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THE PRAIRIE SPRING EARTHQUAKE SWARM: A SEISMIC EVENT IN THE CHUPADERA MESA REGION, CENTRAL NEW MEXICO

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Abstract—A strong earthquake swarm located a short distance west of Chupadera Mesa produced 348 shocks with magnitudes of 0.2 or greater from 14 February 1990 through 31 August 1990. The cumulative seismic moment for the swarm in combination with assumptions on the ratios of rupture width to length and rupture displacement to length yielded an estimate of 2.9 km^2 for the rupture area. This estimate is in agreement with the rupture areas estimated from the geographic distribution of epicenters and focal depths, and the fault dip from a composite fault mechanism based on P-wave first motions. An eye fit to the distribution of 68 epicenters indicates the fault rupture had a strike on the order of N66W. The strike of the composite fault-plane solution is on the order of N48W. Uncertainties in both estimates indicate an average strike of ~N57W, an unusual orientation compared to the northerly strikes for most faults in the Socorro area. This suggests that the Prairie Spring swarm location and mechanism may be related to the WNW trending Capitan lineament. Activation of the fault producing the swarm earthquakes may have been caused by stresses created by steady–state inflation of the Socorro mid–crustal magma body.

INTRODUCTION

The Prairie Spring earthquake swarm occurred over a six and one-half month period in 1990 on the eastern border of the Rio Grande rift in the transition zone between the Jornado del Muerto basin and the western boundary of the Chupadera Mesa. The swarm was centered 33°57.75′N and 106°34.70′W (Fig.1B). Excluding earthquakes probably induced by oil and natural gas production procedures (well outside the study area), the Prairie Spring swarm produced 5.0% (6 of 120) of New Mexico shocks of magnitude 3.0 or greater in the 43–yr period 1962 through 2004. The location of the fault rupture produced by the swarm suggests a possible relation to the WNW trending Capitan lineament (Chapin et al., 1978) where it crosses the eastern margin of the ~3400 km^2, ~150–m–thick, and ~19–km–deep Socorro Magma Body (Balch et al., 1997; Ake and Sanford, 1988; and Hartse et al., 1992). Injection of magma as evidenced by surface uplift (Larsen et al., 1986; Fialko and Simons, 2001; and Finnegan and Pritchard, 2009) is producing stresses in the upper crust that are responsible for abnormally high earthquake activity in the Socorro area (Sanford et al., 2002; Sanford et al., 2006; and Sanford, 2008).

ACQUISITION OF SWARM EARTHQUAKE DATA

Events in the Prairie Spring swarm were recorded by stations in the permanent New Mexico Tech (NMT) seismograph network in the Socorro area (Fig. 1A). Data from this eight-station network were used to establish temporal variations in the strengths and numbers of earthquakes for the duration of the swarm. The Prairie Spring swarm was located at distances that ranged from 15 km to 72 km to the stations in the NMT permanent network. The azimuths of the stations relative to the swarm ranged from 245° to 351°. Because the swarm was outside the network, locations with low errors could not be obtained with the network data alone. To minimize errors in epicenters and hypocenters, one to five temporary stations were placed at distances of ~1.5 km to ~8 km from the center of the swarm (Fig. 1B). Swarm events

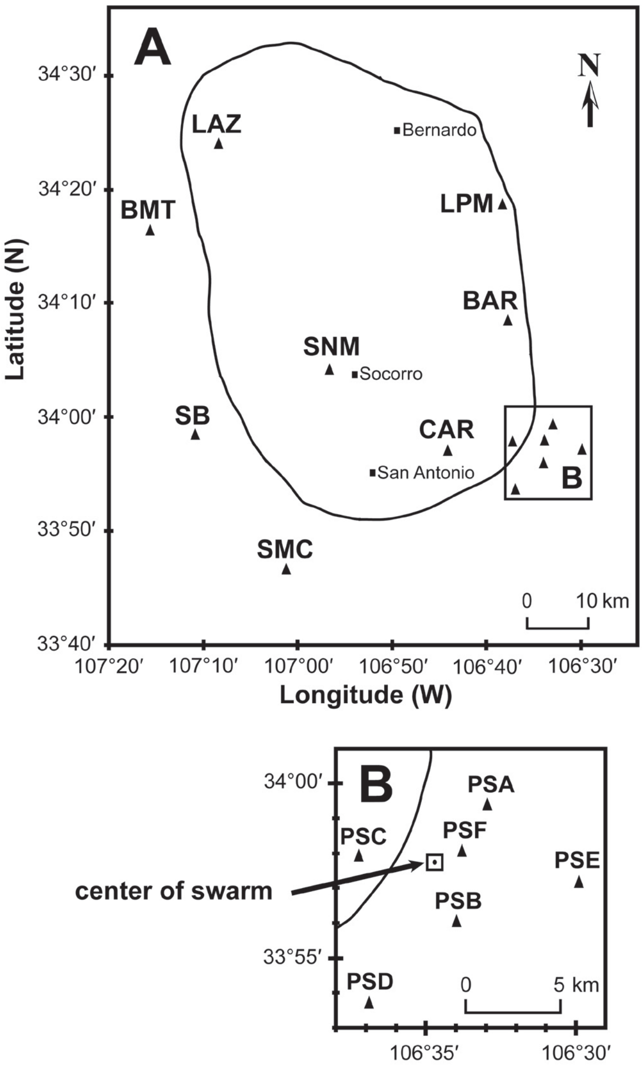

FIGURE 1. **A**. Locations of stations in the New Mexico Tech seismograph network. Also shown is the outline of the Socorro Magma Body (Balch et al., 1997). **B.** Locations of temporary stations used to record Prairie Spring swarm earthquakes relative to the southeast edge of the magma body. Also shown (square symbol) is the center of the swarm epicenters.

recorded by the temporary stations were used in conjunction with data from the NMT permanent network to estimate the spatial extent and mechanism of the fault rupture during the swarm.

EARTHQUAKE SWARM STATISTICS

Listed in Table 1 are the daily variations in numbers and strengths of swarm earthquakes from 14 February 1990 through 31 August 1990. The table is restricted to the 348 swarm events with magnitudes of 0.2 or greater because data for weaker shocks are not complete.

Temporal variation in number of earthquakes M≥0.2

The swarm had a weak beginning with only 14 shocks in the first week. This changed abruptly on 21 February when the activity in terms of number of shocks (42) was greatest of any day of the swarm. Activity subsided in the following five days (22–26 February) with only a daily average of ~12 quakes. This was followed by the five-day interval (27 February–3 March) that produced a total of 142 quakes, 41% of the total 348. Again the activity subsided in the next five days (4–8 March) with a daily average of 8 shocks. The number of earthquakes after 8 March was particularly low in the 150 days from 20 March through 16 August when only 12 events occurred. The final pulse of swarm earthquakes took place in the interval 17 August through 31 August, particularly on 18 August when 20 of the 33 shocks in this 14–day cluster occurred.

Temporal variation in strengths of earthquakes M≥0.2

In general, days with a large number of earthquakes also had the strongest shocks. But there were exceptions; for example, 28 February had 32 quakes of M≥0.2, but none of M≥2.0. The five–day period of greatest number of events from 27 February through 3 March also produced the most quakes of M≥3.0, including the strongest one in the swarm, M=3.9. A characteristic of earthquake swarms is for its strongest earthquake to occur some time after its beginning; for the Prairie Spring swarm it was two weeks after 14 February.

Number of earthquakes versus magnitude

The total number of earthquakes in the separate categories of M≥0.2, M≥2.0, M≥3.0, and M≥3.5 (Table 1) were used to establish the Gutenberg-Richter relation between the cumulative number of earthquakes in the swarm and their magnitudes:

$$\mathrm{Log}_{10}\Sigma N = a - bM = 2.67 - 0.639\,M \quad (1)$$

This relationship indicates that the number of earthquakes in the swarm of M≥0.0 was 468 and that the number of earthquakes increased by a relatively low rate of 4.4 for each unit decrease in magnitude. Steacy and McCloskey (1999) suggest that this low rate indicates a relatively high degree of roughness on a fault surface.

TABLE 1. Temporal Variation in Numbers and Magnitudes of Prairie Spring Swarm Earthquakes.

1990	Number of Earthquakes				Moment
Day-Mo	**M≥0.2**	**M≥2.0**	**M≥3.0**	**M≥3.5**	**Nmx10^{14}**
14-Feb	4				
15-Feb	1				
16-Feb	1				
17-Feb	1				
18-Feb	6	1			0.02
19-Feb	1				
20-Feb					
21-Feb	42	8	2		3.64
22-Feb	12	1			0.11
23-Feb	10	1			0.06
24-Feb	17				
25-Feb	11				0.01
26-Feb	9	1			0.02
27-Feb	34	3	2	1(3.9)	9.74
28-Feb	32				
1-Mar	19				
2-Mar	26	2	2		1.59
3-Mar	21				0.01
4-Mar	7				
5-Mar	10	2			0.03
6-Mar	7				0.01
7-Mar	9				0.01
8-Mar	7				0.01
9-Mar					
10-Mar	2				
11-Mar					
12-Mar	1				
13-Mar	2				
14-Mar	1				
15-Mar	4				0.01
16-Mar	1				
17-Mar					
18-Mar					
19-Mar					
From 20 Mar. through 16 Aug.(150 days): 12 quakes, strongest M=1.6					
17-Aug	1				
18-Aug	20	4			0.13
19-Aug	3				
20-Aug					
21-Aug					
22-Aug					
23-Aug					
24-Aug	1				
25-Aug	3	2			0.03
26-Aug					
27-Aug					
28-Aug					
29-Aug					
30-Aug	3				
31-Aug	2				
TOTALS	**348**	**25**	**6**	**1(3.9)**	**15.44x10^{14}**

Cumulative seismic moment and extent of faulting

Listed in the last column of Table 1 is the cumulative moment M_0 for each day of the swarm. Seismic moment is a much better measure of the physical rupturing in an earthquake than magnitude. An empirical equation (Scholz, 1990) was used to calculate seismic moment from magnitudes. The cumulative seismic moment for the entire swarm was 15.4 Nm, a value equivalent to the seismic moment for a single earthquake of M = 4.05.

With assumptions, the cumulative seismic moment can be used to obtain an estimate of the extent of crustal rupture during the swarm using the relation:

$$\Sigma M_0 = GDA \qquad (2)$$

where G is the crustal shear modulus, A is the fault rupture area, and D is the average displacement over the rupture area A (Reiter, 1990). The first assumption is that the length and width of the rupture area A are equal, i.e., $A = L^2$. The second assumption is that D is some very small fraction of L. Extrapolating Wells and Coppersmith (1994) relationships for average displacement D and subsurface rupture length L for an M = 4.05 yields a D/L ratio of 0.90×10^{-5}. Using these assumptions to calculate L, equation (2) becomes:

$$L^3 = \Sigma M_0 / G \times 0.90 \times 10^{-5} \qquad (3)$$

The crustal shear modulus G is estimated to be 3.1×10^{10} Nm on the basis of the observed upper crust shear wave velocity of 3.41 km/sec in the Socorro region (Hartse et al., 1992) and a crustal density of 2.65×10^3 kg/m^3 (Clark, 1966).

From equation (3) the value of L is ~1.7 km. When this L is used in combination with the D/L ratio of 0.90×10^{-5}, an average displacement over the rupture surface of ~1.5 cm is obtained. With the assumption that the length and width are equal, the estimated rupture area A is ~2.9 km^2. Considering the uncertainties in the calculation, particularly the D/L ratio, this estimated area is remarkably close to the area determined later in this paper from the distribution of epicenters and focal depths in the swarm.

LOCATION OF SWARM EARTHQUAKES

The spatial distribution of epicenters and focal depths were obtained from the inverse method computer program SEISMOS (Hartse, 1992) using a Socorro area velocity model and station corrections established specifically for the Prairie Spring swarm. The epicenters and focal depths presented in this section are restricted to 68 earthquakes that satisfy the following conditions:

1. Magnitude 0.2 or greater.
2. Recorded at two or more of the temporary stations.
3. Azimuth gap between stations less than 171°.
4. One standard deviation error in epicenter less than 0.71 km.
5. One standard deviation error in focal depth less than 0.95 km.

Epicenters

Figure 2 shows the geographic position of the 68 selected earthquakes relative to 33°57.0 N and 106°35.5 W. Epicenters have a WNW orientation with a trendline selected by eye of N66W. Note on Figure 2 that two lines parallel to the trendline are placed 0.70 km above and below that line, and all epicenters are within the encompassed area. The one standard deviation error in the epicenters range from 0.33 km to 0.70 km and average ~0.5 km. Considering these errors, it is probable that all of the earthquakes shown in Figure 2 could have occurred on a single fault with a WNW strike.

The distribution of epicenters indicates the possible maximum lateral extent of the faulting could extend ~2 km from the most northwestern epicenter to the most southeastern epicenter. A possible minimum lateral extent is the maximum ~2 km length less twice the average one standard deviation error in epicenters, i.e., ~1 km.

Focal depths

A focal depth and its one standard deviation were calculated for each of the 68 earthquakes in the restricted data set. All but

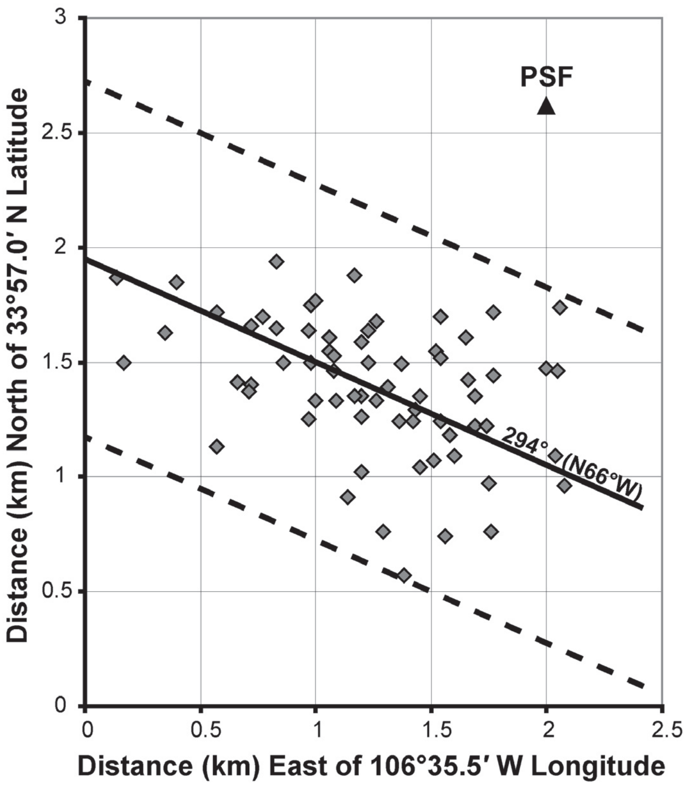

FIGURE 2. Epicenters for 68 Prairie Spring swarm earthquakes having recording parameters that minimize epicenter error, for example, number of temporary stations ≥2, station gap<171^0, and magnitude ≥0.2. The solid line is an eye-fit trendline for the epicenters. The dashed lines parallel to the trendline are offset by 0.70 km, the maximum one standard deviation epicenter error. Note how close station PSF was to the swarm earthquakes.

one of the focal depths was between 3.5 km and 7.0 km and 64% were between 4.5 km and 6.0 km. Depths falling outside this 1.5 km interval can be attributed to the one–to–two standard deviation errors in depth that averaged 0.66 km and 1.32 km.

FAULT MECHANISMS OF SWARM EARTHQUAKES

Two data sets were used for establishing the fault mechanisms of earthquakes in the Prairie Spring swarm: (1) P–wave first motions observed when three to five temporary stations were deployed, and (2) P–wave first motions observed for earthquakes with M≥2.4 (Table 2). The first data set covers the time interval 22 February to 3 March, the second data set covers the time interval 21 February to 18 August. An important observation is the agreement in P–wave first motion directions between the two data sets, an indication that they can be combined to obtain a composite fault mechanism for the swarm.

Figure 3 is a standard projection of the P–wave first motions in Table 2 onto the upper focal sphere using the azimuths and inclinations of raypaths leaving the focal region. Continuing with the probability that all swarm earthquakes occurred on a single fault, these azimuths and inclinations in Figure 3 were calculated using the distance to the center of swarm events in Figure 2.

A fault mechanism that appears to satisfy the distribution of all P–wave first motions in Figure 3 except at station PSF is a normal fault striking N48W and dipping 56°in a S42W direction. P–wave first motions are equally satisfied by a normal fault also striking N48W but dipping 34° in a N42E direction. Low angle normal faults are rare, so the latter fault mechanism was rejected.

The majority of P–wave first motions at station PSF (10 of 15) are "Down" and in agreement with the composite fault mechanism. However, there are five clearly recorded "Up" first motions that do not fit the solution shown or any other fault mechanism satisfying first motions at all other stations.To remove the misfit all PSF first motions need to be shifted to the northeast until they are close to a nodal plane on the focal sphere. One way to do this is to acknowledge that the computed locations are not the true locations. This can be a common occurrence for a number of reasons; for example, the true crustal structure is different from the one used in the computer location program. Generally the differences between computed and true locations are small and do not significantly affect positions of most first motions on the focal sphere. But in the case of station PSF, the distance to the center of the computed epicenters is ~1.5 km (Fig. 2). Therefore, a small shift of all epicenters 1 km to 2 km to the northeast could bring all the PSF first motions into close agreement with the fault-plane solution shown in Figure 3. Another explanation for the misfit is that the local geology between the hypocenters and station PSF produces azimuths and inclinations for first motions which do not match those calculated assuming a constant crustal velocity. The latter are the values used in Figure 3.

Projecting the approximate 1.5 km range in focal depths onto a fault surface with a 56°dip angle yields a rupture surface width of approximately 1.8 km. Combining this width with a rupture length from 1 km to 2 km based on the epicenters produces rupture area estimates from 1.8 km^2 to 3.6 km^2. These estimates are in good agreement with the one based on the cumulative seismic moment.

TABLE 2. P-wave First Motions: (1) Earthquakes Recorded by Three or More Temporary Stations and (2) Earthquakes of Magnitude 2.4 or Greater.

	Earthquakes Recorded by Three or More Temporary PS Stations			Earthquakes of Magnitude 2.4 or Greater		
Station	**Total**	**Up**	**Down**	**Total**	**Up**	**Down**
PSA	4	4		1	1	
PSB	18		18	1		1
PSC	6		6	1		1
PSD	12	7	5	2		2
PSE	14	8	6			
PSF	15	5	10			
CAR	18	18		9	9	
BAR	16	15	1	10	10	
SNM	0			5	3	2
LPM	16	15	1	10	10	
SMC	12	12		10	10	
SB	6	6		9	9	
LAZ	2	2		11	1	10
BMT	0			9	4	5

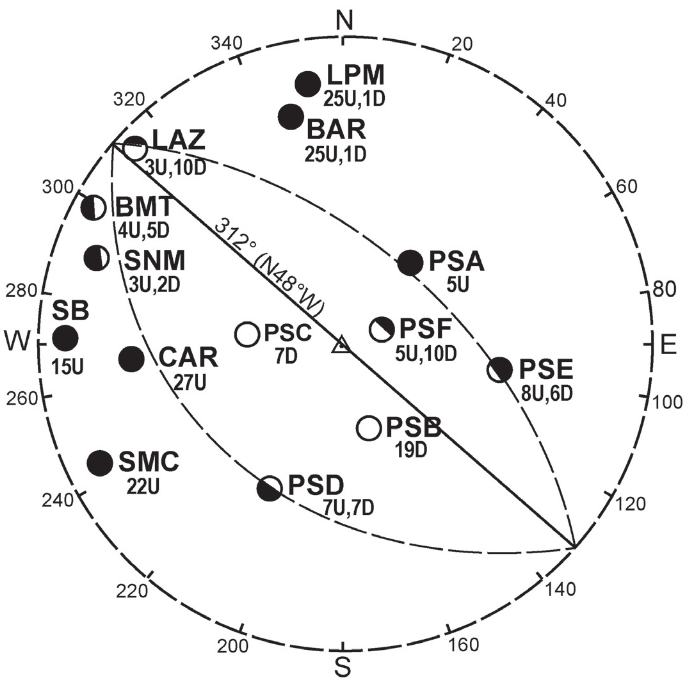

FIGURE 3. Composite fault-mechanism for the Prairie Spring swarm based on earthquakes with clearly recorded P-wave first motions. U (Up) is a compression P–wave arrival and D (Down) is a rarefaction P–wave arrival.

GEOLOGIC SETTING OF THE PRAIRIE SPRING SWARM

The two detailed geologic maps that cover the Prairie Spring swarm area (Wilpolt and Wanek, 1951; and Osburn, 1984-1985) do not agree in all aspects. However, both maps place epicenters for the swarm on Quaternary piedmont gravels. Also both maps have rocks of Tertiary age or older outcropping 400m to 800m to the north and the northeast of the center of the swarm. The nearest mapped fault is located ~2.5 km north of the swarm on both maps. The latter normal fault strikes N58W, an orientation similar to the strike of the composite Prairie Spring fault mechanism in Figure 3. However, the dips for the two faults are opposite.

The swarm epicenters are within the proposed location of the WNW Capitan lineament (Chapin et al., 1978) and also on the northern edge of the Jornado del Muerto basin—a late Cenozoic basin of the Rio Grande rift (Cather, this guidebook). The Capitan lineament is a tens-of-kilometers wide WNW-trending Paleozoic shear zone defined by WNW-striking faults (numerous on the geologic maps of Wilpolt and Wanek (1951) and Osburn (1984)) and magmatic intrusions (Chamberlin, personal commun. 2009). The WNW-trending normal fault that produced the Prairie Spring swarm is located within the Capitan lineament a short distance from the edge of the Socorro mid–crustal magma body (Fig. 1). It is possible that ongoing inflation of the Socorro Magma Body created stresses that led to the rupture of a weak fault and the resulting Prairie Spring swarm.

SUMMARY

The Prairie Spring earthquake swarm occurred from 14 February 1990 through 31 August 1990 and was centered 33°57.75 N and 106°34.70 W, approximately 30 km S20E of Socorro, NM. This strong New Mexico swarm produced 348 earthquakes of magnitude 0.2 or greater. Six earthquakes had magnitudes from 3.0 to 3.9, 5.0% of the total for the state from 1962 through 2004. Day-to-day swarm activity was highly variable with the strongest earthquake (3.9) occurring 14 days after the beginning of the swarm. The number of swarm earthquakes increased by a factor of 4.4 for each unit decrease in magnitude—a low rate indicating a relatively high degree of roughness on the fault producing the swarm.

Locations obtained for 68 swarm shocks with epicenter errors less than 0.71 km and focal depth errors less than 0.95 km indicated activity along a 1.0 to 2.0 km length of a single fault at depths of 4.5 km to 6.0 km. An estimate of the area of rupture based on the cumulative seismic moment of the swarm is in agreement with the epicenter and focal depth observations.

A composite fault mechanism based on P–wave first motions for the swarm earthquakes indicates movements along a normal fault striking N42W and dipping 56° S48W towards the Jornado del Muerto basin. The many faults of similar orientation that occur in the region define the broad limits of the WNW trending Capitan lineament. The fault that produced the Prairie Spring swarm is located within the Capitan lineament at distance of ~ 2 km from the edge of the Socorro mid-crustal magma body. A possible explanation for the swarm are stresses on a weak fault produced by ongoing steady-state inflation of the Socorro Magma Body.

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