RESEARCH ARTICLE

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Key Points:

- We record 927 tectonic earthquakes in the vicinity of the Rio Grande Rift
- Modern crustal extension related to the Rio Grande Rift occurs hundreds of kilometers east and west of the geological rift
- Deformation in the central rift takes place along the Colorado Plateau-Rio Grande Rift transition zone along the western Jemez Lineament

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3

Correspondence to:

J. S. Nakai,
jenny.nakai@colorado.edu

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Seismicity of the rocky mountains and Rio Grande Rift from the EarthScope Transportable Array and CREST temporary seismic networks, 2008–2010

J. S. Nakai^{1,2} , A. F. Sheehan^{1,2} , and S. L. Bilek³
¹Department of Geological Sciences, University of Colorado Boulder, Boulder, Colorado, USA, ²Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado, USA, ³Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA

Abstract We developed a catalog of small magnitude (M_L -0.1 to 4.7) seismicity across Colorado and New Mexico from the EarthScope USArray Transportable Array and CREST (Colorado Rocky Mountains Experiment and Seismic Transects) seismic networks from 2008 to 2010 to characterize active deformation in the Rio Grande Rift. We recorded over 900 earthquakes in the Rio Grande Rift region, not including induced earthquakes and mine blasts, and find that the rift is actively deforming both broadly and in distinct regions. Seismic events that are likely induced, mostly in the Raton Basin, make up 66% of the catalog (1837 earthquakes). Neogene faults in the northern rift in north central Colorado are seismically active in the North Park Basin and northwestern Colorado. The central rift from the San Luis Basin (southern Colorado) to south of the Socorro Magma Body is the most seismically active rift region, and seismicity delineates the deformation in the Colorado Plateau transition zone, which is spatially correlated with volcanic vents, dikes, and faults within the western Jemez Lineament. The eastern Jemez Lineament is nearly aseismic and surrounded by a halo of seismicity culminating in boundaries defined by recent moderate (M_w 3.9 and M_w 3.3) earthquakes. The southern rift is characterized by diffuse seismicity in Texas and Mexico. This study provides an updated seismic catalog built with uniformity in seismometer coverage and low epicentral uncertainties (~ 2 km) that allows for regional evaluation of seismicity. During this time period, clusters of seismicity and moderate magnitude earthquakes characterize deformation in a low-strain rate extensional environment.

1. Introduction

The Rio Grande Rift is a continental, east-west extending rift geologically defined by Quaternary faulting, sedimentary basins, and volcanism beginning in Mexico and ending in northern Colorado (Figure 1) [Chapin, 1978; Eaton, 1987; Chapin and Cather, 1994]. It is superimposed on tectonic deformation from the Laramide orogeny, Cretaceous burial, and Ancestral Rockies uplift and erosion [Tweto, 1979]. Our understanding of the Rift has several gaps, including the spatial extents of the Rift and associated deformation, as well as a robust picture of where seismicity occurs within the Rift. Because of fairly sparse seismic station distribution, previous catalogs have not distinguished whether seismicity occurs continuously along the Jemez Lineament, a northeast striking alignment of Quaternary and Neogene volcanics, or near Quaternary or Neogene faults. With recent seismometer deployments associated with the EarthScope Transportable Array and other temporary networks in Colorado and New Mexico, we have the unique opportunity to observe spatially unbiased small magnitude seismicity in and around an active rift, which helps us investigate the relationship between the Rio Grande Rift and surrounding active tectonic regions. Using this seismic data set, we detect, locate, relocate, and study earthquake locations to clarify the spatial extent of the rift using small magnitude earthquakes, identify the features correlated with seismicity, resolve seismicity between the rift and the Jemez Lineament and Colorado Plateau, and address whether or not the rift is active and deforming uniformly from east to west and north to south. We use data from 2 years (February 2008 to February 2010) of EarthScope Transportable Array (TA), a temporary deployment of broadband seismometers spanning the conterminous U.S. with a station spacing of ~ 70 km (Figure 1). The addition of cotemporal Colorado Rockies and Seismic Transect (CREST) array [Hansen et al., 2013; MacCarthy et al., 2014] and permanent USGS seismometers densified the station spacing (Figure 1) and increased the number of seismometers used in this study to 317. The Advanced National Seismic System (ANSS) backbone and New Mexico Institute of Mining and Technology seismic networks have provided a much longer temporal record of seismicity

Figure 1. Map of seismic stations used in this study. Triangles are TA stations (black), and ANSS backbone network (orange), circles are CREST stations (red), and black lines are Quaternary faults [USGS, 2006]. The northern, central, and southern Rio Grande Rift are outlined, and the Jemez Lineament is dashed.

along the Rio Grande Rift, but this study complements previous studies by developing an earthquake catalog with smaller epicentral uncertainties based on uniform station density across a region previously studied in fragments and interprets these earthquakes in the context of the Rio Grande Rift. Here, we use the unbiased spatial coverage of the TA seismic network to study seismicity related to extension of the Rio Grande Rift in the context to the active tectonics of the Rocky Mountains, Colorado Plateau, and Great Plains.

1.1. Structural and Tectonic Setting

The topographic expression of the Rio Grande Rift varies along its length, with a relatively narrow surface expression of 50 km in northern Colorado and 300 km in southern New Mexico [Seager and Morgan, 1979]. Thermochronologic evidence supports exhumation in the Miocene as far north as the Gore Range [Landman and Flowers, 2013], and the evidence for a north-central and northwestern rift in Colorado relies on evidence of Neogene faulting and the Yampa basin sediment and volcanics [Tweto, 1979; Eaton, 1987; Leat et al., 1991; Cosca et al., 2014]. Quaternary faulting continues south along the Texas-Mexico border and blends into the Basin and Range style faulting in Mexico [Seager and Morgan, 1979]. Mantle seismic tomography suggests that the subsurface width of ~270 km of the central rift is much greater than the surface expression in central New Mexico [Gao et al., 2004]. Crustal thickness along the strike of the rift is estimated to vary from about 35 km in the south near Deming, New Mexico (southern New Mexico) to 52 km in the north in the region of Craig, Colorado [Shen et al., 2013; MacCarthy et al., 2014]. There is an abrupt

change in crustal thickness from the relatively thin crust (~35 km) of the rift eastward to the thick crust (~45 km) of the Great Plains in the south and central rift and a gradual thickening west (to ~40 km) into the Colorado Plateau. A comparison of models of the crust from past seismic experiments indicates *P* wave speeds are higher in the lower crust of the Great Plains (~7 km/s) than in the Colorado Plateau and the Rocky Mountains (~6.7 km/s) [Snelson *et al.*, 1998; Levander *et al.*, 2005]. Lower crustal *P* wave speeds are relatively low in the Rio Grande Rift (~6.5 km/s) compared to surrounding provinces [Toppozada and Sanford, 1976]. Lin *et al.* [2014] find low *S* wave speeds in the lower crust throughout the southern Rocky Mountains, the western Jemez Lineament/Colorado Plateau transition zone, and into the Great Plains near the Colorado-New Mexico border.

The highly varied terrain along the rift and the variable width of rift basins led many to believe that the rift was not extending uniformly [Chapin and Cather, 1994], and even today there is disagreement from GPS studies whether the Colorado Plateau is rotating about a Euler pole or whether the rift is uniformly extending east-west [Kreemer *et al.*, 2010; Berglund *et al.*, 2012]. The northern, central, and southern rift were exhumed at roughly the same time, with early extension as far back as 32 Ma [McIntosh *et al.*, 1992]. The most recent epeirogenic uplift occurred at ~10 Ma from southern New Mexico up to the Gore Range in Colorado [Baldridge *et al.*, 1980; Kelley *et al.*, 1992; May *et al.*, 1994; Landman and Flowers, 2013; Ricketts *et al.*, 2015]. Although seismicity can only tell us about present-day rifting, it can tell us whether or not the rift is active and deforming uniformly.

The Jemez Lineament is a 50–80 km wide alignment of Neogene and Quaternary volcanics (13 Ma to 1200 BP) that extends from Arizona to the edge of southeast Colorado. There is no obvious time progression of volcanic eruptions, and the lineament has been interpreted as a leaky crustal flaw with Precambrian origins through which magmas ascended [Karlstrom and Humphreys, 1998]. Mantle scale studies of the rift cannot differentiate between the Jemez Lineament and the Rio Grande Rift [Gao *et al.*, 2004; Roy *et al.*, 2005; van Wijk *et al.*, 2008], but the surface expression of the Jemez Lineament and the rift are distinct. Aldrich and Laughlin [1984] proposed that the Lineament is a transition between stress orientations from the Colorado Plateau (extension oriented SW-NE) to the Rio Grande Rift (extension oriented E-W), and subsequent studies have found that a transition in mantle seismic wave speeds [Gao *et al.*, 2004], densities [Roy *et al.*, 2004], and migration of mantle sourced basalts [Crow *et al.*, 2011] is evident from the Colorado Plateau to the Rio Grande Rift.

1.2. Historical Seismicity

Machette [1998] called the record of seismicity in the Rio Grande Rift “relatively short and generally unimpressive” due to the absence of seismicity around major Quaternary faults of the rift. He noted the existence of historic earthquakes from magnitude 4–5 in the Great Plains and the Colorado Plateau, which he suggested could be due to the Jemez Lineament acting as a transfer zone of the rift. Thus far, seismicity studies in and around the Rio Grande Rift have been conducted separately by state [Frohlich and Davis, 2002; Kirkham and Rogers, 2000; Sanford *et al.*, 2002; Wong *et al.*, 2004]. The most spatially uniform earthquake catalog is the USGS ANSS Comprehensive Earthquake Catalog (ComCat) 1973–2015, which consists of ~700 events in this region (area shown in Figure 1). The USGS catalog (ComCat) includes ~90 events in our study area (area shown in Figure 1) during the 2008–2010 catalog time period [USGS, 2017]. During the USArray TA deployment in our region, ~1100 events were located by the Array Network Facility, though these events include both mine blasts and earthquakes [Astiz *et al.*, 2014].

1.2.1. Colorado

Colorado hosts three permanent ANSS seismograph stations (ISCO, MVCO, and SDCO). The US Bureau of Reclamation operates two seismic networks: the Paradox Valley network which records induced seismic activity from saltwater injection [Ake *et al.*, 2005; Block, 2010; Block *et al.*, 2014; Yeck *et al.*, 2015], and the Ridgway seismic network which records seismic activity around Ridgway Dam and Reservoir [Ake *et al.*, 2002]. Temporary seismic networks have been deployed to study the Crested Butte 1986 earthquake swarm [Bott and Wong, 1995], Colorado Front Range seismicity [Bott *et al.*, 2003], large (M_w 4.6 and 5.3) earthquakes in the Raton Basin [Meremonte *et al.*, 2002; Rubinstein *et al.*, 2014], and a statewide broadband network deployed to study mantle structure [Sheehan *et al.*, 1995; Lee and Grand, 1996; Monsalve *et al.*, 2008]. Many thorough but nonpeer-reviewed and hard to find assessments of local seismicity in Colorado have been undertaken for seismotectonic evaluations for dams [Unruh *et al.*, 1993, 1994, 1996; Ake *et al.*, 2002]. The Colorado Geological Survey has in the past published volumes of seismicity, fault activity observations, and

historical felt reports in Colorado [Kirkham and Rogers, 1981, 1986, 2000]. Tectonic earthquakes in Colorado are interpreted to occur along reactivated Laramide and older structures, at sites of evaporite deformation [Bass and Northrop, 1963; Mallory, 1971; Guter et al., 1988; Kirkham, 1997], and near Quaternary faults, but little seismicity is attributed to the Rio Grande Rift [Kirkham and Rogers, 1981; Bott and Wong, 1995; Kirkham and Rogers, 1985, 2000; Kirkham and Scott, 2002; Bott et al., 2003].

1.2.2. New Mexico

One ANSS backbone station (ANMO) is operating in New Mexico, and semipermanent seismic networks include the Los Alamos network (established in 1972), which monitors seismicity from the Valles Caldera and the nearby Pajarito fault [Macon and Mello, 1997]. There are two dense, vertical component, short-period seismic networks operated by New Mexico Institute of Mining and Technology. The first is in the Dagger Draw oil field, established in 1999 in order to monitor seismicity near the Waste Isolation Pilot Plant, and the second is the Socorro network, established in 1962 in order to monitor seismicity above the active Socorro Magma Body [Sanford et al., 2002; Sanford et al., 2006; Pursley et al., 2013]. These stations, combined with other local networks, have led to comprehensive monitoring of seismicity in two portions of the Rio Grande Rift [Sanford et al., 2002]. In New Mexico, it is believed that most tectonic earthquakes are related to rifting and volcanic activity on the Jemez Lineament [Sanford et al., 2002], but the broad, diffuse seismicity is also interpreted as a high level of background seismicity not associated with specific faults or tectonic features [Wong et al., 1996; Wong et al., 2004]. However, the location uncertainty of earthquakes outside the dense network footprints is very large due to distant, irregular station spacing and generally poor azimuthal coverage of the network. In previous catalogs, seismicity in the New Mexico portion of the Colorado Plateau may be contaminated by mine blasts and make up some of the diffuse seismicity that is difficult to interpret.

1.2.3. West Texas

Seismicity in west Texas is monitored with a small network at the University of Texas at El Paso and two ANSS backbone stations (AMTX and MNTX), but associations between earthquakes in the Texas-Mexico regions with the Rio Grande Rift, Basin and Range extension, and Quaternary faults have mostly been made in independent studies of seismicity and historical earthquakes [Doser, 1987; Suter, 2001; Castro et al., 2010; Suter, 2015]. The University of Texas El Paso network data have also contributed to New Mexico's seismicity catalog [Sanford et al., 2002].

1.2.4. Maximum Magnitude Estimates

Many of the Quaternary faults in Colorado have been assigned maximum earthquake values in the M_w 6 to 7.5 range [Unruh et al., 1994]. In comparison, the background seismicity in New Mexico is thought to indicate a maximum magnitude earthquake of M_w 6 to 6.5 [Ake et al., 2002]. The estimated location of the largest historic earthquake (estimated at M_w 6.6) in Colorado history was in the Front Range east of the North Park Basin in 1882 [Kirkham and Rogers, 1986; Spence et al., 1996], although an earlier study determined the epicenter was in northwestern Colorado [McGuire et al., 1982]. Based on Quaternary fault displacement and an estimate of fault length, paleoseismic evidence suggests that M_L 6.8–7.4 events have occurred on the Sangre De Cristo fault zone [McCalpin, 1982]. Active Quaternary faults are most numerous in the central rift [USGS, 2006] but also occur in the northern and southern rift (Figure 1) [Eaton, 1987]. Historical large earthquakes ranging from M_L 5.4 to M_w 6.6 have occurred in the Texas Panhandle and in Socorro, New Mexico [Frohlich and Davis, 2002; Sanford et al., 2002]. Paleoseismic evidence suggests that a M_w 7–7.5 has occurred on the central San Andres Mountains fault in the Southern Rio Grande Rift near the Texas border [Machette, 1987]. The 1931 M_w 6.5 Valentine earthquake occurred on the eastern side of Basin and Range/Rio Grande Rift extension near El Paso, Texas [Doser, 1987]. The largest historic earthquake in the vicinity of the Rio Grande Rift was a M_w 7.5 [Suter, 2015] in 1887 near Sonora, Mexico [Aguilera, 1920; Machette, 1998], which occurred on the western edge of the rift on the east flank of the Sierra Madre Occidental.

2. Data and Methods

2.1. Initial Event Location

We used the Antelope software package [Pavlis et al., 2004] to detect, associate, estimate single-event locations and estimate magnitudes of earthquakes following the procedures outlined by Lockridge et al. [2012]. To detect events, we used the short-term average/long-term average algorithm *dbdetect* on bandpass filtered (3–10 Hz) continuous broadband waveform data. We defined our short-term and long-term average windows to be 1 and 5 s, respectively, and required a signal-to-noise ratio of at least 3.5 to create a

Figure 2. (a–c) Example seismograms which are all unfiltered at the closest station to the event. (a) M_L 4.7 in the Colorado Great Plains recorded at station TA R27A, epicentral distance 22 km, (b) M_L 1.2 at Mt. Taylor, New Mexico recorded at station TA W21A, 29 km distance, and (c) mine blast from Navajo Mine, New Mexico as recorded at station TA U20A at distance of 21 km. Local magnitude (M_L) is calculated based on the highest peak amplitude on horizontal components after the onset of the P wave arrival at each station.

detection. We associated detections into potential earthquake hypocenters with the *dbgrassoc* algorithm. To associate an event, we required a matching trigger time at four stations within a 2° radius, with the spatial scale determined to balance the number of observations needed to locate an earthquake with the number of false associations that arise with larger distances. The associations, or preliminary events, include earthquakes, mine blasts, mine collapses (see supporting information; Walter *et al.*, 1996; Swanson *et al.*, 2002), as well as false associations. We processed the data by hand, picking P and S wave arrival times for all events, flagging mine blasts [Stump *et al.*, 2002; McLaughlin *et al.*, 2004], removing false associations, and ignoring events located outside the network, with the exception of events near the Texas/New Mexico-Mexico border. Sample seismograms from local earthquakes and a mine blast are shown in Figure 2.

2.2. Regional 1D Velocity Model Inversions

To improve the accuracy of our event locations, we inverted local earthquakes to create five regional P and S wave velocity models: the Great Plains, the Raton Basin, the Colorado Plateau, the Rio Grande Rift/Basin and Range, and the Rocky Mountains (Table 1). We used earthquakes greater than M_L 1.8 in the inversion to ensure adequate numbers of arrival times (smaller earthquakes are generally seen at fewer stations) with spatial coverage of the provinces, as we want the velocity model to represent as broad of a region over the province as possible. We use *VELEST*, a simultaneous velocity model, earthquake location, and station correction least squares inversion [Kissling *et al.*, 1995]. *VELEST* requires an a priori velocity model to calculate initial travel times (Table 1). Starting models were based on available refraction and reflection experiments (Table 1). *VELEST* calculates travel times with station elevations taken into account, which is important given the high topographic variation. We constructed Wadati diagrams [Wadati, 1933] to determine the V_p/V_s ratio for five regional starting velocity models (Table 2). We used arrivals within 30 s of the origin time (~ 170 km) in the linear regression to avoid the scatter of more distant arrivals. V_p/V_s ratios determine the starting S wave velocity models, but *VELEST* independently inverts for the S wave velocity model. With the exception of the Rio Grande Rift/Basin and Range model, we used only arrivals with an epicentral distance of less than 170 km in the inversion to avoid fitting scatter in the travel time data due to P_g to P_n crossovers. In the rift, we only used arrivals within 130 km of the epicenter to invert for a velocity model as this region has a thinner crust and therefore a decreased P_g/P_n crossover distance. We base our models of crustal thickness on previous studies [Shen *et al.*, 2013], adjusting the models when necessary from travel time observations. We fixed upper mantle velocities to 8.00 km/s which agreed with all regional travel time observations from our earthquake data. No S_n picks were made for any earthquakes, so we set S wave upper mantle velocities to values from Shen *et al.* [2013]. We selected final velocity models based on low data variance, root mean squared travel time residual, and good visual fit to the travel time data.

Table 1. 1D Inversion Starting Parameters Including Physiographic Region, Number of Earthquakes, and Starting Model Used for Each 1D Model/Earthquake Relocation Inversion

Region	No. of Earthquakes	Starting Model
Great Plains	86	<i>Levander et al.</i> [2005]
Raton	249	P. Friberg (personal communication), [2015]
Rio Grande Rift/ Basin and Range	77	<i>Topozada and Sanford</i> [1976]
Colorado Plateau	35	<i>Snelson et al.</i> [1998]
Rocky Mountains	33	<i>Snelson et al.</i> [1998]

through a Markov chain Monte Carlo search. Bayesloc estimates parameter uncertainty from the posterior distribution of every model parameter. Misspicks and outliers are removed if they are not close to a predicted time. The velocity models start at the average regional elevation (1.7 km for the Great Plains, Colorado Plateau, and Rio Grande Rift, and 2.0 km for the Raton Basin and Rocky Mountains). Accordingly, Bayesloc depths are with respect to the average elevation for each region. For the relocation of the entire catalog, we used arrivals within 1.7° for the Colorado Plateau, Great Plains, Raton Basin, and Rocky Mountains, and we used arrivals within 1.5° in the Rio Grande Rift. Therefore, no *Pn* arrivals are used to locate events, although we picked these arrivals. The RMS residuals improve dramatically with use of Bayesloc and regional VELEST models compared to our initial dblocsat2 hypocenters (supporting information Figures S1 and S2).

2.4. Magnitude Scaling and Moment Release

We estimate a magnitude completeness of M_L 1.3 (computed with Antelope's *mlrichter*) with the maximum curvature method [Wiemer and Wyss, 2000] and a *b* value of 0.8 (Figure 3) for our full earthquake catalog. Local magnitudes are calculated based on the highest peak amplitude after the onset of the *P* wave arrival at each station. Station distance corrections are those from *Richter* [1958] for use in California, so our magnitudes are consistently greater than USGS M_L , M_{blg} , and M_w determinations, and we calculate a conversion for M_w based on shared events (plots and conversions are in supporting information Figure S3). This difference

can be large, as in the case of the widely felt Great Plains M_L 4.7 event (17 August 2009), for which the USGS estimated M_w 3.9 and a M_{blg} 4.1. We then use M_w to calculate seismic moment based on *Kanamori and Brodsky* [2004]:

$$M_0 = 10^{(M_w + 6.07)1.5}$$

where M_0 is the seismic moment. A comparison between the USGS historical catalog (ComCat) [USGS, 2017] and our TA catalog (Figures 4a and 4b) shows a dramatic increase in both the number and density of earthquakes, while faithfully representing the overall spatial coverage of the longer-term catalog.

We also locate more than 2500 mine-related events (supporting information Figure S4 and Tables S2 and S3), partially for the purpose of assessing absolute location errors. To obtain absolute location uncertainties, we relocated mine blasts in

Table 2. 1D Velocity Models for the Five Physiographic Study Regions^a

Depth to Top of Layer (km)	V_p (km/s)	V_s (km/s)
Great Plains ($V_p/V_s = 1.73$)		
0	5.41	3.20
5.7	6.26	3.60
44.7	8.00	4.00
Raton Basin ($V_p/V_s = 1.69$)		
0	3.49	1.87
2	4.38	3.49
3	5.97	3.60
20	6.32	3.60
47	8.00	4.30
Colorado Plateau ($V_p/V_s = 1.69$)		
0	6.04	3.52
6.7	6.15	3.62
40.7	8.00	4.10
Rio Grande Rift/Basin and Range ($V_p/V_s = 1.70$)		
0	6.04	3.58
18.6	6.55	3.58
36.7	8.00	4.41
Rocky Mountains ($V_p/V_s = 1.69$)		
0	5.90	3.53
7	6.02	3.58
48	8.00	4.50

^a V_p/V_s in parentheses from Wadati diagrams. Zero depth is at the average surface elevation.

Figure 3. Earthquake recurrence plot where the b value is 0.84 calculated from the maximum curvature method. *Unruh et al.* [1994] found b values of 0.81 and 0.80 for the Rocky Mountains and Great Plains, respectively. The magnitude completeness is estimated at M_L 1.3. Diamonds are the frequency of earthquakes per 0.1 units M_L , and bars are cumulative frequency of earthquakes.

Bayesloc and measured the distance between blast locations and the Google Earth location of the mine. Blasts associated with the Cripple Creek Mine, on the west side of the Front Range in Colorado, and Navajo Mine, in northeast New Mexico, located at the mine sites, implying an extremely low (<200 m) epicentral uncertainty. Blasts at two mines in northwest Colorado showed a location bias of 2 km and 1.5 km; thus, our estimate of average epicentral uncertainty is ± 2 km from comparison to mine blasts. Depth uncertainty is difficult to quantify. Besides the formal depth errors that Bayesloc produces, there is an inherent bias that relies on accurate shallow velocity structure for shallow earthquakes, which we are not able to reliably invert for given the coarse station spacing

of the TA and CREST networks. We adopt the Bayesloc depth errors with the understanding that there is an inherent velocity model bias and depths may differ by several kilometers for shallow earthquakes and earthquakes farther from stations, but may be quite accurate for earthquakes less than half a focal depth from stations (35 km or deeper for the TA and 15 km or deeper within the CREST array). Comparing depths for larger earthquakes with the St. Louis University regional waveform moment tensors [Herrmann, 2016] resulted in depth differences of ± 5 km for earthquakes in the Great Plains, Rocky Mountains, and Colorado Plateau and ± 3 km for the Raton Basin area. The mine blasts relocated at average depths of 3–4 km below mean surface elevation in the Colorado Plateau and 8–9 km in the Rocky Mountain province, hinting at the magnitude of depth errors in those regions.

3. Results

We located 2764 earthquakes for the 24 month period from February 2008 to February 2010 (Figure 5). Earthquakes are listed in supporting information Table S1, mine blasts in supporting information Table S2, and mine collapses in supporting information Table S3. We examined clusters of seismicity as a way of identifying seismically active tectonic features (Figures 6 and 7). These clusters were identified as locations where three or more closely spaced events (in an area of less than ~ 3 km²) occurred. The focus of this paper is seismicity of the Rio Grande Rift, so other sources of seismicity (induced earthquakes and nonrift tectonic earthquakes) are discussed in the supporting information rather than in the main body of the text, including earthquakes in southwest Colorado, near the San Juan Volcanic field [Steven *et al.*, 1974; Steven and Lipman, 1976; Lipman *et al.*, 1978; Baars and Ellingson, 1984; Lipman, 1984; Hail, 1989; Cunningham *et al.*, 1994; Bachmann and Bergantz, 2003; Drenth *et al.*, 2012]. We identify nearby mapped faults that may be associated with these earthquakes Tweto *et al.*, 1978, but some earthquakes are not near mapped faults and are occurring on buried or unmapped faults, or are of volcanic origin. Further information (i.e., moment tensors and well-constrained depths) is needed to determine whether earthquakes are occurring on faults close to the epicenters. We divide the study into four regions, the northern rift, the Great Plains, the central rift, and the southern rift (Figure 1).

3.1. Northern Rio Grande Rift

We consider the northern Rio Grande Rift as the section from north-central Colorado, near the Wyoming border [Tweto, 1979; Eaton, 1987], to the northern edge of the San Luis Basin, which coincides with the terminus

Figure 4. (a) USGS seismicity from 1973 to 2016 with moment tensors, 1962–2016 [Herrmann, 2016]. (b) This catalog, from 2008 to 2010 with moment tensors from the same time period [Herrmann, 2016]. Our catalog is spatially similar to the longer-term seismicity (M_L -0.1 to 4.7) and shows considerably more detail than the USGS catalog. The minimum magnitude in the USGS catalog is a 2014 M_L 1.3 earthquake in Greeley, Colorado, and the maximum is a 2014 M_{WR} 5.2 earthquake on the southern Arizona-New Mexico border. Heavy black lines are physiographic province boundaries (Colorado Plateau, Southern Rocky Mountains, Rio Grande Rift, and Great Plains). Socorro Magma Body is outlined with a solid black line in south central New Mexico. Thin black lines are Quaternary faults [USGS, 2006].

of the Sangre de Cristo fault (Figure 1). In the northern rift in Colorado, there are three clusters of earthquakes that coincide with the Rio Grande Rift system [Kirkham and Rogers, 1981]: Craig (3), Steamboat Springs (2), and Clark (1) in Figure 6a. Although the Craig earthquakes are west of the northern Rio Grande Rift province, Kirkham and Rogers [1981] comment that movement on the fading rift is translated to movement on faults in the Uinta-Elkhead provinces, where Craig is located.

3.1.1. Craig, Colorado

A cluster of four earthquakes includes a M_L 4.2 (M_w 3.7 event) that was felt at a Modified Mercalli (MM) intensity of III in Craig, Colorado on 18 August 2009 (Figure 6a, cluster 3). Three northeast trending normal faults with late Cenozoic movement [Izett, 1975; Tweto, 1976] lie 3 km from the M_w 3.7 and 3 additional collocated earthquakes. The normal faults have been active since the Miocene-Pliocene with limited evidence of Holocene movement [Kirkham and Rogers, 1981], although the moment tensor shows strike-slip motion on a plane close to these faults (planes striking 55° and 145°) of the 18 August 2009 earthquake [Herrmann, 2016]. Rangely, Colorado, 120 km to the southwest of Craig, experienced years of earthquakes when water was injected into a formation overlying the crystalline basement [Raleigh et al., 1976]. The vast majority of Rangely earthquakes showed right lateral nodal planes oriented $N60^\circ W$, the strike of the Rangely epicenters [Raleigh et al., 1976], and a similar orientation to the 2009 event.

3.1.2. Steamboat Springs, Colorado

We find a cluster of six earthquakes (Figure 6a, cluster 2, and Figure 7a) which took place in an 8 day period in June 2009, over an area of 0.25 km^2 on the east flank of the Park Range bounding the North Park basin. Earthquake magnitudes in the cluster range from M_L 1.0 to 2.6. Two additional earthquakes occurred 4.5 km (M_L 2.0) and 12 km (M_L 1.8) to the northwest of this cluster. This cluster of earthquakes lies within

Figure 5. Map shows earthquakes located in this study. Tertiary volcanics are bright red, and Quaternary volcanics are dark red. Various features referred to in the text are shown.

2 km of four normal faults along the western North Park basin inferred to be active in the Neogene [Tweto, 1976, 1979; Eaton, 1987; Kirkham and Rogers, 1981]. Three faults strike southwest and one fault to the northeast. Kirkham and Rogers [1981] included both sides of the Park Range in the northern Rio Grande Rift province. A M_w 3.9 earthquake felt at MM Intensity IV occurred 9 km south of the cluster in 2005, and a M_w 3.0 occurred 9 km southwest of the cluster in 2000. Kirkham and Rogers [1981] considers the west side of the Parks Range as part of the northern Rio Grande Rift.

3.1.3. Clark, Colorado

Five earthquakes occurred within the 2008–2010 period on the west flank of the Park Range of north central Colorado, 1 km south of an east-west trending normal fault with Miocene-Pliocene displacement, within 4 km of several normal faults with north-south and east-west orientations, and in the center of Tertiary intrusions [Izett, 1975; Tweto, 1976; Kirkham and Rogers, 1981] (Figure 6a, cluster 1, and Figure 7a). This area may also be a section of the Rio Grande Rift system [Kirkham and Rogers, 1981].

With the exception of one earthquake on the Quaternary Mosquito fault near Leadville, Colorado, the major Quaternary faults of the northern rift (Frontal fault, Williams Fork, and Sawatch fault) were aseismic during the 2008–2010 period. The aseismic nature of Quaternary faults has been observed in other studies [McCalpin, 1982; Kirkham and Rogers, 2000]. Proximity of the earthquakes in Craig, Steamboat Springs, and Clark to Neogene faulting and Miocene-Pliocene basins suggests that faults associated with the northern Rio Grande Rift are potentially active.

3.2. Great Plains

The Great Plains is east of the Front Range and Sangre de Cristo mountains and has high mean elevation but low relief. The Jemez Lineament crosses both the Rio Grande Rift and the Great Plains, and there is at least one Quaternary fault in the Great Plains [Kirkham and Rogers, 1981; Crone et al., 1997]. We find that small

Figure 6. (a, b) Maps of Colorado and New Mexico showing numbered clusters of earthquakes and labeled geologic features. 1-Clark, 2-Steamboat Springs, 3-Craig, 4-White River Uplift, 5-Aspen, 6- Limon, 7-Ridgway 1, 8-Ridgway 2, 9-Needles, 10-Antonito, 11-Tres Piedras, 12-Tierra Amarilla, 13-Carson, 14-Coyote, 15-Espanola, 16-Cuba, 17-Amistad, 18-San Ysidro, 19-Mt. Taylor 2, 20-Mt. Taylor 1, 21-Rio Rancho, 22-Canoncito, 23-Zuni-Bandera, 24-Isleta, 25-El Malpais, 26-Mountainair, 27-Datil North, 28-Corona, 29-Alpine, 30-San Antonio E, 31-San Antonio, 32-Mogollon, 33-Carrizozo. Black lines are Quaternary faults from the USGS Quaternary Fault and Fold database.

Figure 7. Magnified images of earthquake clusters earthquake epicenters are light blue circles. (a) Near Steamboat, Colorado, on the east and west sides of the Park Range with faults active in the Neogene. (b) Jemez Lineament west. Spatial patterns of earthquakes (blue shaded area, which we refer to in the text as a stair-step pattern) outside of the Rio Grande Rift are NNE or ENE along the major volcanic features of the lineament (Zuni-Bandera, Mt. Taylor, Valles Caldera). The Nacimiento, Gallina, and Embudo faults are active Quaternary faults.

magnitude seismicity forms a continuous belt from the central rift in northeast New Mexico to the Texas border.

3.2.1. Great Plains, Eastern Colorado

The largest earthquake in our catalog during the 2008–2010 time period occurred on 17 August 2009 in the Great Plains in southeast Colorado, 43 km from the Quaternary Cheraw fault (Figures 1 and 4b) [Scott, 1970; Kirkham and Rogers, 1981; Crone *et al.*, 1997]. The moment tensor shows extension to the northwest [Herrmann, 2016], and the earthquake was felt at MM Intensity IV throughout southeast Colorado and western Kansas over an area of 30,000 km² [Herrmann, 2016]. The USGS catalog (ComCat) from 1973 to 2015 contains seven earthquakes in the Colorado Great Plains region [USGS, 2017], but only one earthquake exists in the USGS catalog in the far southeast corner of Colorado, where we find 12 earthquakes (Figures 4a and 4b).

3.2.2. Aseismic Eastern Jemez Lineament

Sanford *et al.* [2002] recognized seismicity in northeast New Mexico (Figure 5) south of the eastern Jemez Lineament and termed it the “Socorro Fracture Zone.” The belt of seismicity appears to extend to Amarillo, Texas, near the M_w 3.3 earthquake (4 February 2010) (Figure 4b). The M_w 3.3 earthquake is 60 km south of a 1948 M_N (felt area magnitude) 5.2 earthquake [Reagor *et al.*, 1982; Frohlich and Davis, 2002]. Whether a subset of the earthquakes in northeast New Mexico is induced by saltwater disposal is undetermined. There were 15 permitted injection wells in the northeast New Mexico/Texas Panhandle region during the TA deployment, and the region also hosts numerous oil and gas wells [New Mexico Oil Conservation Division, 2016]. The permitted injection rates at these wells are relatively low, averaging less than 10,000 bbl/month with a maximum of 100,000 bbl/month, far lower than the 300,000 bbl/month associated with a higher probability of inducing seismicity earthquakes close to a well [Weingarten *et al.*, 2015]. Although the injection of wastewater may explain some of the earthquakes near the wells, it cannot explain the larger regional patterns of seismicity. Further work is needed to determine whether a subset of the earthquakes in northeast New Mexico or the Texas Panhandle are related to wastewater injection.

The seismicity in northeast New Mexico is diffuse; 89 earthquakes distributed over an area of approximately 44,000 km² (Figure 5). The seismic belt (which we call the Great Plains seismic belt) to the south of the Jemez Lineament extends to west of Amarillo, Texas, which has a long history of M_L 2.5 and above earthquakes (Figures 4a and 5). The Great Plains seismic belt differs from the Socorro Fracture Zone because we do not associate the earthquakes in northwest New Mexico with a seismic lineament beginning in western New Mexico and passing through Socorro. During the TA occupation, a M_w 3.3 occurred on 4 February 2010 with a moment tensor compatible with strike-slip faulting (Herrmann, 2016) (Figure 4b). There are few mapped surface faults or dikes in the broad area, and they are all to the west closer to the rift (Figure 4b). The seismicity surrounds but does not include Jemez Lineament volcanics because the Ocate and Raton-Clayton volcanic fields are sandwiched between the belt of seismicity to the south and the diffuse seismicity in the Great Plains to the north in Colorado (Figure 5). The general strike of the earthquakes is northeast, similar to the Jemez Lineament (Figures 5 and 8b), which is just north of the Great Plains seismic belt. Aldrich *et al.* [1986] recognized that the western and eastern Jemez Lineament have different least principle horizontal stress orientations based on fault and dike orientations in the last 5 Ma (generally northwest-southeast and northeast-southwest, respectively), and the patterns of seismicity are also different from the western to eastern lineament. Seismicity in the west is concentrated on planes orthogonal to current or past least compressive stress directions [Aldrich and Laughlin, 1984], and seismicity surrounding the eastern Jemez Lineament is diffuse and strikes in the same direction as the broad pattern of the lineament.

There are two possible explanations for the absence of seismicity in the eastern Jemez Lineament, or the seismic halo, around the volcanics. The first is that the pattern of seismicity that we observe bordering the eastern Jemez Lineament (Figure 8b) is similar to the seismicity flanking the Snake River Plain in Idaho and Wyoming. In both cases, seismicity is nearly absent in the region of Tertiary and Quaternary volcanism, and seismicity is concentrated along the edge of the volcanic region. Anders *et al.* [1989] proposed that the seismic parabola (an absence of seismicity in the Snake River Plain surrounded by an arc of seismicity) was due to strengthening of the crust by basaltic volcanics in the Plain [Sparlin *et al.*, 1982]. In the eastern limb of the Jemez Lineament, basaltic volcanics residing in the crust beneath the Ocate and Raton-Clayton volcanic field are also strengthening the crust [Magnani *et al.*, 2005], which may explain the absence of seismicity directly over the Jemez Lineament, with an arc of seismicity surrounding this region. Distinct strong reflectors at 10 and 15 km depth along a reflection transect of the CD-ROM experiment were interpreted as mafic sills

Figure 8. Cumulative seismic moment distribution of (a) the USGS historical catalog (ComCat) (1973–2015) [USGS, 2017] and (b) this catalog (2008–2010). Moment density in $\log_{10}$ scale in N m. Areas of high moment density include the Raton Basin, the Socorro Magma Body, the western Jemez Lineament, the seismic belt south of the eastern Jemez Lineament, and isolated earthquake clusters in the Southern Rocky Mountains and northwest Colorado.

intruding the crust beneath the surface volcanics. These mafic sills could be of Tertiary or Precambrian age if the crustal weakness had existed for a long period of time [Magnani *et al.*, 2005], and shallow high velocities east of the reflection line were interpreted as a continuation of these crustal magma sills [Levander *et al.*, 2005]. Basaltic andesites from Ocate and Raton-Clayton show significant crustal mixing and contamination consistent with emplacement of a mafic body in the crust. This analysis is also consistent with mafic intrusions residing in the crust, thereby increasing the integrated lithospheric strength [Anders *et al.*, 1989]. The aseismic area may be acting as a rigid block with higher strain rates in the surrounding regions [Payne *et al.*, 2008]. We also believe a similar mechanism is responsible for the lack of seismicity in the San Juan volcanic field (see supporting information). A second possible explanation for the lack of seismicity is ductile, aseismic deformation in the eastern Jemez Lineament, surrounded by brittle failure due to thermal stresses from the low velocity mantle and intruded volcanics [Anders and Sleep, 1992]. In an investigation of radial anisotropy of the Jemez Lineament, Fu and Li [2015] suggested strong horizontal alignment of magmas in the western Lineament (positive radial anisotropy) and possible vertical alignment of dikes or migrating partial melts in the eastern Lineament (negative radial anisotropy). A low velocity zone appears in the lower crust in the eastern Lineament, which may be evidenced by high temperatures or melt [Fu and Li, 2015]. This would support the second hypothesis. Further investigation of the plausibility of these two hypotheses is warranted. We favor the first hypothesis because of the seismic evidence of dense mafic sills in the crust and an existing analog in the Snake River Plain.

We interpret the Great Plains seismic belt (Figures 5 and 8b) as possible extension through movement along strike-slip faults in crust that is weak relative to the basalt strengthened lower crust of the eastern Jemez Lineament and the strong, aseismic northeast (Colorado) and southeast (New Mexico) Great Plains.

3.3. Central Rio Grande Rift

The central Rio Grande Rift encompasses the most seismically active features associated with the rift, including the Jemez Lineament, the Socorro Magma Body, and the highest concentration of Quaternary faults

along the rift. One earthquake occurred along the Sangre de Cristo fault zone during the TA occupation. In order to study seismic hazard in the Albuquerque-Belen-Santa Fe, New Mexico corridor, *Wong et al.* [2004] considered only independent earthquakes (foreshocks, aftershocks, and swarm events were culled from the catalog) from the New Mexico catalog [*Sanford et al.*, 2002] and acknowledged that background seismicity not related to known faults is common in this part of the Rio Grande Rift.

3.3.1. Southeast Colorado Plateau Boundary/Western Jemez Lineament

The Jemez Lineament (Figures 5 and 7b (western Jemez Lineament)) is defined by volcanism within the last 12–0.08 Ma and by a series of NNE and NE trending dikes and faults [*Mayo*, 1958; *Aldrich and Laughlin*, 1984]. It is a transition from the Colorado Plateau stress province to the Rio Grande Rift/Basin and Range stress provinces where dominant NE-SW extension transitions via strike-slip faulting to the E-W directed extension [*Zoback and Zoback*, 1980; *Aldrich et al.*, 1986; *Wong and Humphrey*, 1989]. The western lineament, which begins roughly west of the Taos-Latir volcanic field, may also be viewed as an actively eroding boundary of the Colorado Plateau, mostly due to the predominance of recent volcanic activity concentrated along the Lineament [*Roy et al.*, 2009; *Crow et al.*, 2011]. The character of seismicity changes dramatically along the Jemez Lineament as it crosses the rift. Trends of seismicity oriented N5°E and N65°E alternate in a stair-step pattern from the north edge of the Mogollon-Datil volcanic field to the Taos-Latir volcanic field (Rio Grande Rift) along the western Jemez Lineament in west central New Mexico (Figure 7b). The N5°E orientation is parallel to Rio Grande Rift, while the N65°E strike is orthogonal to post 5 Ma stress orientations (parallel to fault and dike orientations) (Figure 7b). This is evidence that the western lineament is indeed a transition with characteristic E-W extension and seismic activity along dike orientations formed in the last 5 Ma. *Sanford et al.* [2002] and *Wong et al.* [2004] noted seismicity coincident with the western Jemez Lineament and earthquakes associated with the Albuquerque volcanoes and the Carrizozo basalt flow. With regards to seismic moment (Figure 8b), the western Jemez Lineament is at least as active as the Rio Grande Rift, but Quaternary faulting, excepting the Nacimiento uplift and Gallina faults, is nearly absent along the stair-step pattern, although Quaternary volcanism is present. The location of seismicity inboard of the Colorado Plateau lends credence to the idea that the Plateau lithosphere is being replaced by asthenosphere [*Gao et al.*, 2004].

Moment tensors for three earthquakes during the study period along the Jemez Lineament are available from St. Louis University [*Herrmann*, 2016]. Two occurred on the Jemez Lineament (strike-slip) near the Tierra Amarilla cluster (19 earthquakes), and one occurred south in the Datil North cluster (E-W normal extension) (Figures 4b and 6b).

Numerous concentrations of seismicity occur on the western Jemez Lineament. The Zuni-Bandera swarm was a series of 49 earthquakes that took place over a year, with most events happening within 60 days of the first event. These magnitudes range from M_L 0.8 to 2.0 and occur at all times of the day (supporting information Figure S5). The spatial migration of the earthquakes follows a path along an exposure of Quaternary basalts, ending within 9 km of volcanic vents which erupted basalts around 0.188 to 2.74 Ma [*Luedke and Smith*, 1978]. Thirty-seven earthquakes occurred at San Ysidro, 1.5 km east of a normal fault and 8 km west of the Quaternary Nacimiento fault (Figure 6b, cluster 18). Earthquakes near Mt. Taylor, a 4.5–1.5 Ma volcano, occur directly beneath the Tertiary basalt and andesite flows (Figure 7b), and the pattern follows the NNE strike of the volcanics and the diffuse pattern matches the occurrence of volcanic cones and necks over the stratovolcano [*Luedke and Smith*, 1978]. The Jemez Lineament and Rio Grande Rift are indistinguishable as far north as the Taos-Latir volcanic field. The Valles Caldera was aseismic during our study period as well as in past studies [*Sanford et al.*, 2002; *Wong et al.*, 1996; *Wong et al.*, 2004]. *Steck et al.* [1998] suggested that the lack of seismicity at the Valles Caldera is likely due to low seismic velocities at 5–15 km, indicating high temperature and possibly partial melt.

3.3.2. Socorro, New Mexico Region

Seismicity in Socorro, New Mexico has been interpreted as the result of the increased pore fluid pressure or direct fluid injection from a magma sill lying at 19 km depth [*Sanford and Long*, 1965; *Ake and Sanford*, 1988; *Balch et al.*, 1997; *Ruhl et al.*, 2010]. *Ruhl et al.* [2010] characterized a swarm of 431 earthquakes in August 2009, during the occupation of the TA network, with seismic activity occurring from 3 to 10 km depth above the sill. The permanent short-period New Mexico Tech seismic network has much higher resolution and better depth control on the earthquake locations on the sill [*Pursley et al.*, 2013] than our study, and we do not find any seismicity in the Socorro region that is not already found in the combined New Mexico Tech catalogs from 1962 to 2015 (supporting information Figure S6). A close-up of these events is shown in Supporting

Information Figure S6 beside the New Mexico Tech Seismological Observatory catalog of events for the same time period. Seismicity due to the magma body occurs outside of the sill defined by InSAR modeling by *Fialko and Simons* [2001]. Earthquakes range from M_L 0.0 to 2.8. There is a boundary at the northern extent of earthquakes associated with the Socorro Magma Body which likely indicates the edges of the magma body.

The *New Mexico Tech Energetic Materials Research and Testing Center* [2016] frequently sets off explosions west of Socorro, New Mexico (supporting information Figure S7d). We have 126 such events in our blast catalog (Table S2), and they are distinguished from earthquakes by the waveforms (similar to mine blasts) and the identification of a sound wave consistent with a source 4 km from TA station Y22D and 14 km from Y22A.

Outside the Socorro Magma Body, the New Mexico Rio Grande Rift is historically characterized by diffuse, low levels of seismicity [*Sanford et al.*, 2002] and seismicity not historically associated with known faults or tectonic features. We observe that several clusters of earthquakes coincide with mapped faults and volcanic flows. Clusters of earthquakes occur in Carrizozo, New Mexico, cutting perpendicular to the 5000 year old (Quaternary) lava flow (Figure 5). Many of the earthquake clusters occur close to Tertiary dikes and/or volcanic vents [*Luedke and Smith*, 1978]. We find a cluster of earthquakes at the north end of the active Quaternary Manzano fault (Figure 7b). Earthquakes occur along the Jemez Lineament/rift boundary at Espanola, Carson, Rio Rancho, and Canonicito. The Canonicito and Rio Rancho earthquakes occur near mapped normal faults outside the active Quaternary faults (Figure 6b, clusters 21 and 22). The broad pattern of earthquakes in the central rift is densely clustered earthquakes following the western rift/Jemez Lineament and encircling the Socorro Magma Body.

Sanford et al. [2002] concludes that the present-day seismicity in New Mexico fails to define the Rio Grande Rift. We agree that the current pattern of deformation does not match the rift as defined by Quaternary faults and sedimentary basins. The central rift is currently the most active part of the rift in terms of number of earthquakes, concentration of Quaternary faulting, and volume of Quaternary volcanism. The Jemez Lineament is not distinguishable from the rift southwest of the Taos-Latir volcanic field, which suggests that the rift is actively expanding into the Colorado Plateau, and this zone of seismicity is the deformational boundary of the Colorado Plateau. The western and eastern Jemez Lineament show different characteristics in terms of seismicity, with the western Lineament related to volcanics and the Colorado Plateau transition zone and the eastern Lineament earthquakes the result of extension surrounding a strong lower crust.

3.4. Southern Rift

This region extends from the south edge of the Socorro Magma Body southward, into Texas and the Mexico Basin and Range (Figure 1). Seismicity in this region is characterized as diffuse. To the west of the rift, at the border between Arizona and New Mexico, large moment release has occurred historically since 1973 and during the 1887 Sonora earthquake and may be a boundary internal to the Basin and Range or, alternatively, the western edge of the rift (Figure 8a).

3.4.1. Texas/Mexico

On the southern edge of the TA network, we find one group of earthquakes near El Paso, Texas. The most earthquakes occur 35 km east of El Paso, and diffuse earthquakes occur 130 km to the southeast (Figure 5 and supporting information Table S1). The largest cluster of nine earthquakes occurs on the east side of the Hueco Bolson in the Hueco Mountains. The seismicity to the southeast is along a continuation of Quaternary faults from the Rio Grande Rift along the western boundary of the Hueco Bolson. In 2011, a series of four earthquakes ranging in magnitude from M_w 3.7 to 4.2 occurred 25 km southwest of the Amargosa River Quaternary fault zone, and all of the moment tensors show NNW extension characteristic of Rio Grande Rift extension [*Herrmann*, 2016]. The relatively large magnitudes and proximity to the rift suggests that the Rio Grande Rift is a continuous active tectonic feature 140 km south of the U.S. border. Neogene sedimentary basins, Quaternary faults, and heat flow contours also suggest that the rift continues throughout the western border of Texas and northern Chihuahua [*Seager and Morgan*, 1979]. At the southwestern corner of New Mexico, we locate events (Figure 5) (several of which overlap with *Lockridge et al.* [2012]) that can be interpreted as aftershock earthquakes on the fault of the 1887 M_w 7.5 Sonora earthquake [*Suter*, 2001].

Our seismicity results show that deformation associated with the current tectonic extension of the Rio Grande Rift is broadly distributed. *Berglund et al.* [2012] found that geodetically measured extension is not occurring

over the narrow geological expression of the rift and is instead broadly distributed over the Great Plains, Colorado Plateau, Rocky Mountains and Basin and Range. The results of our study do not show uniform deformation over a short time scale. Figures 8a and 8b show a clear variation from north to south of the earthquake moment release. *Kreemer et al.* [2010] suggest that motion between southwest Arizona and stable North America is taken up in the southern Rio Grande Rift, but the highest concentration of earthquake activity in this catalog is in the central Rio Grande Rift and Great Plains. Both studies agree that the majority of the rift is in extension, but *Kreemer et al.* [2010] determined that extension stops north of the Sawatch fault. Strike-slip and normal moment tensors [*Herrmann*, 2016] from the earthquakes support the claim that the rift and surrounding regions are in extension. The zone of deformation from earthquakes across the Rio Grande Rift is ~350–800 km wide, with the widest section at 31° latitude. The extension, not limited to the Rio Grande Rift, extends into the Great Plains. The seismicity suggests the boundary of the transition to the stable midcontinent is farther north and east (Figure 8b), extending into central Colorado and the Texas Panhandle. Our detailed 2008–2010 earthquake catalog shows broad similarity to the historical USGS catalog and the 1962–2002 New Mexico catalog [*Sanford et al.*, 2002]. This similarity suggests that the seismicity patterns that we observe and interpret here, with the exception of the zones where earthquakes are likely induced [*Nakai et al.*, 2015], are not ephemeral.

4. Discussion

Seismicity related to the Rio Grande Rift extension can be viewed in four distinct regions, the northern rift (north central Colorado to the north end of the Sangre de Cristo fault), the central rift (the Sangre de Cristo fault to just past the southern boundary of the Socorro Magma Body), the Great Plains (east of the Front Range or east of longitude -105°), and the southern rift (south of the Socorro Magma Body into Mexico, along the Texas border) (Figure 1). In previous studies [*Unruh et al.*, 1996; *Sanford et al.*, 2002; *Wong et al.*, 2004], epicentral uncertainties varied widely throughout the region, and it was known that earthquake detection was spatially biased [*Kirkham and Rogers*, 1981; *Ake et al.*, 2002]. The predominant tectonic interpretation of these earthquakes in Colorado was reactivation of Laramide or older structures. These earthquakes were often interpreted to occur on faults favorably oriented to the current stress field [*Raleigh et al.*, 1976; *Unruh et al.*, 1994]. New Mexico's seismic coverage has been more complete than Colorado's, and our catalog compares favorably with the historic 1962–1998 New Mexico seismic catalog (*Sanford et al.*, 2002), but our relatively small epicentral uncertainties and multiple-event relocation sharpens seismicity patterns related to specific features such as volcanoes. This catalog shows higher levels of seismicity in southeast Colorado (Great Plains) and northwest Colorado (northern rift) than previously observed, and we relate the earthquakes in Colorado to the broad extension of the Rio Grande Rift. The seismicity in the northern rift indicates that the Rio Grande Rift extends north to the Park Range and potentially follows Neogene faults to the west near the Colorado-Wyoming border. *Unruh et al.* [1994] acknowledged that earthquake swarms are a characteristic form of energy release in Colorado, and this can be extended to New Mexico.

The central rift is the most tectonically active zone of the Rio Grande Rift, evidenced by earthquakes, densely clustered seismicity, Quaternary volcanics, and a high density of Quaternary faulting. The rift is not distinguishable from the western Jemez Lineament by seismicity alone, especially from the Taos-Latir volcanic field southwards. There are earthquake clusters near Quaternary faults, for example, the Gallina, the Nacimiento, Embudo, San Mateo, Manzano, and San Andres faults near the Valles Caldera in north-central New Mexico. Based on the spatial correlation of seismicity with Tertiary and Quaternary volcanics and faults along the lineament, we suggest that the western Jemez Lineament is an active tectonic boundary between the Colorado Plateau and the Rio Grande Rift, and active deformation is taking place in a distinct pattern with two orientations, N5°E and N65°E, that are similar to past and current dike stress orientations [*Aldrich and Laughlin*, 1984]. Earthquake clusters on the Jemez Lineament are spatially correlated to Quaternary volcanic vents and dikes at Mt. Taylor and the Zuni-Bandera volcanic field and their origin may be volcanic. The west and the east Jemez Lineament shows markedly different patterns of seismicity, which indicates that they are distinct features.

The seismicity in the Great Plains occurs in a halo surrounding the nearly aseismic eastern Jemez Lineament. We hypothesize that the lack of seismicity on top of the volcanics is due to basaltic lower crustal strengthening or, alternatively, ductile, aseismic flow due to an elevated geotherm from intrusion of volcanics. In the

latter case, thermal stresses from the elevated geotherm may be responsible for the earthquakes in the halo surrounding the eastern lineament. Active extensional deformation (based on GPS and compatible with moment tensors) extends eastward into the Great Plains, and seismicity does not clearly delineate the physiographic boundary between the Rocky Mountains and the stable North American craton.

Northeast Colorado, apart from Rocky Mountain Arsenal induced earthquakes [Evans, 1966; Healy *et al.*, 1968], was aseismic until 2013 [Yeck *et al.*, 2016], when induced earthquakes due to wastewater injection began. Sparse seismicity occurs in southeast New Mexico, with the exception of likely induced seismicity in the Dagger Draw oil field [Sanford *et al.*, 2002; Edel *et al.*, 2014; Herzog, 2014]. Further investigation is needed to determine if there are earthquakes in eastern Colorado and northeast New Mexico that are induced by wastewater disposal.

The southern rift is characterized by diffuse seismicity in our catalog, although the region has hosted seven earthquakes over M_w 3 since 2010, as well as the historic 1887 M_w 7.5 Sonora and 1931 M_w 6.5 Valentine earthquakes, both of which occurred to the south of our study area [Doser, 1987; Suter, 2015]. The western extent of seismicity (near the Arizona-New Mexico border) in the southern rift may be an internal boundary in the Basin and Range or the western edge of the Rio Grande Rift. Clusters of seismicity occur on Quaternary faults at the Texas-New Mexico border, supporting the notion that the rift continues into Texas and the Mexican Basin and Range.

5. Conclusions

Using data from 317 seismometers deployed throughout Colorado and New Mexico as part of the USArray and CREST experiments, we located 2764 earthquakes from 2008 to 2010 ranging in magnitude from M_L -0.1 to 4.7 , with an estimated catalog completeness of M_L 1.3 . Of the entire catalog, 927 of the earthquakes are believed to be of tectonic origin and even fewer are related to the Rio Grande Rift. The remaining 1837 earthquakes, mostly in the Raton Basin, are suspected to have an anthropogenic origin and will be the subject of a separate paper. The patterns of tectonic seismicity that we find are similar in overall coverage to those from the longer-term catalogs from the USGS and New Mexico Tech but provide considerably more detail along the entire rift. Based on seismicity, the northern rift extends into north central Colorado, and earthquakes are spatially correlated with Neogene faulting. The central rift is seismically active and characterized by many earthquake clusters correlated with faults and volcanic dikes and vents, and earthquakes are concentrated along the western Jemez Lineament, which forms the boundary of deformation between the Rio Grande Rift and Colorado Plateau. Extension, based on GPS and compatible with moment tensors, occurs east into the Great Plains. Further investigation is needed to determine whether the lack of seismicity in the eastern Jemez lineament is attributed to either a strong lower crust or a ductile lower crust with surrounding thermal stresses. The seismicity and least principle horizontal stress orientations (generally northwest-southeast and northeast-southwest, respectively) in the western and eastern Jemez Lineament are different, and therefore, the Lineament changes character after it crosses the Rio Grande Rift. The southern rift extends into Mexico and follows Quaternary faulting south along the Texas-Mexico border. Although most of the seismicity occurs in the central Rio Grande Rift, the most active part of the rift during this time period, earthquakes in the northern rift have historically had and currently have a high moment release. The 1887 M_w 7.5 in Sonora, Mexico occurred near the western edge of the southern rift along with the M_w 6.5 Valentine, Texas earthquake in 1931. These two events indicate a potential for high moment release earthquakes in the southern rift. Further work is needed to determine if any small magnitude seismicity is evidence of slip on Quaternary or mapped faults. A spatial comparison of our seismicity and moment release with the USGS catalog (ComCat) shows that the short-term catalog is faithfully representing the medium-term record of earthquakes.

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