Relocation and characterization of the August 2009 microearthquake swarm above the Socorro magma body in the central Rio Grande Rift

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1. Introduction

Earthquake swarms, often attributed to magma or fluid movement in the uppermost crust, have differing statistics depending on tectonic setting, with volcanic swarms producing b-values of up to 2.5 and continental rift swarms having b-values ~0.8-1. Along the Rio Grande continental rift (RGR) in the western US, earthquake swarms have occurred in the area of the Socorro Magma Body (SMB), including the 2009 swarm of 431 events (magnitudes ~1.0 to 2.5) over 26 days. We characterize the 2009 swarm to define spatial and temporal patterns to help understand the role of the SMB on the swarm. Our relocations suggest a small seismogenic volume of 3.45 km³ and focal mechanisms of the largest events are consistent with regional stress patterns. The b-value of 0.9 is more characteristic of continental rift zones than volcanic swarms, suggesting more emphasis on the preexisting highly fractured crust rather than direct influence of magmatic movement. Citation: Ruhl, C., S. L. Bilek, and J. Stankova-Pursley (2010), Relocation and characterization of the August 2009 microearthquake swarm above the Socorro magma body in the central Rio Grande Rift, Geophys. Res. Lett., 37, L23304, doi:10.1029/2010GL045162.

2. Data and Methods

The SMB (Figure 1) is located at ~19-km depth, with an areal extent of >3400 km² and total thickness of <150 m [Balch et al., 1997]. Reflected seismic phases suggest a strong mid-crustal discontinuity with reflection coefficients supporting an underlying low-velocity, molten layer [e.g., Sanford and Long, 1965; Brocher, 1981]. Seismicity occurs in the upper 10 km of crust, [Sanford et al., 2002] implying an aseismic zone due to heat and/or fluids above the SMB [Brocher, 1981; Rinehart and Sanford, 1981; Sanford et al., 1983]. Temperatures for depths ~6–10 km within the central to northern portions of the SMB are estimated at ~200–300°C [Reiter, 2005]. Surface deformation has been observed from 1912–2009 using InSAR, historic leveling, and geologic data [e.g., Fialko et al., 2001; Finnegan and Pritchard, 2009; Pearse and Fialko, 2010].

[1] Swarms, often attributed to magma or fluid movement in the uppermost crust, have differing statistics depending on tectonic setting, with volcanic swarms producing b-values of up to 2.5 and continental rift swarms having b-values ~0.8-1. Along the Rio Grande continental rift (RGR) in the western US, earthquake swarms have occurred in the area of the Socorro Magma Body (SMB), including the 2009 swarm of 431 events (magnitudes ~1.0 to 2.5) over 26 days. We characterize the 2009 swarm to define spatial and temporal patterns to help understand the role of the SMB on the swarm. Our relocations suggest a small seismogenic volume of 3.45 km³ and focal mechanisms of the largest events are consistent with regional stress patterns. The b-value of 0.9 is more characteristic of continental rift zones than volcanic swarms, suggesting more emphasis on the preexisting highly fractured crust rather than direct influence of magmatic movement. Citation: Ruhl, C., S. L. Bilek, and J. Stankova-Pursley (2010), Relocation and characterization of the August 2009 microearthquake swarm above the Socorro magma body in the central Rio Grande Rift, Geophys. Res. Lett., 37, L23304, doi:10.1029/2010GL045162.

[2] Seismic swarms occur most commonly in volcanic and magmatic regions and often exhibit earthquake statistics that differ from standard patterns observed for mainshock-aftershock sequences [e.g., Sykes, 1970; Smith and Sbar, 1974; Hill, 1977]. Swarm generation mechanisms are poorly understood, although the migration of hydrothermal or magmatic fluids in a near a volcanic conduit, the existence of concentrated stresses in a highly fractured, highly heterogeneous subsurface, and/or the succession of many small shear failures are among common explanations [e.g., Mogi, 1963; Hill, 1977]. Earthquake swarms are also common in continental rifts and are attributed to fluctuations of fluids derived from the magma bodies at depth [Ibs-von Seht et al., 2008]. The SMB within the central RGR (Figure 1) has been linked to many microearthquake swarms. We use these earthquakes to explore the role of mid-crustal magma features within rift zones on the seismicity, specifically trying to understand if these swarms act more like volcanic swarms with strong magma influence or like those common in rifts.

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The 2009 swarm region, with earthquakes (circles, sized by magnitude) from 20 August 2009 to 14 September 2009, and faults (thin lines [Cather et al., 2004; Love et al., 2009]), focal mechanisms and SSN stations (triangles). Stars show locations of 1983 (black) and 2005 (white) swarms. Inset shows map area and SMB outline. Focal mechanism solution for the first earthquake, $M_d 2.29$ (A), occurring on 20 August 2009 01:57 (UTC) with impulsive P-wave polarities shown (dilation, triangles; compression, octagons) and focal mechanisms for three earthquakes on 30 August 2009: $M_d 2.5$, 00:31 (B), $M_d 2.34$, 06:39 (C), $M_d 2.26$, 07:09 (D).

north-striking normal faults, while mechanism C shows northwest-striking normal fault motion. The Veranito fault, the largest of several roughly north-striking normal faults, dips from $70^\circ$–$80^\circ$W in this area, and is located ~1.5 km east of the swarm [Cather et al., 2004]. The fault surface projected at depth intersects some of the earthquake locations, but the overall event locations suggest some shallowing of a possible fault plane. All four mechanisms are reasonable for this highly faulted area of the RGR, consistent with 5 additional northward striking normal fault mechanisms found by Stankova-Pursley et al. [2009]. Focal mechanisms for swarms in May and July of 1983 and October of 2005 south of the 2009 swarm indicate more northerly striking normal faults than found for the 2009 events, although solutions from the older swarms have fewer station observations to constrain them [e.g., Ake, 1984; Stankova et al., 2008].

3. Earthquake Relocation

[6] Waveform cross-correlation techniques have been widely applied to improve locations of groups of similar events in a variety of seismic sequences including mainshock-aftershock, reservoir-induced, and swarms [e.g., Shearer, 1997; Rowe et al., 2002]. Cross-correlation techniques capitalize on the similarity of events in a given data set by computing differential times for well-correlated waveforms on a station-by-station basis [e.g., Shearer, 1997]. Waveform similarity in a spatially concentrated earthquake swarm is ideal for cross-correlation-based pick adjustment techniques to improve arrival time pick consistency and refine locations.

[7] We relocated a subset of 374 events in the main swarm from 00:00 (UTC) 23 August to 00:00 (UTC) 15 September 2009 using adjusted arrivals of P and S phases on up to 5 SSN stations as well as some SMB-reflected phases recorded on station LEM (Table S1 of the auxiliary material). All event waveforms for one station are windowed around one phase arrival pick (Figure 2) and correlation coefficients are computed for the raw data. Events with correlation coefficients >0.55 are then lag-adjusted at the sample level in an iterative process to achieve the highest possible correlation. The final adjustment is refined to the sub-sample level by weighing the adjustments based on individual event correlation (Figure 2).

[8] Correlation coefficients varied among phases and stations (Table S1). Three stations showed high correlation values with averages greater than 0.85 (Figure 3a), although SsS and SsP phases show significantly lower correlation values, reflecting noisier data later in the wavetrain. The use of these reflected phases, however, allows us to better constrain the depths to primarily 4–6 km (Figure 3). Maximum absolute location change is 0.42 km (Figure S1 of the auxiliary material).

4. Swarm Characteristics

[9] The first event on 20 August 2009 occurred at 106.86°W, 34.07°N, however the majority of the events were centered 10 km north around 106.85°W, 34.17°N within a 34.5 km$^3$ volume. The overall seismicity lacks a clear south-to-north migration from 20 August 2009 to the main activity, possibly due to partial data loss on 22 August 2009, although there is no evidence of migration from 20 August through early 22 August. The seismicity exhibits weak east to west migration (Figure 3). Event depths are typical for SMB seismicity, ranging from 1.1 to 8.9 km, with the main concentration between 5–7 km depth, shallowing 8–11 days after the first event, indicating vertical progression with time at a rate of ~0.08 km/day (Figure 3). Events $M_d > 2$ tended to be shallower with an average depth of 4.2 km relative to the depth average of 5.6 km ± 0.8 km for the entire swarm. The relatively flat nature of the swarm suggests the faults in this area may be listric at these depths, a reasonable geometry given the rifting environment and presence of the SMB. The upward migration of events could be connected to the diffusion of fluid moving upward from depth as suggested by Hainzl [2004].

[10] We also examine moment release and aftershock-decay rates of the swarm (Figure 4). The largest increase in seismic moment, $7.08 \times 10^{12}$ N-m, occurred 30 August 2009 00:31 (UTC) due to the largest $M_d 2.5$ event (Figure 1, Mechanism B). Typical mainshock-aftershock sequences exhibit aftershock decay according to the modified form of Omori’s Law [Utsu, 1961]. Using a range of decay rates, represented by the $p$ exponent with typical values around 1, we were unable to fit any of the power-law decay curves to our data (Figure 4a), indicating swarm behavior.

[11] The $b$-value for an earthquake catalog describes the relative frequency of small and large earthquakes [Gutenberg and Richter, 1944]. Typical mainshock-aftershock sequences and global catalog estimates suggest $b$-values of 1, however

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1 Auxiliary materials are available in the HTML. doi:10.1029/2010GL045162.
b-values in volcanic and earthquake swarm regions are often much larger than 1 [e.g., Gutenberg and Richter, 1944; Sykes, 1970]. The b-value of the 2009 earthquake swarm based on local magnitudes is 0.9 (1σ = 0.09, estimated by bootstrap resampling) for events $M_d$ 0–2.5 (Figure 4c). The b-value of the entire catalog of SMB-related seismicity from September 2004 to December 2009 is 1.1 (1σ = 0.08). The swarm included four of the largest events occurring in this area, likely contributing to the lower b-value observed than for the entire five-year catalog. These b-values are lower than expected for a volcanic or magmatic swarm region, instead consistent with typical b-values of mainshock-aftershock faulting sequences and to those found by Ibs-von Seht et al. [2008] for continental rifts generally and the RGR specifically (0.8).

5. Discussion

[12] Another well-located earthquake swarm occurred in this area in October 2005, approximately 15 km southwest of the August 2009 sequence. The 2005 swarm included over 1600 detectable and 85 locatable events over a 32-day period, concentrated near 34.06°N, 106.96°W [Stankova et al., 2008]. This swarm occurred in an area of previous swarm activity in May and July 1983 with similar waveforms and focal mechanisms.

[13] The b-value for the 2005 swarm is 1.3, higher than in the 2009 sequence (0.9) [Stankova et al., 2008]. The higher b-value seen in the 2005 swarm suggests a more volcanic or active magmatic origin for swarm activity than seen in 2009, however, maximum moment release in the 2005 swarm is an order of magnitude lower than for the 2009 activity (Figure 4b). The two swarms show very different frequency-time relationships as well (Figure 4d). The 2005 sequence appears to exhibit an aftershock fall-off compared to the late activity in the 2009 swarm, however the 2005 swarm was also poorly fit by standard decay rates [Stankova et al., 2008]. The significant differences in the 2005 and 2009 SMB earthquake swarms suggest that swarm-like sequences...
in this area are quite variable. The 2009 swarm occurred in an area of long-term uplift with line-of-sight velocity rates of 1.75 mm/yr estimated from InSAR data [Finnegan and Pritchard, 2009], while the 2005 swarm occurred in an area of transition between uplift and subsidence. There was no change in the rate of vertical deformation associated with the 2009 swarm based on continuous GPS measurements from stations ~7 km from the 2009 swarm (A. Newman, personal communication, 2009). The differences in seismicity of the two swarms might indicate a diverse stress field dependent on location relative to the deformation.

[14] Based on a comparison to other earthquake swarm regions, Stankova et al. [2008] suggest that it is the interaction of fluid-induced processes with extensive, preexisting fault systems linked to inflation of the SMB and regional tectonics that causes the swarm-like seismicity here over decadal time scales. The upward migration of events seen in the 2009 swarm suggests fluid diffusion may play an important role in seismic generation [e.g., Hainzl, 2004]. Obviously the presence of the SMB at depth and resulting surface deformation is an important influence on the seismicity. However, based on low b-values we do not classify these as volcanic swarms with a strong direct magmatic influence on the seismicity.

6. Conclusions

[15] The August 2009 swarm included 431 locatable microearthquakes over a 26-day period. Using waveform cross-correlation techniques, we relocated 374 events within a concentrated volume (34.5 km$^3$). We find weak evidence of temporal migration with the swarm. Earthquake statistics suggest this sequence was a swarm rather than a typical mainshock–aftershock sequence, and a low b-value of 0.9 is more similar to other continental rifing areas rather than the high b-values found in active volcanic areas.

References


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