

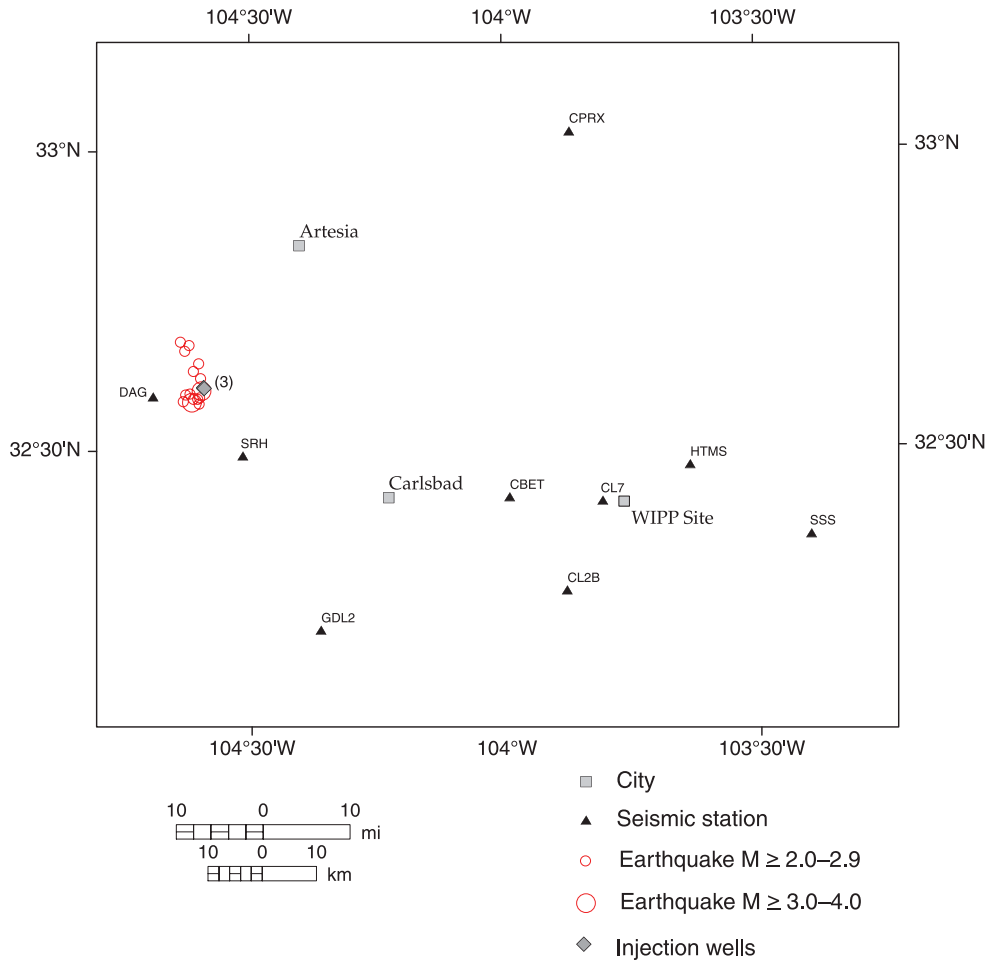

FIGURE 3—Southeastern New Mexico seismograph network stations. Epicenters shown for 15 earthquakes in the Dagger Draw swarm, 1999–2004, with magnitudes of 2.0 or greater, epicenter errors of 3.0 km or smaller, and gaps of 140° or smaller. The location of a tight cluster of three waste water disposal wells is also shown.

TABLE 3—Dagger Draw swarm earthquakes with magnitudes of 2.0 or greater: 1998–2004. Asterisks indicate earthquakes with epicenter errors less than or equal to 3.0 km and gaps less than or equal to 140°.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1std (km)	Gap (degrees)	Magnitude
1	1998	3	20	1	42	12.93	32	35.83	104	40.38	6.00	162	2.0
2	1998	6	16	5	52	19.68	32	35.10	104	37.76	4.48	158	2.0
3	1998	7	8	5	17	40.78	32	36.62	104	37.70	4.44	162	2.7
4	1998	7	27	12	47	23.25	32	35.66	104	41.49	2.65	273	2.0
5	1999	3	1	8	0	23.54	32	34.37	104	39.12	3.18	155	2.7
6	1999	3	14	1	10	15.73	32	41.06	104	37.39	4.17	143	2.2
*7	1999	3	14	22	43	18.09	32	34.84	104	36.94	2.58	84	3.9
8	1999	3	15	8	17	29.73	32	34.07	104	40.97	3.74	158	2.3
9	1999	3	17	12	29	23.17	32	34.52	104	39.90	3.40	156	3.5
10	1999	3	23	17	0	10.28	32	33.99	104	37.88	5.21	163	2.6
11	1999	4	20	4	39	6.99	32	34.41	104	37.97	3.96	153	2.1
12	1999	5	30	19	4	26.36	32	34.72	104	39.24	3.39	102	3.9
13	1999	5	30	20	47	42.18	32	35.65	104	41.26	4.28	156	2.7
14	1999	6	1	21	42	24.44	32	39.76	104	35.06	3.93	153	2.0
15	1999	6	7	22	28	46.78	32	35.00	104	41.57	4.62	170	2.3
16	1999	8	9	6	51	22.51	32	34.98	104	39.49	3.98	165	2.9
17	1999	8	9	19	28	42.59	32	32.02	104	43.47	4.25	178	2.0
18	1999	8	24	11	43	1.27	32	32.86	104	40.01	4.80	171	2.2
19	1999	9	6	16	39	24.11	32	33.54	104	39.73	4.90	169	2.7
20	1999	11	25	18	4	0.02	32	40.73	104	36.71	5.38	155	2.2
21	2000	2	2	7	14	19.30	32	33.49	104	42.45	4.50	174	2.5
22	2000	6	18	15	28	49.10	32	35.17	104	39.69	3.04	155	2.1
23	2000	12	1	4	9	42.06	32	33.66	104	43.74	4.12	102	2.1
24	2000	12	15	18	50	14.54	32	31.38	104	39.45	5.00	270	2.1
25	2001	3	19	16	18	36.62	32	41.48	104	39.10	3.56	145	2.4
26	2001	7	28	11	35	28.82	32	34.26	104	41.32	3.95	165	2.6
27	2002	1	9	10	23	1.97	32	35.26	104	38.32	5.08	159	2.0
28	2002	1	19	8	13	49.67	32	35.15	104	32.16	21.59	252	2.1

TABLE 3—continued

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1std (km)	Gap (degrees)	Magnitude
29	2002	2	9	1	35	1.83	32	32.69	104	40.91	3.43	160	2.1
30	2002	2	11	5	20	33.94	32	33.41	104	39.03	6.13	106	2.1
31	2002	6	13	9	15	7.38	32	36.70	104	41.28	6.81	118	2.0
32	2002	8	12	23	28	30.67	32	35.14	104	39.86	4.49	162	2.8
33	2002	8	12	23	36	29.80	32	32.48	104	41.59	9.30	314	2.1
34	2002	8	14	23	17	33.01	32	34.34	104	38.36	3.66	160	2.9
35	2002	8	19	18	51	52.87	32	34.75	104	40.36	5.30	163	2.1
36	2002	8	22	20	19	0.90	32	34.40	104	40.04	3.75	148	2.2
37	2002	8	23	10	21	17.75	32	33.55	104	40.77	4.80	165	2.2
38	2002	8	30	7	7	55.55	32	40.09	104	36.59	4.99	156	2.1
39	2002	9	17	15	45	14.92	32	35.46	104	38.91	3.71	143	3.5
40	2002	9	17	23	34	19.32	32	34.87	104	38.81	4.59	160	3.2
41	2002	9	22	22	58	10.20	32	40.85	104	41.13	5.98	111	2.1
42	2002	9	25	5	15	5.54	32	38.22	104	38.60	10.58	153	2.0
43	2002	10	28	2	15	38.61	32	36.03	104	39.43	2.96	160	2.0
44	2002	10	28	14	4	31.28	32	33.87	104	38.97	3.31	162	2.6
45	2002	10	28	16	55	42.24	32	33.85	104	38.06	4.22	161	2.1
46	2003	1	19	15	31	32.76	32	35.75	104	39.48	11.02	160	2.2
47	2003	1	20	16	34	23.35	32	34.25	104	39.77	4.00	163	2.2
48	2003	1	20	18	47	39.79	32	34.78	104	38.46	3.58	153	2.5
49	2003	2	11	13	13	59.69	32	41.56	104	39.92	3.73	154	2.2
50	2003	2	13	0	28	19.95	32	41.68	104	38.20	5.01	156	2.3
51	2003	2	14	7	25	39.50	32	41.53	104	38.03	4.74	111	2.1
52	2003	2	20	17	24	26.97	32	43.39	104	43.49	6.24	277	2.4
53	2003	2	20	17	27	42.33	32	42.19	104	36.94	4.23	149	2.2
54	2003	2	23	0	14	11.02	32	42.24	104	45.20	6.16	280	2.0
55	2003	2	24	19	47	15.40	32	43.37	104	49.74	34.09	286	2.0
56	2003	2	27	13	10	0.40	32	41.00	104	39.15	6.47	159	2.0
57	2003	3	19	8	35	12.36	32	39.06	104	36.44	3.22	151	3.0
58	2003	3	28	17	58	27.49	32	35.08	104	41.76	5.38	170	2.1
59	2003	4	15	21	48	54.24	32	33.24	104	38.32	7.05	309	2.0
60	2003	5	8	13	0	32.11	32	40.96	104	39.88	4.30	158	2.7
61	2003	5	18	2	34	33.78	32	34.20	104	39.09	4.21	162	2.1
62	2003	6	13	18	37	18.14	32	41.65	104	39.92	4.44	159	2.0
63	2003	6	17	12	27	37.94	32	35.68	104	51.81	6.53	289	2.0
64	2003	6	21	2	3	9.00	32	42.32	104	37.86	2.84	150	3.3
65	2003	6	21	3	24	39.81	32	41.09	104	38.87	4.57	158	2.3
*66	2003	9	15	11	27	6.23	32	35.15	104	36.77	2.22	124	2.9
67	2003	10	19	3	41	2.16	32	42.21	104	37.85	3.13	112	2.3
68	2003	11	13	19	59	17.23	32	41.47	104	36.79	2.55	154	2.1
69	2003	11	19	7	11	15.44	32	32.12	104	38.22	2.89	164	2.2
70	2003	12	23	12	40	35.26	32	41.33	104	35.75	2.76	201	2.1
*71	2004	1	5	22	20	43.80	32	40.53	104	37.24	1.86	106	2.1
*72	2004	1	30	7	50	27.03	32	37.96	104	36.74	1.82	103	2.1
73	2004	2	12	15	12	38.33	32	31.29	104	41.34	5.25	171	2.1
*74	2004	2	19	11	27	26.74	32	37.23	104	35.90	2.47	104	2.3
75	2004	2	24	20	57	21.20	32	33.98	104	37.55	3.46	146	2.4
*76	2004	3	3	23	14	20.99	32	39.96	104	37.75	2.42	106	2.6
*77	2004	3	14	15	6	37.06	32	34.93	104	37.96	2.12	132	2.4
78	2004	3	21	23	12	47.05	32	34.45	104	38.39	3.06	144	2.1
*79	2004	3	29	3	35	17.65	32	35.62	104	37.68	2.54	117	2.1
80	2004	4	20	17	41	57.70	32	31.28	104	40.94	3.31	163	2.2
*81	2004	4	24	22	40	27.20	32	40.90	104	38.23	1.56	99	2.0
*82	2004	5	23	9	22	4.83	32	35.96	104	35.76	1.80	111	3.9
*83	2004	5	23	12	9	49.10	32	35.15	104	36.26	2.30	122	2.0
*84	2004	5	29	2	46	1.57	32	38.71	104	36.11	2.85	106	2.1
*85	2004	6	22	8	55	2.62	32	34.70	104	36.08	2.62	136	3.0
86	2004	6	22	9	14	3.63	32	35.05	104	35.90	2.55	162	2.1
*87	2004	7	2	19	41	34.45	32	35.70	104	37.16	2.68	136	2.5
88	2004	7	18	19	19	38.65	32	32.70	104	39.68	2.15	158	2.2
89	2004	7	19	0	42	45.65	32	40.75	104	36.72	3.53	251	2.0
90	2004	7	19	9	51	6.90	32	32.34	104	38.17	2.23	156	2.0
91	2004	8	26	18	45	17.26	32	33.78	104	38.67	2.17	155	2.7
*92	2004	10	28	2	59	3.73	32	35.29	104	36.02	2.38	120	3.0
93	2004	11	1	16	24	22.14	32	32.01	104	38.35	2.37	169	2.0
94	2004	12	20	20	42	52.43	32	31.41	104	37.44	2.20	169	2.0

opment of coalbed methane in the Raton Basin of New Mexico (Hoffman and Brister 2003). Water is removed from producing zones at depths of ~300 m to ~900 m and injected into disposal wells at depths of ~1,800 m to 2,100 m . The cumulative volume of water removed and then injected from the beginning of coalbed methane development in October 1999 to 1 January 2005 was 6,072,125 m^3, equivalent to a lake with a depth of 2 m and a diameter of 2 km. By comparison, this amount is 11 times the fluid injected during the induced Denver earthquake swarm from 1962 through 1967 (Healy et al. 1968).

The observation that suggests the Raton Basin earthquake sequence is the result of injection of large volumes of water is the

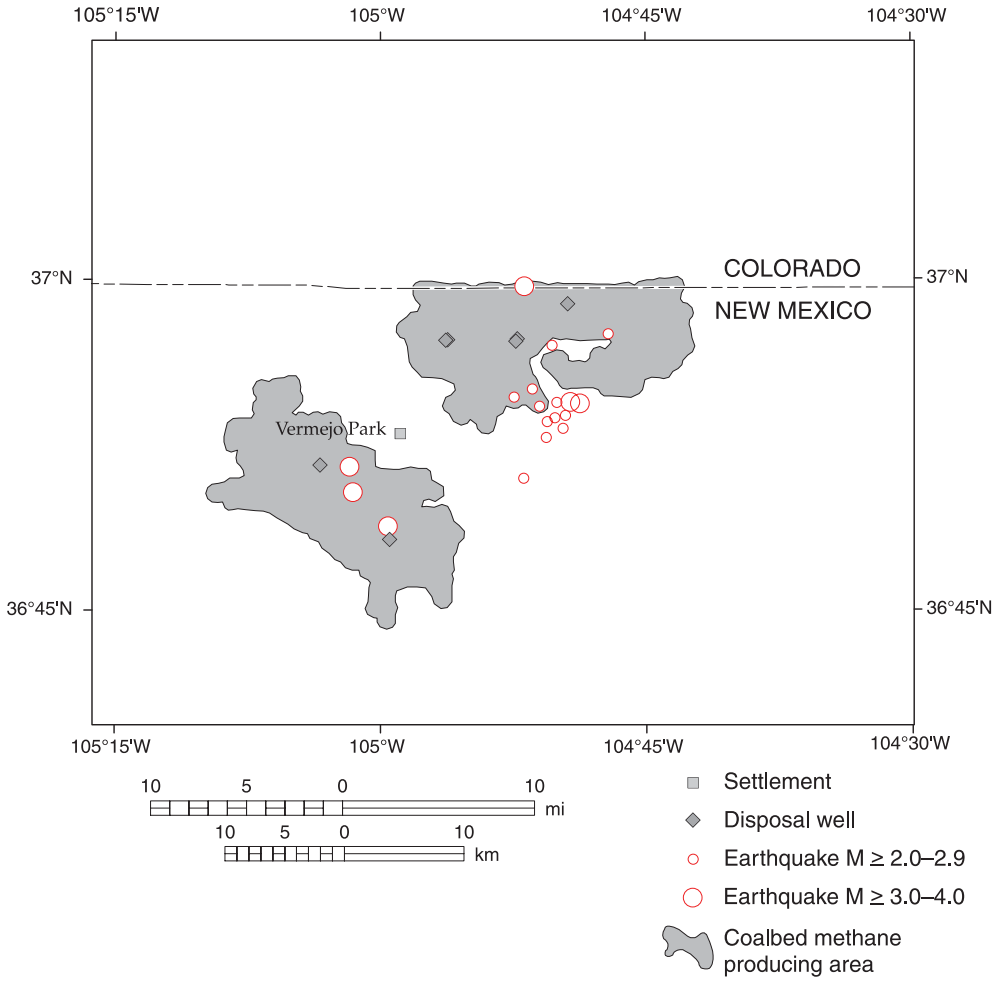

FIGURE 4—Epicenters of 18 earthquakes in the Raton Basin swarm, 2001–2004 with magnitudes of 2.0 or greater, epicenter errors of 5.0 km or smaller, and gaps of 140° or smaller. The locations of five waste water disposal wells and the outline of the coalbed methane fields are also shown.

proximity of earthquake epicenters to disposal wells. The average epicenter errors for the 18 earthquakes in Figure 4 are 4.1 km (1 s.d.) and 8.2 km (2 s.d.). Considering these errors, the earthquakes could have occurred at or near the five disposal wells. Earthquakes can be generated if the disposal of water increases pore pressure, which then reduces the frictional resistance to faulting because the effective normal stress across the fault plane is decreased (Healy et al. 1968). The authors do not have critical information, for example, on injection pressures at disposal wells that would indicate conclusively that disposal of large volumes of water is generating the earthquakes within the coalbed methane fields.

The diffuse distribution of epicenters in Figure 4 might suggest two additional mechanisms for inducing earthquakes in the coalbed methane fields: (1) sudden subsidence of overburden because of removal of water and (2) hydro-fracturing to increase production of methane. Rapid ground subsidence over areas of gas and petroleum production has been observed (Fielding et al. 1998) and can induce earthquakes (Richter 1958; Kanamori and Hauksson 1992). The authors do not know whether subsidence is actually occurring in the coalbed methane producing areas of the Raton Basin, but Synthetic Aperture Radar might be able to answer the question (Fielding et al. 1998). Hydro-fracturing is being used in the coalbed methane fields of the Raton Basin to enhance the production of methane (EPA 2004), and it can induce earthquakes (Kanamori and Hauksson 1992; Fehler et al. 2001).

Preliminary studies indicate that the Raton Basin earthquake sequence in New Mexico continued through 2005 at the same intensity as observed from 2002 through 2004 and with the same general epicenter distribution as shown in Figure 4. About 12 earthquakes of magnitude 2.0 or greater occurred, one of these was magnitude 4.5, probably the strongest of the Raton Basin swarm.

Summary and conclusions

The number of magnitude 3.0 or greater earthquakes for the 6-yr 1999–2004 period is fairly impressive: 15 for the Raton Basin swarm, 10 for the Dagger Draw swarm, and nine for the remainder of New Mexico. This level of activity for a 6-yr period is comparable to other active 6-yr periods, for example, 1965–1970, 1971–1976, and 1990–1995 (Sanford et al. 2002). However, what makes the 1999–2004 period different from the earlier periods is that 75% of the magnitude 3.0 or greater earthquakes were generated in two very small regions located close to where very large amounts of water are being produced and disposed of by injection, a necessary procedure accompanying the production of gas and oil. Comparable periods of intense activity over several years from small areas did not occur anytime during the period 1962 through 1998. The 6-yr 1999–2004 interval is a truly unique period in the region's earthquake history.

Another characteristic of earthquake activity from 1999 through 2004 is a continuation of abnormally low activity in the Socorro Seismic Anomaly that commenced in 1993. Important characteristics of seis-

TABLE 4—Raton Basin swarm earthquakes with magnitudes of 2.0 or greater: 2001–2004. Asterisks indicate earthquakes with epicenter errors less than or equal to 5.0 km and gaps less than or equal to 140°.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1std (km)	Gap (degrees)	Magnitude
1	2001	12	15	7	58	30.63	36	57.97	105	3.98	11.81	304	3.0
2	2002	1	26	1	6	4.62	36	49.37	104	48.13	8.69	297	3.0
3	2002	2	7	5	19	54.30	37	1.37	104	54.43	13.36	313	2.4
4	2002	3	20	14	33	7.87	36	50.25	104	53.16	11.80	313	2.3
5	2002	3	20	23	16	55.37	36	46.88	104	53.47	8.23	309	2.0
6	2002	6	18	9	12	37.20	36	55.91	104	50.03	5.61	92	3.0
*7	2002	11	14	3	44	39.97	36	53.71	104	50.14	4.68	133	2.6
8	2002	11	14	4	56	52.73	36	54.96	104	48.51	5.43	129	3.0
*9	2002	12	9	17	30	41.35	36	55.02	104	51.42	3.86	134	2.0
*10	2002	12	31	19	2	30.03	36	59.69	104	51.86	4.84	131	3.6
*11	2002	12	31	19	34	45.25	36	56.99	104	50.30	4.73	78	2.2
12	2003	4	28	7	32	25.78	36	55.16	105	2.40	8.93	218	3.3
*13	2003	6	3	18	9	28.05	36	57.52	104	47.11	3.94	106	3.0
*14	2003	6	15	0	22	18.70	36	54.43	104	49.27	4.21	120	3.3
*15	2003	6	20	3	10	20.89	36	52.81	104	50.62	3.28	111	2.4
*16	2003	8	14	0	11	9.28	36	53.24	104	49.67	4.03	91	2.7
17	2003	9	8	11	2	50.32	37	19.93	104	44.77	7.02	178	2.7
*18	2003	9	13	15	22	41.63	36	48.79	104	59.57	4.44	75	3.6
19	2003	9	19	18	14	25.15	36	59.55	104	53.70	6.91	211	2.5
20	2003	9	19	18	18	34.60	36	54.07	104	46.48	6.17	210	2.4
21	2003	10	25	12	55	57.77	37	2.08	104	46.67	6.39	99	3.1
*22	2003	11	5	20	17	39.55	36	53.81	104	49.55	4.91	133	2.1
23	2003	11	24	7	5	59.17	36	56.86	104	55.27	6.06	136	3.2
24	2003	12	12	17	24	12.85	36	49.36	105	1.86	12.24	313	2.3
*25	2004	1	10	4	7	11.29	36	50.98	104	51.90	3.96	115	2.1
26	2004	1	14	1	14	15.07	36	56.65	104	47.17	5.09	91	3.1
*27	2004	2	3	14	34	22.80	36	53.53	104	50.57	4.34	78	2.7
*28	2004	3	22	12	9	56.38	36	50.35	105	1.54	3.16	81	3.6
*29	2004	3	30	1	2	55.30	36	54.66	104	52.43	3.74	77	2.8
*30	2004	3	30	2	23	37.85	36	54.41	104	50.02	3.79	78	2.7
*31	2004	3	30	2	41	5.79	36	54.24	104	51.01	3.71	78	2.9
*32	2004	5	31	3	27	43.38	36	54.37	104	48.73	3.16	78	3.1
*33	2004	8	1	6	50	46.79	36	51.50	105	1.75	4.19	101	3.8

mic activity exclusive of the Socorro Seismic Anomaly, the Raton Basin swarm, and the Daggar Draw swarm are: (1) an unusually large percentage of quake epicenters in the Great Plains of west Texas, (2) a diffuse band of earthquakes extending from the SSA to the New Mexico–Texas border, and (3) the near absence of earthquakes in the Rio Grande rift except for the Socorro Seismic Anomaly.

Acknowledgments

This report would not have been possible without the assistance of a long list of talented undergraduate and graduate research assistants at NMT. Their help ranged from maintenance of the NMT Seismological Observatory to major research contributions. Two important examples are: (1) Hans Hartse' development of SEISMOS, the computer program that has proved so useful in locating earthquakes within the Socorro Seismic Anomaly and throughout New Mexico and bordering areas, and (2) Kuo-wan Lin's additions to SEISMOS to improve locations of regional earthquakes with poor azimuthal station coverage.

We would like to thank the following individuals for providing data useful in the location of some of the earthquakes in the catalogs: Diane Doser (University of Texas–El Paso) and Hans Hartse (Los Alamos National Laboratory). As noted in this report, we used data available from seismograph stations operated by the U.S. Geological Survey, the Incorporated Research Institutions for Seismology (IRIS Consortium), and the U.S. Bureau of Reclamation. Finally we wish to thank Gretchen Hoffman and Brian Brister for information on the development of coalbed methane in the Raton Basin of New Mexico, and Susan Bilek for her assistance in generating the figures for this report.

The paper was greatly improved by thoughtful and careful reviews by Gretchen Hoffman, Ron Broadhead, and Dave Love (New Mexico Bureau of Geology and Mineral Resources) and Susan Bilek (Department of Earth and Environmental Science), New Mexico Institute of Mining and Technology.

We are indebted to Jane Love and Nancy Gilson (New Mexico Bureau of Geology and Mineral Resources) for improving the text, figures, and tables of our original manuscript and for putting the paper into the final form presented here.

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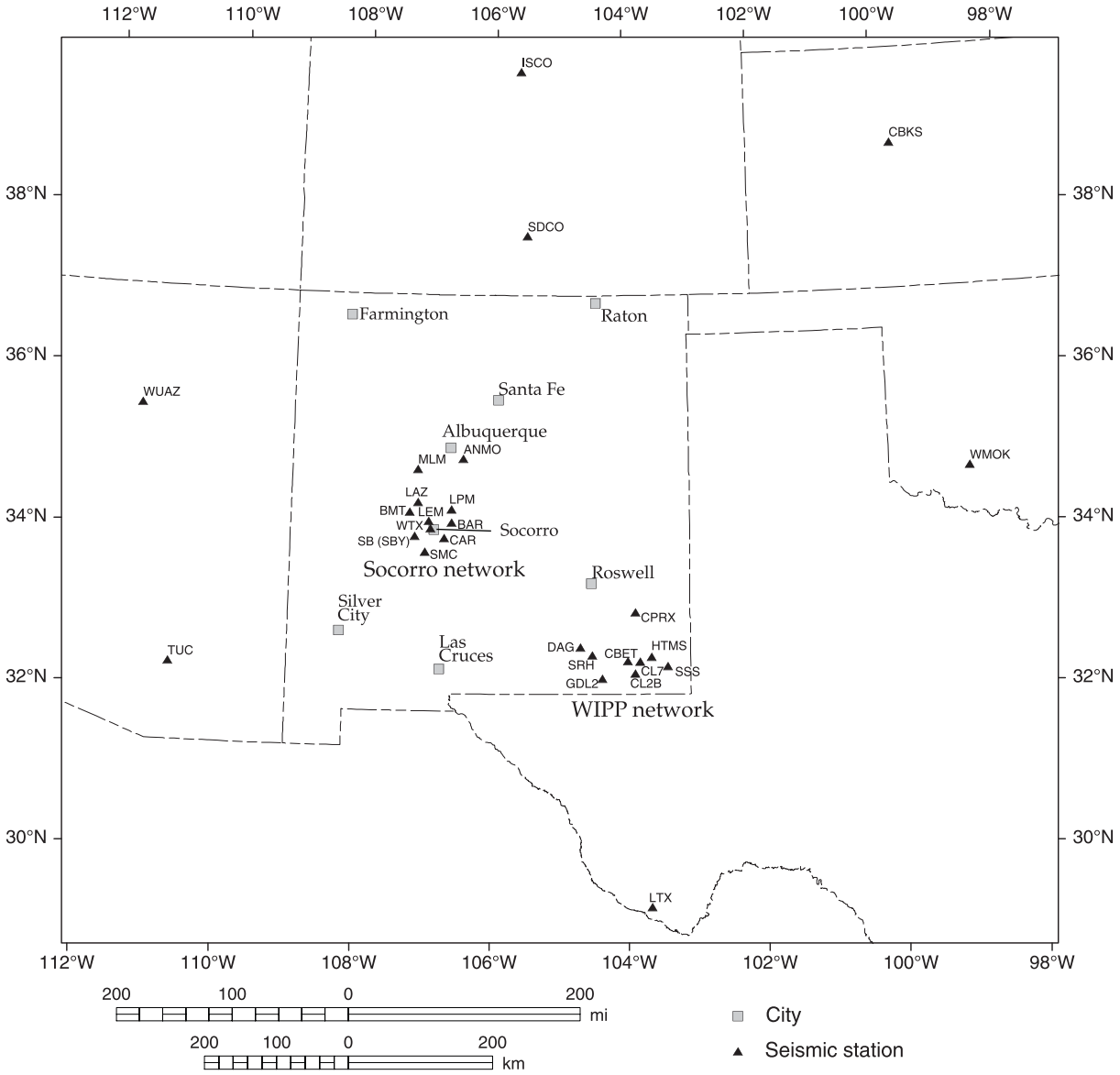
[1]Data are not currently available online but will be available online in the future.

[2]The model has four layers: the first a thickness of 10 km, a P-wave velocity of 5.95 km/sec, and a Poisson's ratio of 0.256; the second has a thickness of 8.75 km, a P-wave velocity of 5.80 km/sec, and a Poisson's ratio of 0.228; the third has a thickness of 14.75 km, a P-wave velocity of 6.50 km/sec, and a Poisson's ratio of 0.250; and the fourth has an infinite thickness with a P-wave velocity of 8.10 km/sec, and a Poisson's ratio of 0.250.

Appendix

Location of seismograph stations used for the study of earthquakes in New Mexico and bordering areas for the period 1999–2004. Code names for the stations in tight clusters near Socorro and in southeastern New Mexico are also shown in Figures 2 and 3.



Code names and coordinates of seismograph stations used to locate earthquakes in New Mexico and bordering areas during the 1999 through 2004 period. The organizations operating the stations and network designations are also listed.

Station code	Latitude	Longitude	Elevation	Network	Network code
ANMO	34.9502	-106.4602	1743.0	Global Seismic Network - IRIS/USGS	IU
TUC	32.3097	-110.7842	906.0	Global Seismic Network - IRIS/USGS	IU
BAR	34.1502	-106.6278	2121.0	New Mexico Tech Seismic Network - Socorro	SC
BMT	34.2750	-107.2602	1972.0	New Mexico Tech Seismic Network - Socorro	SC
CAR	33.9525	-106.7345	1662.0	New Mexico Tech Seismic Network - Socorro	SC
LAZ	34.4020	-107.1393	1853.0	New Mexico Tech Seismic Network - Socorro	SC
LEM	34.1655	-106.9742	1698.0	New Mexico Tech Seismic Network - Socorro	SC
LPM	34.3117	-106.6318	1737.0	New Mexico Tech Seismic Network - Socorro	SC
MLM	34.8142	-107.1450	2088.0	New Mexico Tech Seismic Network - Socorro	SC
SB (SBY)	33.9752	-107.1807	3230.0	New Mexico Tech Seismic Network - Socorro	SC
SMC	33.7787	-107.0193	1560.0	New Mexico Tech Seismic Network - Socorro	SC
WTX	34.0722	-106.9458	1555.0	New Mexico Tech Seismic Network - Socorro	SC
CBET	32.4205	-103.9900	1042.0	New Mexico Tech Seismic Network - WIPP	SC
CL2B	32.2642	-103.8787	1045.0	New Mexico Tech Seismic Network - WIPP	SC
CL7	32.4132	-103.8075	1033.0	New Mexico Tech Seismic Network - WIPP	SC
CPRX	33.0308	-103.8667	1356.0	New Mexico Tech Seismic Network - WIPP	SC
DAG	32.5913	-104.6918	1277.0	New Mexico Tech Seismic Network - WIPP	SC
GDL2	32.2003	-104.3635	1213.0	New Mexico Tech Seismic Network - WIPP	SC
HTMS	32.4725	-103.6342	1192.0	New Mexico Tech Seismic Network - WIPP	SC
SRH	32.4918	-104.5153	1270.0	New Mexico Tech Seismic Network - WIPP	SC
SSS	32.3547	-103.3968	1073.0	New Mexico Tech Seismic Network - WIPP	SC
CBKS	38.8140	-99.7374	677.0	USGS Seismic Network	US
ISCO	39.7997	-105.6134	2743.0	USGS Seismic Network	US
LTX	29.3339	-103.6669	1013.0	USGS Seismic Network	US
SDCO	37.7456	-105.5012	2569.0	USGS Seismic Network	US
WMOK	34.7379	-98.7810	486.0	USGS Seismic Network	US
WUAZ	35.5169	-111.3739	1592.0	USGS Seismic Network	US