Earthquake catalogs for New Mexico and bordering areas: 2005-2009

Jana Pursley, Susan L. Bilek, and Christine J. Ruhl

New Mexico Geology, v. 35, n. 1 pp. 3-12, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v35n1.3

This page is intentionally left blank to maintain order of facing pages.

Earthquake catalogs for New Mexico and bordering areas: 2005–2009

Jana Pursley, janas@ees.nmt.edu, and *Susan L. Bilek,* Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico 87801;
Christine J. Ruhl, Nevada Seismological Laboratory, University of Nevada–Reno, Reno, Nevada 89557

This latest report on earthquake activity in New Mexico and bordering areas by New Mexico Institute of Mining and Technology (NMT) investigators covers the 5-yr period 2005–2009. 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 and for 1999 through 2004 published in New Mexico Geology (v. 28, no. 4, pp. 99-109) (Data are available online at ***http://geoinfo.nmt.edu/publications/circulars/210/.****)*

Abstract

The earliest documented records of large earthquakes in New Mexico go back to the early 1900s, and seismicity has been monitored instrumentally since the early 1960s. This catalog is a continuation of previous catalogs spanning 1962 through 2004 and includes 165 earthquakes $M_d \geq 2.0$. In addition it also includes all located events with $M_d \geq 0$ in New Mexico. Similar to the 1999–2004 catalog, we found that a large number of earthquakes $M_d \geq 2.0$ were located in two distinct regions. One of these regions is in southeastern New Mexico near the Dagger Draw oil field (32% of all events with $M_d \geq 2.0$), and the other is in northeastern New Mexico within and surrounding the coalbed methane fields near Raton (44% of all events with $M_d \geq 2.0$). Only 5% of the larger earthquakes occurred in the Socorro Seismic Anomaly region. The remaining events were scattered throughout New Mexico, southeastern Colorado, eastern Arizona, northern Mexico, and western Texas.

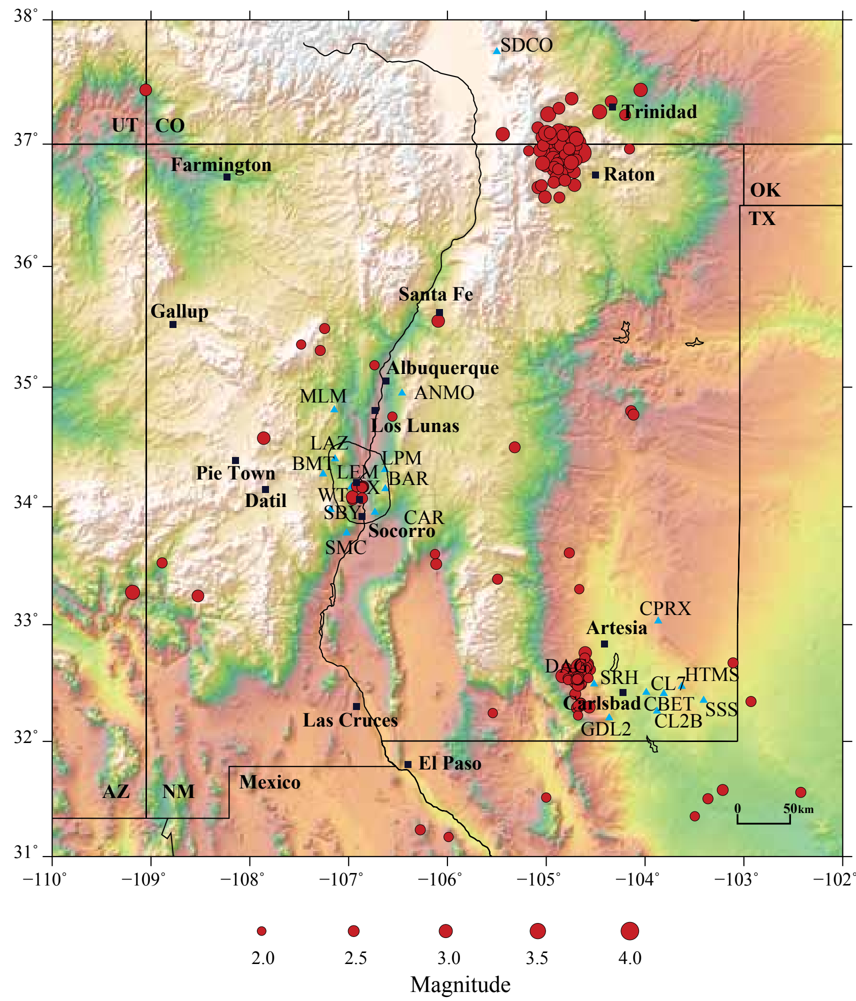

FIGURE 1—$M_d \geq 2.0$ earthquakes that occurred in New Mexico and surrounding regions during the 2005–2009 time period (165 events, red circles, scaled by magnitude). The two large clusters are focused in the Raton area (73 earthquakes) and near Carlsbad (53 earthquakes in the Delaware Basin). Also shown are major cities (squares) and the seismic station locations (blue triangles). The Socorro Seismic Anomaly (SSA, black outline [Balch et al. 1997]) in the central Rio Grande rift contains a cluster of eight $M_d \geq 2.0$ events.

Introduction

This catalog summarizes earthquake activity in New Mexico and surrounding regions from 2005 through 2009. It is a continuation of the earthquake catalogs for the 42-yr period 1962–2004 (Sanford et al. 2002, 2006). We include here all locatable events that occurred in New Mexico and surrounding regions with $M_d \geq 0$, as well as a subset of events magnitude 2.0 and greater for direct comparison with the previous catalogs. The signal processing and reported earthquake location parameters are defined in Sanford et al. (2006). In addition to signal processing from our local seismic network (network code SC), we were able to improve locations of events that occurred during the Earthscope USArray deployment in New Mexico due to the denser seismic station coverage all over the state during the 2008–2009 time period.

Earthquakes with $M_d \geq 2.0$

From 2005 through 2009 there were 165 earthquakes of $M_d \geq 2.0$ in New Mexico and surrounding regions within an area spanning 31°–38° N latitude and 101°–111° W longitude (Fig. 1). Most of these events were in three distinct clusters with 32% (53 earthquakes) of all earthquakes located in southeastern New Mexico, 44% (73 events) near Raton, northern New Mexico, and 5% (8 events) in the Socorro Seismic Anomaly (SSA), which is an approximately 5,000 km^2 region in central New Mexico. The remaining 19% of $M_d \geq 2.0$ earthquakes (31 events) were scattered throughout New Mexico and the border areas of Arizona, Texas, and Colorado.

Past catalogs suggest that the two largest clusters, the Dagger Draw sequence in southeast New Mexico and the Raton sequence in northern New Mexico, are induced (Sanford et al. 2006). In southeast New Mexico, the oil production in the Delaware Basin might be responsible for most of the seismic activity near the Dagger Draw oil field. In the Raton area many earthquakes might be the result of injecting

New Mexico Geology, **v. 35, no. 1, pp. 3–12; Data Repository 20130001.**

TABLE 1—Socorro Seismic Anomaly earthquakes with magnitudes of 2.0 or greater: 2005–2009.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
1	2005	10	30	2	57	35.79	34	3.66	106	57.59	0.41	70	2.3
2	2007	5	23	5	16	58.85	34	4.80	106	57.67	0.42	68	2.8
3	2008	9	29	15	32	36.51	34	10.16	106	55.00	0.93	75	2.4
4	2009	8	20	1	57	24.86	34	4.26	106	51.78	0.26	39	2.3
5	2009	8	27	6	51	45.85	34	10.05	106	51.25	0.27	51	2.0
6	2009	8	30	0	31	1.11	34	9.92	106	51.28	0.26	45	2.5
7	2009	8	30	6	39	48.54	34	9.85	106	51.54	0.36	72	2.3
8	2009	8	30	7	9	44.63	34	9.68	106	51.77	0.37	72	2.3

and/or removing large quantities of water associated with the production of coalbed methane. The remaining 39 earthquakes are separated into the SSA region events and the remainder of New Mexico and bordering area events (RNM). To be consistent and for comparison purposes, we follow the division into these regions used in the past catalogs.

In the previous catalogs, SSA contained 23% of $M_d \geq 2.0$ events during the 1962–1998 time period (Sanford et al. 2002) and 15% of the earthquakes in the 1999–2004 time period (Sanford et al. 2006). In this catalog, the SSA contributes 21% of the earthquakes (8 out of 39 events) if we ignore the induced seismicity in the two largest clusters.

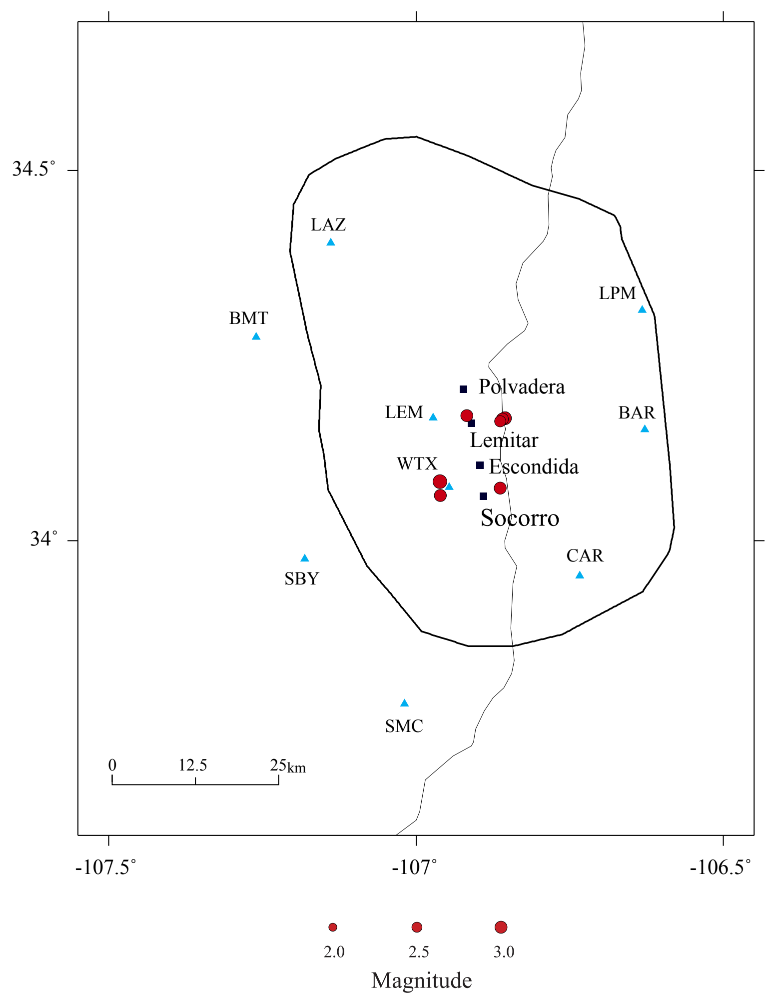

FIGURE 2—Locations of eight $M_d \geq 2.0$ earthquakes (red circles scaled by magnitude) that occurred within the Socorro Seismic Anomaly (SSA, solid line [Balch et al. 1997]) from 2005 through 2009. Also shown are station locations of the Socorro Seismic Network (blue triangles).

Earthquakes with $M_d \geq 0.0$

We also publish the results of $M_d \geq 0.0$ events in Appendix A of this catalog (available online at **http://geoinfo.nmt.edu/repository/index.cfm?rid=20130001**). This group consists of 1,375 instrumentally located earthquakes from 2005 through 2009. Slightly more than one-half of these events (735 earthquakes, 53%) were within the SSA region (Fig. A1). There were 271 events located in the Dagger Draw region bounded by 32.5°–32.75° N latitude and 104.4°–104.8° W longitude (20%, Fig. A2). The remainder of the events (369 earthquakes, 27%) were just outside of the boundaries for SSA and Dagger Draw, or were scattered throughout New Mexico and bordering states. There were no detectable events in the Raton–Trinidad area with $0.0 \leq M_d < 2.0$ recorded on our network, due to the large distance between the area and our seismic stations. We detect events with very small magnitudes (as small as −1.5) in the Dagger Draw and SSA areas due to the station proximity. However, events near the west and especially north borders of New Mexico need to be at least M_d 1.5 for us to locate them.

Procedures

Earthquake data

The Socorro Seismic Network (SC) provided most of the data used for earthquake location. This network consists of nine short-period stations located in southeast New Mexico surrounding the Waste Isolation Pilot Plant (WIPP) and 10 short-period stations located in central New Mexico bordering the SSA. Data are also obtained from nearby stations located in Arizona, Colorado, and Texas (the Arizona Seismic Network, network code AE; the Global Seismograph Network, network code IU; and the United States National Seismic Network, network code US). In late 2009 the New Mexico Tech geophysics group adopted a broadband USArray station Y22A, which is now also a part of the SC network. In addition to the permanent stations, data from several 120 sec to 50 Hz broadband Earthscope Transportable Array stations were available

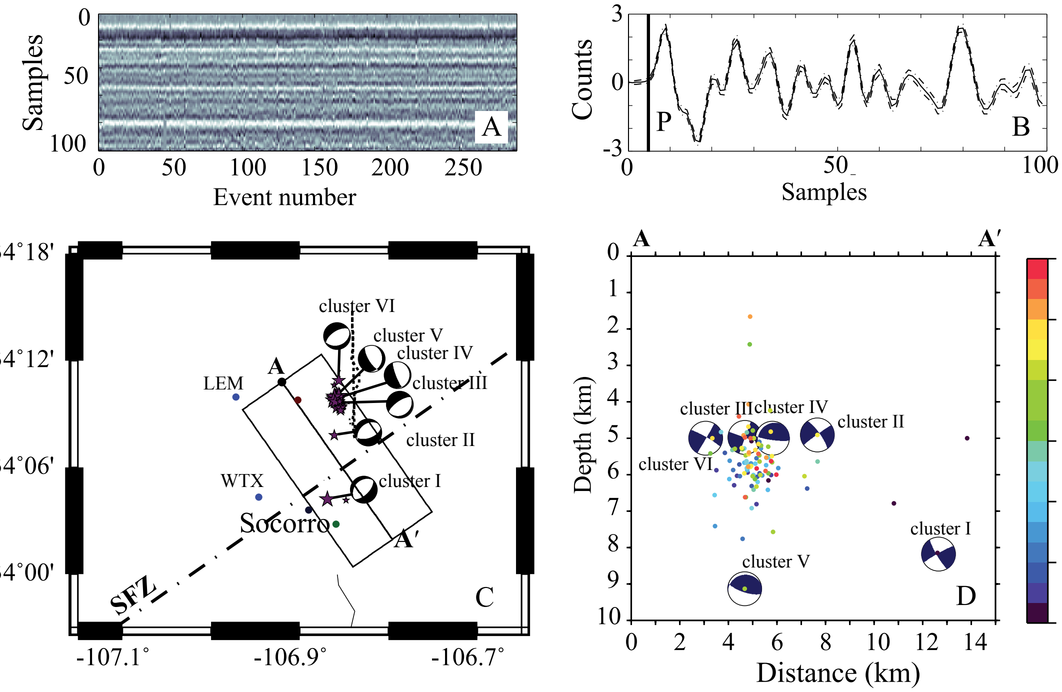

FIGURE 3—Lemitar earthquake sequence details (modified from Ruhl et al. 2010): **A**—Waveforms of 298 earthquakes recorded at station BAR, aligned on first arriving P (at 0 samples, y-axis). All waveforms meet cross-correlation threshold of 0.55. **B**—Stack of the 298 cross-correlated waveforms from station BAR. **C**—Plane view of the largest 105 cross-correlated events with focal mechanisms (white quadrangle represents dilatation, black compression) for each subcluster. Socorro Fracture Zone (SFZ, Sanford and Lin 1998) is approximated with a dash-dot line. The Veranito fault is shown with a dotted line (Cather et al. 2004). **D**—Cross section (A–A′ from panel C) of the events and focal mechanisms in C. Note that event symbols are color-coded based on relative time since the first event in the data set.

for most of 2008–2009. The data from these additional stations helped greatly to improve event location parameters and quality, especially for the Raton earthquakes.

Earthquake size and location

The magnitudes for all the events within these catalogs were determined using a local duration-based magnitude formula (Ake et al. 1983):

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

where τ_d is the manually selected duration of the earthquake signal in seconds. The magnitude of an event is determined using signal duration recorded on the short-period (100 samples/sec) stations only.

Hypocenters and origin times were estimated using direct and reflected phase arrivals off the Socorro Magma Body (SMB) in the SEISMOS location algorithm (Hartse et al. 1992). This algorithm uses regionally tailored velocity models for events within the SSA, near Raton, and for the remainder of New Mexico. Direct P- and S-wave arrivals were used in all of the regions; the reflected arrivals were used only in the SSA area. Focal depths are generally unconstrained with default depth fixed at 5 km (e.g., Sanford et al. 2006). Only events with reflected phases in the SSA region have a constrained depth solution.

Socorro Seismic Anomaly (SSA)

Earthquakes in the SSA are very likely caused by the extensional tectonic system of the Rio Grande rift, largely because the SSA region overlies a thin and extensive magma body (the Socorro Magma Body, SMB) at a depth of approximately 19 km (Balch et al. 1997). The $M_d \geq 2.0$ events within the SSA region from 2005 through 2009 are listed in Table 1, and locations are shown in Figure 2 ($M_d \geq 0.0$ events are listed in Table A1, and plotted in Fig. A1). The median of earthquake epicentral errors was 0.36 km, and the median of the station coverage gap was 69°. These values are about 25% lower than the median values for the 1999–2004 catalogs, which we attribute to the additional station coverage from the Earthscope USArray network. Six out of the eight events with $M_d \geq 2.0$ that were located within the SSA borders occurred during the deployment period of these additional stations. All eight events within the SSA region with magnitude 2.0 or greater were between Socorro and Polvadera. Four out of the eight events located near Lemitar occurred within a 10-day period in 2009. These events were part of an extended earthquake sequence during the August–September 2009 period described below. The other four events were near Socorro Peak (two events), near Escondida (one event), and near Polvadera (one event).

2009 Lemitar earthquake sequence

As most of the $M_d \geq 2.0$ events in the SSA region occurred during a continuous earthquake sequence, we describe that sequence in more detail here. This sequence started with a magnitude 2.3 event near Escondida, just north of Socorro, on 20 August 2009 (event #4, Table 1). Two days later seismicity shifted north of this initial event by approximately 10 km; however, this shift lacks a clear migration pattern. Between 23 August and 15 September 2009, 431 events were located in proximity to the second location (e.g., event #5, Table 1) within a 34.5 km^3 volume (Ruhl et al. 2010).

These events were at shallow depths (1.1–8.9 km), with magnitude 2.0 and greater earthquakes occurring on average 1.5 km shallower than the smaller events. The depth errors ranged between 0.31 and 1.68 km, with an average of 0.51 km (median 0.43 km). Focal mechanisms computed using on average 22 first-motions (data from the SC and TA networks) of seven earthquakes from this sequence suggest that these events occurred along north-to northwest-striking normal faults. Some of the earthquakes intersect the nearby north-striking Veranito fault at depth (dotted line in Fig. 3C, Cather et al. 2004). The fault's most recent surface rupture is weakly constrained, but it is older than early to middle

TABLE 2—Remainder of New Mexico and bordering areas earthquakes with $M_d \geq 2.0$: 2005–2009.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
1	2005	1	13	22	13	3.45	34	48.02	104	8.50	4.30	251	2.4
2	2005	1	30	11	32	37.73	31	33.42	102	25.42	10.39	331	2.2
3	2005	7	29	5	8	49.85	33	23.25	105	29.55	12.74	324	2.2
4	2005	9	27	11	42	32.11	31	34.91	102	18.27	4.77	249	2.0
5	2006	6	15	6	13	4.25	30	60.00	105	32.77	7.04	40	2.0
6	2006	6	23	12	13	18.62	35	18.44	107	17.28	3.82	299	2.3
7	2006	7	17	8	42	16.33	33	36.47	104	45.96	3.35	186	2.2
8	2007	4	3	6	19	59.72	32	40.26	103	6.47	6.88	310	2.2
9	2007	8	15	6	53	2.17	35	32.97	106	5.51	2.89	142	2.7
10	2007	9	8	7	15	36.06	33	16.43	109	11.14	5.81	289	3.1
11	2007	9	10	10	27	37.80	31	30.84	105	00.01	4.63	265	2.1
12	2007	9	15	5	26	28.12	33	31.40	108	53.34	6.15	299	2.2
13	2007	11	3	9	30	47.06	33	14.65	108	31.57	5.14	292	2.5
14	2007	12	21	17	38	18.52	33	18.11	104	39.91	2.91	174	2.0
15	2008	4	16	9	6	7.89	33	30.82	106	6.80	2.93	158	2.4
16	2008	5	23	21	21	41.70	32	14.51	105	32.34	6.62	229	2.1
17	2008	6	6	20	10	7.69	37	26.15	109	3.07	12.22	288	2.6
18	2008	11	2	13	57	25.00	33	35.87	106	7.55	2.27	187	2.0
19	2008	11	24	9	12	14.09	34	29.87	105	19.22	8.70	218	2.4
20	2009	3	3	22	58	14.60	34	46.35	104	7.07	5.69	268	2.4
21	2009	6	5	17	17	1.86	31	14.03	106	16.44	7.23	281	2.3
22	2009	6	5	18	10	25.61	31	10.26	105	59.35	6.76	279	2.0
23	2009	6	30	13	51	37.14	31	34.63	103	12.86	9.38	325	2.3
24	2009	7	1	15	9	6.93	31	30.07	103	21.72	8.63	312	2.1
25	2009	7	3	16	20	26.33	31	20.97	103	29.83	8.91	313	2.0
26	2009	7	17	5	26	10.64	35	21.26	107	28.78	5.82	224	2.0
27	2009	8	12	0	12	43.14	35	29.13	107	14.52	6.52	211	2.2
28	2009	9	23	13	3	17.60	34	34.55	107	51.51	3.59	240	2.7
29	2009	9	29	3	43	41.52	34	45.23	106	33.27	3.14	227	2.0
30	2009	10	25	14	5	24.08	32	20.48	102	55.74	8.65	323	2.2
31	2009	11	28	18	13	50.20	35	10.98	106	44.25	3.20	159	2.1

Pleistocene (S. Cather, pers. comm., 2012). The earthquake locations form a generally flat volume at depth, which suggests that this fault becomes listric with depth (Fig. 3).

Due to the similar waveform character of events in this swarm, we applied a cross-correlation technique to improve user picks and refine earthquake locations (e.g., Shearer 1997; Rowe et al. 2002). Cross-correlation techniques compute differential P-, S- or reflected-wave travel-times for well-correlated waveforms on a station-by-station basis (e.g., Shearer 1997). These differential times were used to adjust the manual arrival time picks and resulted in better constrained locations for 298 out of 341 events with a correlation threshold of 0.55 (Figs. 3A and 3B). The cross-correlation results of the 105 largest events with a correlation threshold of 0.60 also suggest that instead of one large cluster, there were several distinct clusters with slight waveform shape variations. Four of these clusters have north-northeast-striking fault plane solutions, whereas two strike roughly north (Figs. 3C and 3D).

Remainder of New Mexico and bordering areas (RNM)

There were 31 earthquakes of $M_d \geq 2.0$ that occurred in New Mexico and the bordering areas, excluding those that were located near Raton, the Delaware Basin, or in the Socorro Seismic Anomaly (Fig. 1, Table 2). These events cover the Rio Grande rift, Great Plains, Mogollon–Datil region, and the borders of the Colorado Plateau. In the last 5-yr catalog (Sanford et al. 2006) there were 64 events located in RNM regions, which is more than double the number of events during 2005–2009 time period.

Delaware Basin earthquake sequence

This sequence consists of closely located and relatively frequent earthquakes near the Dagger Draw oil field region (Table 3). The Dagger Draw oil field (Dagger Draw north pool and Dagger Draw south pool) is approximately 40 km northwest of Carlsbad, New Mexico. The Delaware Basin sequence, also known as the Dagger Draw swarm, started with the initiation of production at this field, which suggests that these earthquakes are most likely induced (Sanford et al. 2006).

There is large temporal variation in the frequency of these events within a year

TABLE 3—Dagger Draw sequence earthquakes with $M_d \geq 2.0$: 2005–2009.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
1	2005	4	4	7	56	12.90	32	35.63	104	37.00	2.01	117	2.3
2	2005	5	4	6	22	11.49	32	35.05	104	37.26	2.62	127	2.3
3	2005	5	13	12	27	7.28	32	34.15	104	36.57	2.30	137	2.4
4	2005	6	15	4	7	1.14	32	19.67	104	38.90	1.76	188	2.2
5	2005	6	15	4	33	57.92	32	18.14	104	40.01	2.07	195	2.6
6	2005	6	15	22	48	55.23	32	18.32	104	39.82	2.68	206	2.0
7	2005	6	19	9	53	40.53	32	17.25	104	41.46	4.46	200	2.4
8	2005	6	29	21	49	5.82	32	19.06	104	39.14	2.78	197	2.3
9	2005	7	1	13	41	35.41	32	19.24	104	38.96	2.89	201	2.3
10	2005	7	20	2	16	49.65	32	37.84	104	47.76	2.79	108	2.1
11	2005	10	11	8	29	53.93	32	35.35	104	37.54	1.71	122	2.1
12	2005	11	4	18	9	13.85	32	30.62	104	38.44	1.46	138	2.2
13	2005	12	19	20	27	38.60	32	37.94	104	39.44	2.82	150	3.8
14	2005	12	19	20	41	18.87	32	33.68	104	50.11	4.13	103	2.9
15	2005	12	19	20	41	42.00	32	45.49	104	36.34	10.58	174	2.7
16	2005	12	19	21	14	55.35	32	33.70	104	44.28	3.18	274	2.0
17	2005	12	19	21	55	46.98	32	36.93	104	33.16	3.47	210	2.3
18	2005	12	20	4	46	38.27	32	35.30	104	43.60	3.50	110	2.1
19	2005	12	20	4	51	18.79	32	33.63	104	41.40	2.81	166	2.0
20	2005	12	22	14	30	10.89	32	37.24	104	37.20	3.08	156	3.4
21	2006	1	27	10	4	55.75	32	39.77	104	34.99	2.03	148	2.5
22	2006	1	27	16	7	45.12	32	38.91	104	35.16	1.91	147	2.5
23	2006	2	4	19	55	10.21	32	38.08	104	35.47	1.91	146	2.0
24	2006	3	20	17	55	28.87	32	42.78	104	36.45	2.11	110	2.3
25	2006	11	2	0	42	39.78	32	33.76	104	38.70	3.45	155	2.3
26	2006	11	21	8	23	29.78	32	24.31	104	42.41	2.70	180	2.4
27	2006	11	26	11	57	14.11	32	37.00	104	36.44	1.90	100	2.1
28	2007	3	21	8	47	25.19	32	29.45	104	42.32	3.48	206	2.0
29	2007	8	11	0	7	35.73	32	32.42	104	46.99	3.43	177	2.0
30	2008	5	23	18	3	6.40	32	29.39	104	38.70	2.55	163	2.2
31	2008	6	26	20	32	33.08	32	30.18	104	38.46	7.74	161	2.3
32	2008	6	27	13	43	49.69	32	13.32	104	40.81	3.76	220	2.0
33	2008	6	30	5	58	8.24	32	17.63	104	34.03	3.79	187	2.5
34	2009	1	29	23	50	27.27	32	33.68	104	38.95	2.27	163	2.0
35	2009	1	30	1	41	21.23	32	33.31	104	39.72	2.53	165	2.5
36	2009	7	24	10	30	55.62	32	18.26	104	40.70	2.51	195	2.2
37	2009	9	6	3	38	14.06	32	31.00	104	42.64	2.43	172	2.8
38	2009	9	6	5	54	48.24	32	32.87	104	39.68	2.99	160	2.1
39	2009	9	6	9	24	30.30	32	33.70	104	38.66	2.51	155	2.0
40	2009	9	7	5	22	7.22	32	28.80	104	40.59	2.43	167	2.6
41	2009	9	23	23	54	48.19	32	33.33	104	40.41	2.39	159	2.3
42	2009	9	23	23	58	56.76	32	32.67	104	40.70	2.92	160	3.1
43	2009	9	24	20	55	45.62	32	32.39	104	40.47	2.71	168	2.0
44	2009	10	9	6	42	1.93	32	32.52	104	40.00	2.90	159	2.1
45	2009	10	14	16	31	45.34	32	32.30	104	40.75	2.70	165	2.5
46	2009	10	18	2	45	33.52	32	33.67	104	39.50	2.57	139	2.4

TABLE 3—continued

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
47	2009	11	17	7	27	23.71	32	34.07	104	38.87	2.83	155	2.6
48	2009	11	17	18	53	6.46	32	32.87	104	40.39	2.78	166	2.6
49	2009	11	17	19	7	36.94	32	32.44	104	40.38	2.45	160	2.3
50	2009	11	27	5	35	1.66	32	31.54	104	46.68	3.55	104	2.0
51	2009	12	10	4	44	20.89	32	31.85	104	41.97	2.62	164	2.2
52	2009	12	11	15	29	47.68	32	32.00	104	41.12	2.71	162	2.2
53	2009	12	24	19	41	38.75	32	32.52	104	34.45	2.50	144	2.0

TABLE 4—Raton Basin earthquakes with $M_d \geq 2.0$: 2005–2009. Asterisks indicate earthquakes with USGS location only.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
1*	2005	1	10	10	14	59.15	37	0.60	104	40.80	n/a	n/a	3.4
2	2005	4	1	10	14	33.82	97	7.87	105	5.04	7.90	175	2.6
3*	2005	4	6	8	45	24.57	36	52.80	104	47.40	n/a	n/a	2.9
4	2005	4	24	11	2	37.84	36	48.38	104	55.86	4.67	193	2.5
5	2005	7	4	10	45	27.14	36	47.76	104	55.27	4.05	174	3.0
6	2005	7	8	6	24	1.78	36	55.18	104	54.57	5.80	175	3.0
7	2005	7	8	6	25	55.78	36	54.07	105	.50	7.26	173	2.1
8	2005	8	10	22	8	20.40	36	55.71	104	38.73	4.77	182	4.3
9	2005	8	10	22	24	38.08	36	52.24	104	46.24	4.00	179	2.8
10	2005	9	30	2	12	31.78	37	5.60	104	45.59	5.44	212	2.7
11	2005	10	20	8	15	41.45	36	48.98	105	.62	4.39	175	2.3
12	2005	11	16	3	11	33.67	37	5.70	104	48.50	5.03	207	2.7
13	2006	1	27	18	48	51.46	36	56.29	104	46.69	4.05	179	2.9
14*	2006	2	11	13	3	50.48	37	4.80	105	26.40	n/a	n/a	2.9
15	2006	5	6	17	7	3.42	37	2.33	104	45.46	4.19	180	3.1
16*	2006	5	14	10	16	33.86	36	50.40	104	45.00	n/a	n/a	2.5
17	2006	5	26	6	14	28.33	36	46.28	104	43.16	4.15	179	2.7
18	2006	7	11	11	53	39.73	37	4.90	104	59.60	5.29	177	2.9
19	2006	8	8	13	41	59.65	36	56.69	105	1.44	6.58	173	2.6
20	2006	8	24	14	4	28.79	37	1.15	104	57.95	3.91	175	2.9
21	2006	9	9	9	54	15.92	37	5.24	104	34.99	2.03	148	2.5
22	2006	9	9	12	53	15.75	37	26.31	104	2.81	5.75	202	2.8
23	2006	9	9	18	5	46.30	37	22.08	104	44.52	4.50	183	2.8
24	2006	9	9	23	14	40.01	37	14.44	104	58.74	4.65	176	3.2
25*	2006	9	10	12	2	59.70	37	17.40	104	52.20	n/a	n/a	2.6
26*	2006	9	14	13	3	24.26	37	0.60	104	52.20	n/a	n/a	3.0
27*	2006	9	28	9	56	37.81	36	57.60	104	46.80	n/a	n/a	2.6
28	2006	9	30	12	40	3.29	37	1.88	105	1.69	4.51	173	2.7
29	2006	10	30	2	35	19.51	36	38.74	105	4.82	3.44	179	2.7
30	2006	11	24	23	22	27.03	37	3.25	105	2.37	4.52	173	2.7
31*	2006	12	24	11	50	21.47	36	56.40	104	45.00	n/a	n/a	3.6
32	2007	1	3	14	34	41.14	37	4.24	104	53.80	3.96	201	3.8
33*	2007	1	14	5	17	36.69	36	52.80	104	55.80	n/a	n/a	3.2
34	2007	2	25	11	24	28.05	36	51.18	104	50.01	4.66	177	2.6

TABLE 4—continued

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
35*	2007	3	12	6	32	14.59	37	3.60	104	56.40	n/a	n/a	3.4
36*	2007	6	9	10	45	44.71	36	55.80	104	47.40	n/a	n/a	3.3
37	2007	10	27	5	32	17.90	36	52.48	104	52.49	5.56	176	2.2
38*	2007	12	17	4	30	29.10	36	57.00	105	3.60	n/a	n/a	2.9
39	2008	1	29	2	30	30.08	36	33.79	104	52.08	4.12	174	2.4
40	2008	2	14	3	60	10.96	36	50.98	104	50.74	5.71	177	2.5
41	2008	2	15	8	4	1.49	36	53.63	105	6.48	5.14	170	n/a
42	2008	4	5	7	13	25.21	36	52.87	104	45.57	5.32	179	2.3
43	2008	4	20	9	39	54.42	36	59.12	104	51.09	4.80	200	2.8
44	2008	4	21	9	36	31.93	36	52.09	104	41.79	6.70	206	2.5
45	2008	4	24	2	21	52.37	37	3.08	104	41.54	5.90	182	2.7
46	2008	7	17	10	34	44.32	36	57.68	104	49.18	5.95	194	2.2
47	2008	7	18	14	59	43.25	36	54.89	104	49.18	7.68	178	2.1
48*	2008	8	24	22	48	31.50	37	6.00	104	52.20	n/a	n/a	3.4
49	2008	9	6	14	34	2.89	36	59.17	104	41.34	5.17	208	2.2
50	2008	9	22	13	55	23.30	37	13.98	104	12.25	7.31	201	2.4
51	2008	9	25	16	55	36.93	37	20.65	104	20.58	4.55	193	2.6
52	2008	10	4	12	41	28.67	37	2.37	104	41.74	4.45	210	3.0
53	2009	2	3	23	27	15.41	36	50.19	104	53.54	4.94	175	2.7
54	2009	2	13	11	2	33.77	36	48.57	104	46.13	4.57	178	2.3
55	2009	3	15	14	21	45.94	36	48.89	104	55.07	5.87	175	2.4
56*	2009	3	22	11	14	40.10	37	15.60	104	27.60	n/a	n/a	3.0
57	2009	5	1	1	34	10.89	36	39.93	104	42.82	4.22	179	2.7
58	2009	6	27	6	44	46.81	36	45.78	104	50.74	4.75	193	2.7
59	2009	6	27	8	24	33.19	36	34.09	105	.84	5.20	181	2.6
60	2009	7	29	9	60	42.67	36	43.29	104	53.16	4.27	175	3.3
61	2009	7	29	14	31	54.22	36	47.76	104	52.72	6.41	180	2.3
62	2009	8	3	23	15	11.82	36	41.31	104	55.44	4.70	174	2.5
63	2009	8	21	11	46	3.61	36	59.27	105	1.72	13.96	215	2.5
64	2009	9	29	11	20	33.91	36	50.53	105	2.09	4.79	172	3.0
65	2009	9	29	22	54	12.64	37	2.82	104	56.60	7.21	181	2.7
66	2009	10	3	18	45	34.73	37	5.24	104	59.84	5.11	175	3.3
67*	2009	10	29	11	23	2.92	37	5.40	104	57.60	n/a	n/a	2.5
68*	2009	10	29	11	38	9.08	37	4.20	104	49.80	n/a	n/a	2.6
69	2009	11	4	19	52	25.03	36	57.61	104	46.03	7.66	203	2.5
70	2009	11	16	1	46	8.64	36	56.64	105	10.74	15.41	221	2.1
71	2009	11	19	8	31	14.15	36	39.67	105	2.90	6.26	170	2.5
72	2009	11	20	14	54	31.08	36	50.96	104	44.88	7.09	206	3.0
73	2009	12	11	20	32	31.91	36	42.18	104	48.72	3.82	195	2.6

as well as between years. For example, in 2005 there were 20 $M_d \geq 2.0$ earthquakes near Dagger Draw, which suggest on average 1.6 events per month. However, five of these events occurred in June (25%) and seven occurred in December (35%) alone. In comparison, during the first quarter of 2005 we did not observe any $M_d \geq 2.0$ events in this region. There is also a large yearly variation in earthquake occurrence. Out of all 53 $M_d \geq 2.0$ events in the Dagger Draw sequence during the 2005–2009 time period, 20 earthquakes (38%) occurred in 2005, seven in 2006 (13%), two in 2007 (4%), four in 2008 (7%), and 20 in 2009 (38%).

Raton Basin earthquake sequence

This earthquake sequence is a cluster of events in the Raton Basin along the northeastern border of New Mexico. This sequence started in late 2001 (Sanford at al. 2006) and continues through the present. The events in this group are relatively large

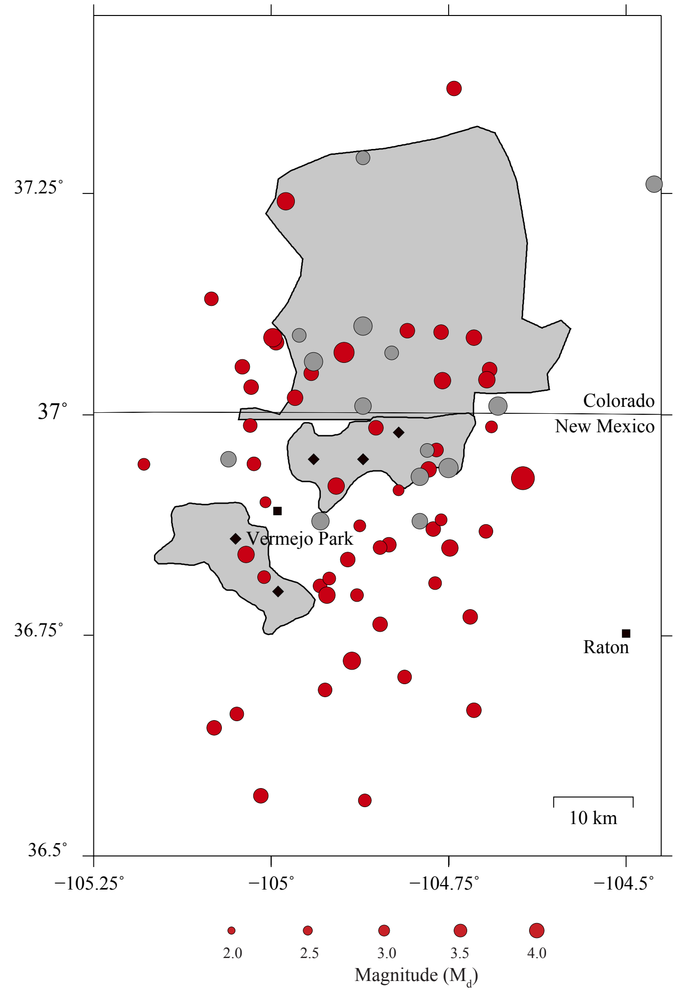

FIGURE 4—Earthquakes near Raton during 2005–2009 time period located using the SC network (57 events, red circles), locations from the USGS only (16 events, gray circles). Also shown are the coalbed methane-producing areas (gray regions) and the waste water disposal wells (black diamonds) in New Mexico, obtained from the New Mexico Bureau of Geology and Mineral Resources. The oil and gas-producing area in Colorado (gray polygon) was obtained from the Colorado Oil and Gas Conservation Commission.

($M_d \geq 2.0$) and generally poorly located by the SC network, as the closest station is a broadband site ANMO near Albuquerque. We were able to improve the location parameters for a group of 23 earthquakes that occurred during the Earthscope USArray station deployment in New Mexico.

From 2005 through 2009 there were 73 earthquakes in the Raton Basin (Table 4). Compared to the last catalogs spanning the period 1999–2004, the frequency of earthquakes in the Raton Basin has more than doubled in the last 5 yrs. This increase is independent of the larger seismic station pool in the area; even without the USArray sites, the earthquakes in the Raton Basin during this time were locatable by our network. Most of the events are concentrated around the coalbed methane fields (Fig. 4); however, we do not have enough information at this time to discuss whether these events are the results of production or natural motion along existing faults.

The Earthscope USArray Transportable Array seismic network (TA) was located in New Mexico during most of 2008 and 2009. We relocated 23 of the 73 Raton Basin earthquakes using the local network (SC) and the nearby USArray stations that were operational when events occurred (red circles, Figs. 5A and 5B; Table 5), and four earthquakes for which we only had a USGS location (blue circles, Figs. 5A and 5B). The location errors, the RMS (root mean square), and azimuth gap values decreased significantly when using data from these additional stations. The locations do cluster closer together; however, not all of the events were within or near the coalbed methane-producing region represented by the gray areas in Figures 5A and 5B. Thus, we suggest that either the coalbed methane production spans larger regions than shown on the map, or that these events occur on nearby faults unrelated to the industrial development. The location parameters, azimuth gaps (Fig. 5C), and epicenter standard deviations (Fig. 5D) improved greatly after relocation.

Conclusions

From 2005 through 2009 we have located 165 $M_d \geq 2.0$ earthquakes and 1,375 $M_d \geq 0.0$ earthquakes in New Mexico and the surrounding regions. The earthquakes were located mainly in three distinct clusters: Dagger Draw region, southeast New Mexico; Raton region, northeast New Mexico; and the SSA region, central Rio Grande rift area. In August and September 2009 there was a swarm of more than 400 earthquakes in the SSA region, which is associated with extensional movement near the Veranito fault. The activity near Dagger Draw region is likely caused by produced water disposal in the nearby wells. In the Raton Basin area, seismicity has been attributed to coalbed methane production; however, the relocated earthquakes with improved location parameters fall outside of the industrial boundaries.

Acknowledgments

These catalogs include the work of several undergraduate and graduate students. They helped with maintaining the seismological observatory and creating the earthquake catalogs. We are also grateful for Hans Hartse's and Kuo-wan Lin's location program that was used for all of the data processing. The USArray program allowed us to greatly improve earthquake locations, especially in the Raton region. We also used data from several stations in the U.S. National Seismic Network (network code US) and the Global Seismograph Network (network code IU). The location of the Veranito fault was provided by the New Mexico Bureau of Geology and Mineral Resources. This manuscript was greatly improved by reviews from Allan Sanford, Kuo-wan Lin, and Noel Barstow.

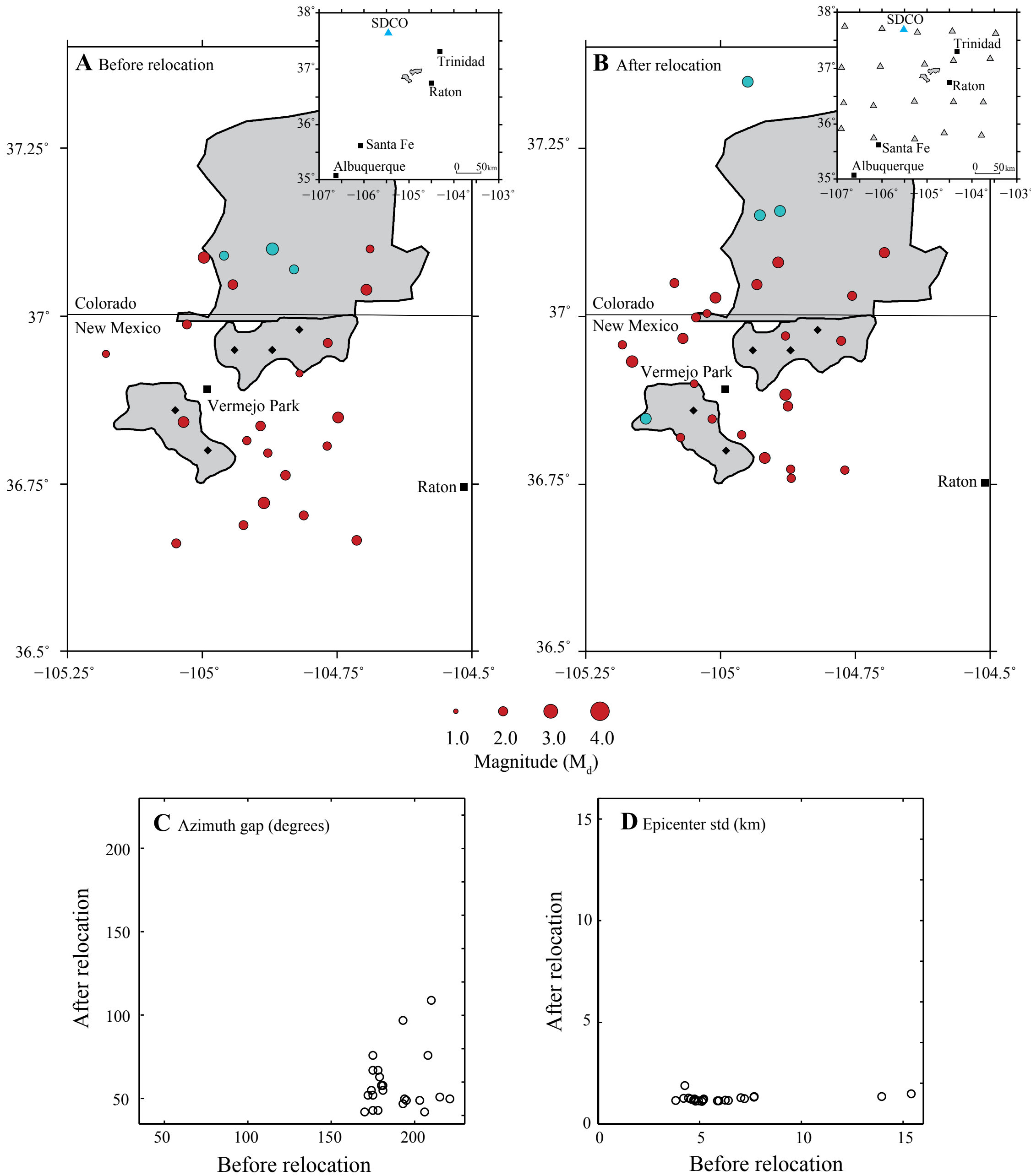

FIGURE 5—**A**—Original locations for 27 events in the New Mexico–Colorado border area. Red circles represent earthquakes located using the SC network (23 events), blue circles are events with a USGS location only (four events. Note one of these events lies out of the map boundaries in the original location). **B**—Earthquakes relocated using the SC network and the USArray stations (gray triangles) in the New Mexico–Colorado border area. Comparison of azimuth gap values (**C**) and the standard deviation of epicenters (**D**) for 23 relocated earthquakes. The original values are on the x-axis, the improved values after relocation using USArray stations are on the y-axis.

TABLE 5—Locations of 23 earthquakes in the Raton Basin relocated using data from the SC network and the USArray stations.

No.	Year	Month	Day	Hour	Minute	Seconds	Lat N	Minutes	Long W	Minutes	1 std (km)	Gap (degrees)	Magnitude
1	2008	7	17	10	34	47.59	37	0.29	105	1.51	1.15	50	2.2
2	2008	7	18	14	59	46.01	36	45.53	104	52.13	1.35	67	2.4
3	2008	9	6	14	34	9.26	36	46.26	104	46.19	1.16	76	2.4
4	2008	9	25	16	55	41.00	37	5.72	104	41.79	1.23	97	2.8
5	2008	10	4	12	41	31.48	37	4.84	104	53.58	1.27	109	3.1
6	2009	2	3	23	27	15.77	36	49.18	105	4.48	1.13	52	2.4
7	2009	2	13	11	2	36.05	36	57.48	105	10.94	1.22	43	2.4
8	2009	3	15	14	21	48.65	36	46.35	104	52.22	1.14	67	2.3
9	2009	5	1	1	34	11.87	36	51.98	104	52.52	1.25	63	2.7
10	2009	6	27	6	44	49.70	36	58.04	105	4.19	1.22	47	2.8
11	2009	6	27	8	24	29.61	37	1.86	104	45.38	1.22	58	2.6
12	2009	7	29	10	0	44.36	36	53.03	104	52.79	1.89	76	3.2
13	2009	7	29	14	31	55.40	36	49.44	104	57.68	1.15	58	2.4
14	2009	8	3	23	15	10.47	36	58.26	104	52.77	1.18	55	2.3
15	2009	8	21	11	46	6.14	37	2.99	105	5.15	1.35	51	2.5
16	2009	9	29	11	20	32.98	37	1.69	105	0.57	1.12	52	3.0
17	2009	9	29	22	54	11.64	37	2.86	104	56.00	1.24	55	2.8
18	2009	10	3	18	45	39.44	36	55.98	105	9.86	1.11	43	3.2
19	2009	11	4	19	52	30.99	36	59.93	105	2.73	1.31	49	2.5
20	2009	11	16	1	46	10.93	36	53.99	105	2.96	1.48	50	2.2
21	2009	11	19	8	31	13.07	36	50.84	105	0.95	1.16	42	2.4
22	2009	11	20	14	54	34.65	36	47.37	104	55.09	1.28	42	3.0
23	2009	12	11	20	32	31.00	36	57.83	104	46.59	1.15	49	2.6

References

Ake, J. P., Sanford, A. R., and Jarpe, S. J., 1983, A magnitude scale for central New Mexico based on signal duration: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 45, 26 pp.

Balch, R. S., Hartse, H. E., Sanford, A. R., and Lin, K-w., 1997, A new map of the geographic extent of the Socorro mid-crustal magma body: Bulletin of the Seismological Society of America, v. 87, pp. 174–182.

Cather, S. M., Colpitts, R. M., and Hook, S. C., 2004, Preliminary geologic map of the Mesa del Yeso 7.5-min quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Digital Geologic Map 92, scale 1:24,000.

Hartse, H. E., Sanford, A. R., and Knapp, J. S., 1992, Incorporating Socorro magma body reflections into the earthquake location process: Bulletin of the Seismological Society of America, v. 82, pp. 2511–2532.

Rowe, C. A., Aster, R. C., Phillips, W. S., Jones, R. H., Borchers, B., and Fehler, M. C., 2002, Using automated, high-precision repicking to improve delineation of microseismic structures at the Soultz geothermal reservoir: Pure Applied Geophysics, v. 159, pp. 563–596.

Ruhl, C., Bilek, S. L., and Stankova-Pursley, J., 2010, Relocation and characterization of the August 2009 microearthquake swarm above the Socorro magma body in the central Rio Grande rift: Geophysical Research Letters, v. 37, no. 23, L23304, doi:10.1029/2010GL045162.

Sanford, A. R., and Lin, K-w., 1998, Evidence for a 1,400 km long Socorro fracture zone: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 89, 18. pp.

Sanford, A. R., Lin, K-w., Tsai, I., and Jaksha, L. H., 2002, Earthquake catalogs for New Mexico and bordering areas: 1869–1998: New Mexico Bureau of Geology and Mineral Resources, Circular 210, 104 pp.

Sanford, A. R., Mayeau, T. M., Schlue, J. W., Aster, R. C., and Jaksha, L. H., 2006, Earthquake catalogs for New Mexico and bordering areas II: 1999–2004: New Mexico Geology, v. 28, no. 4, pp. 99–109.

Shearer, P. M., 1997, Improving local earthquake locations using the L1 norm and waveform cross correlation: Application to the Whittier Narrows, California, aftershock sequence: Journal of Geophysical Research, v. 102, pp. 8269–8283, doi:10.1029/96JB03228.

Some abbreviations used in this paper

AE	Arizona Seismic Network
IU	Global Seismograph Network
RMS	root mean square
RNM	remainder of New Mexico and bordering states
SC	Socorro Seismic Network
SFZ	Socorro Fracture Zone
SMB	Socorro Magma Body
SSA	Socorro Seismic Anomaly
TA	Earthscope USArray Transportable Array seismic network
US	United States National Seismic Network
USGS	U.S. Geological Survey
WIPP	Waste Isolation Pilot Plant