FINAL TECHNICAL REPORT

USGS/NEHRP Grants Program Assistance Award 03HQGR0091

Colorado Front Range Seismicity and Seismic Hazard

Principal Investigator: Anne Sheehan

University of Colorado at Boulder
Department of Geological Sciences and
Cooperative Institute for Research in the Environmental Sciences (CIRES)
399 UCB, Benson Earth Sciences Building
Boulder, Colorado 80301
Telephone (303) 492-4597; Fax (303) 492-2606; email afs@cires.Colorado.edu
http://cires.colorado.edu/science/groups/sheehan/

Research supported by the U.S. Geological Survey (USGS), Department of Interior, under USGS/NEHRP Award number 03HQGR0091. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Non-technical Abstract:

This project included the archiving of broadband earthquake seismic data from a temporary seismic experiment in Colorado from 1992, and analysis of these data for local earthquakes. The seismic experiment consisted of thirty broadband seismograph stations deployed throughout the state of Colorado for six months in 1992. These stations continuously recorded data, but the local earthquakes were not examined as part of the original NSF project that funded the data collection. As part of this NEHRP project, we archived these old data, and they are now available to anyone through the IRIS DMC. Archiving these data more than 10 years after the original experiment was a major task. The second major part of this project was the use of these data to study small local earthquakes in Colorado. While the large majority of the events that we identified and located were mining blasts, we did identify 24 local earthquakes.

Investigations undertaken:

Data management and archiving at IRIS DMC

This project involves the study of seismicity in the state of Colorado and surrounding areas using data from the 1992 IRIS Passcal Rocky Mountain Front (RMF) experiment. The RMF experiment involved the deployment of 30 broadband seismic stations throughout Colorado and into Kansas and Utah for six months in 1992. The stations recorded in both continuous and triggered modes. The experiment was run before IRIS required submission of continuous data in SEED format to the IRIS DMC, so all that had been submitted to IRIS were parsed events (mostly teleseisms). Thus a large part of the data set had not been archived, and no work had been done on local seismicity using this data set. The archiving of this data set made our own proposed work possible, as well as making the data available to others.

Archiving these data more than 10 years after the original experiment was a major task. Our efforts involved acquiring all of the original RMF field tapes from Lamont, reading them on to computer disk, and formatting them into SEED format for submission to the IRIS Data Management Center. Converting the data from 32 Gb of raw field dumps to 20 Gb of archival SEED format data was a major task. Dealing with timing corrections proved to be particularly challenging, as the data were collected using a mix of timing systems, each with their own quirks. For example, the radio wave Omega timing system (which no longer exists) had a leap second in the middle of the experiment that needed to be corrected for, and had cycle skips (10 s period) related to the period of the Omega wave signal. GPS clocks at that time were fairly new, and had some issues with 1 s timing jumps and wanting to locate the experiment in Dallas (the home of Reftek).

The Rocky Mountain Front data were imported into an Antelope database for formatting and preparation of SEED volumes, data management , and analysis. The standard steps of using Antelope codes refrate and clockcor to apply the timing corrections could not be applied in the standard manner due to the variety and age of timing systems used in the RMF experiment. The Passcal time correction files had to be recreated for each Reftek DAS, and each of these had to be checked visually for problematic areas (for example, a bad battery will have large nearly sinusoidal corrections with a period of a day). There was a '1988' bug (about 5-10% of the files had 1988 as the date, a common bug) that had to be corrected, and the leap second correction had to be applied to DAS's that used omega timing, but not to those with a GPS clock. This was done for all 10 sps continuous data and the triggered 20 sps data. Many checks were performed to verify the timing.

The Antelope code dbsteimu was used to create the wfdisc (waveform database). The script mkfull_db.csh was used to create parameter files RMF_Dbcorr, affiliation, calibration, instrument, lastid, sensor, network, site, sitechan, and stage files. The code dbfixchanids was run to make sure that the Reftek DAS's were mapped to the right stations. After this, dbverify was run to check the database. Some minor reformatting was needed.

Data processing for local earthquakes

All data were processed and analyzed for local earthquakes. The results are in a paper that was recently submitted to Seismological Research Letters. We will summarize that paper and its results here. The following pages of this technical report contain excerpts from the paper "An assessment of Colorado seismicity from a statewide temporary seismic station network" by G. Monsalve, C. Viviano, and A. Sheehan, submitted to Seismological Research Letters in January 2008.

Summary of Colorado Seismicity Study

The Rocky Mountain Front (RMF) broadband seismic experiment consisted of the installation of 33 broadband seismic stations spread across the state of Colorado, with an inter-station distance of approximately 75 km. The six months of continuous ground motion data from these stations are used here to determine local seismic event hypocenters and magnitudes. Based on a magnitude versus frequency curve, we found that our RMF event catalog is complete for events of magnitude 2.5 and greater throughout the state of Colorado. The majority of the events detected during this time were determined to be man-made blasts (about 80%) based upon the time of day at which they occur, location, magnitude and characteristics of their associated seismograms. After removing the most likely man-made events, we created a new catalog with 24 earthquake events for the six-month period of the deployment. This brief experiment provides useful information on the background levels of seismicity in Colorado.

Introduction

Knowledge of the seismic hazard in Colorado is limited due to the short historical record of seismicity, the lack of permanent seismographic coverage, and the existence of man-induced earthquakes (Matthews, 2003). The rate of seismicity in Colorado is characterized as low to moderate (Kirkham and Rogers, 1981), yet it has a history of occasional large magnitude events (M > 5.5) (Talley and Cloud, 1962; Kirkham and Rogers, 2000), including an earthquake with estimated moment magnitude of 6.6 in north-central Colorado in 1882 (McGuire, 1982; Spence et al., 1996). Perhaps the best known earthquakes in Colorado have been those induced by the disposal of waste fluids at the Rocky Mountain Arsenal near Denver (Evans, 1966; Healy et al. 1968; Herrmann, 1981) and secondary oil recovery in western Colorado at the Rangely oil field (Gibbs et al., 1973). Earthquake swarms in Colorado are not uncommon (Bott & Wong 1995; Meremonte et al., 2002).

There is evidence of Quaternary tectonic activity of faults throughout Colorado (e.g., McCalpin, 1986), with fourteen faults with an assigned Maximum Credible Earthquake from M 6.25 – 7.5 (Widman et al., 1998). These faults indicate potential for much larger earthquakes than those recorded to date (Matthews, 2003). The occurrence of earthquakes has been documented in a variety of areas in Colorado, but in most cases the seismograph station coverage has been spatially limited to specific regions (e.g. Goter and Presgrave, 1986; Keller and Adams, 1975; Bott and Wong, 1995; Sheehan, 2000; Sheehan et al., 2003).

In 1992, the Rocky Mountain Front (RMF) broadband seismic experiment was conducted to image the crust and upper mantle of Colorado (Sheehan et al., 1995; Lee and Grand, 1996; Lerner-Lam et al., 1998). The RMF experiment consisted of the installation of 33 broadband seismic stations spread throughout Colorado with a few additional stations in Kansas and Utah. The use of this relatively dense seismic network, with an average seismometer separation of 75 km (Figure 1), allows for the detection and location of Colorado earthquakes on a regional scale.

Data and Method

The Rocky Mountain Front (RMF) broadband seismic experiment was conducted between May and December of 1992. It was one of the first Incorporated Research Institutions for Seismology (IRIS) Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) experiments, and one of the largest broadband experiments of the early years of the PASSCAL program. Although the main purpose of the deployment was to record distant earthquakes (teleseisms) in order to image the crust and upper mantle under the Rocky Mountain Front, the instruments continuously record local events as well as teleseisms. The 33 three-component broadband (Guralp CMG3-ESP and Streckeisn STS2) sensors recorded both continuous (10 samples per second) and triggered (20 samples per second) data streams. These sample rates are less than ideal for microearthquake studies but in many cases provide adequate signals, particularly with the 20 sps data stream. The data were originally archived at the IRIS Data Management Center (DMC) as event-extracted data in SAC format with only teleseismic and regional events (no local events). More than ten years after the original deployment the continuous and triggered data were downloaded from the exabyte network day tapes and converted to SEED format for full archival at the IRIS Data Management Center. In addition to the SEED data submitted to the IRIS DMC the data were kept in a local Antelope (Boulder Real Time Systems) database at the University of Colorado.

An automated algorithm using the program dbdetect was run on the continuous RMF seismograms to make initial detections of the P-arrivals, using a Short Term Average (STA) / Long Term Average (LTA) algorithm (Lee and Stewart, 1981). This method occasionally skips small seismic events or picks faulty events, thus a manual scan of the time series was performed as well. Earthquake catalogs from two other small networks operating in Colorado in 1992 (Ridgeway and Paradox Valley and Microgeophysics Corporation, L. Block and J. Ake, personal communication, Bott et al., 2003) were combined with the RMF catalog to locate some of the events missed by the detection program. Using the picks from the automated algorithm and the combined catalogs as a starting point, the P and S-arrivals were then manually identified along with an associated pick uncertainty. P-wave arrivals were mostly picked from the vertical component of the seismograms and S-arrivals were predominantly picked using the horizontal component. We picked a total of 2387 P-arrival times with a mean uncertainty of 0.36 seconds, and 1475 S-arrivals with a mean uncertainty of 0.57 seconds. Events with associated arrivals at three or more stations were located using the GENLOC library of the BRTT ANTELOPE software (Pavlis et al, 2004). Located events had an average of 9 associated arrival times (P and S). The hypocenters were determined using an iterative weighted least-squares method, with weight assigned to each arrival based upon its uncertainty, the event-station distance, and the size of the time residual after each iteration. A three-layer velocity model for the Rocky Mountain region (Snelson et al., 2005, Table 1) was utilized in the location process. The Root Mean Square (RMS) of the weighted differences between predicted and observed arrival times had an average of 0.69 seconds. The mean uncertainty of the epicenter (latitude and longitude, not including depth) was 1.1 km.

Depth (km)	Vp (km/s)	Vs (km/s)
0	5.8	3.3
25	6.7	3.9
> 36	7.3	4.2

Table 1: Three-layer velocity model used for earthquake location (from Snelson et al., 2005)

In order to minimize the error due to the trade-off between event depth and origin time, we tested an interval of plausible depths for each earthquake by running several inversions with a fixed depth, and chose the one that gave the best fit (minimum RMS). Resulting depth uncertainties are typically less than 5 km. The hypocentral depths were constrained to be at or below zero meters below sea level, so events occurring on the surface appear to be up to 3 km below their real depth.

Magnitudes for all events were calculated using a coda duration method (e.g. Sheehan et al., 2003). The magnitude was calculated using the following equation:

$$Mdur = A\,[\log(\text{coda length})] - B,$$

where A = 1.8998 and B = 0.2572. A linear regression between the magnitudes given by the Paradox Valley (PAR) catalog and the coda duration calculated from the RMF catalog for common events were used to solve for A and B. We determined the coda length using an automated algorithm that compares event amplitude to average noise. The background noise for each waveform was averaged over a 25 second interval before the first P-arrival. Then, beginning at the P-arrival, 2-second segments were scanned across the waveform to calculate the average amplitude for each segment. When the average signal amplitude decreased to twice the calculated average noise, the elapsed time from the P-arrival was measured, yielding the coda length of the event. A total of 117 local seismic events with duration magnitudes between 1.3 and 3.5 were detected and located using the RMF data (Figure 2a).

Earthquakes vs. blasts

Considerable mining activity in Colorado raises the question about possible contamination of our seismic catalog with man-made events. Our first criterion to identify mining-related seismicity was the time of day at which the event occurred, as described by Agnew et al. (1990) and Rydelek and Hass (1994). Figure 2b shows a histogram plotting the number of events in 60-minute intervals through the day, revealing a large number of events at around 4 pm local time. Blasting in Colorado occurs mostly in the afternoon (Dewey, 1998). We used the Schuster's Method, as presented by Rydelek and Hass (1994), to estimate the amount of blasts in our catalog based on the time of day at which events occur. This test uses the sum of event phasors, which have unit magnitude and a phase angle that corresponds to their time of day, to produce a phasor "walkout". Deviations of the phasor walkout from a phasor that resembles Brownian motion can be used to estimate the nonrandom component of the seismicity. This method suggests that between 70 and 80% of the events in our initial catalog of 117 events are man-made.

Other criteria, such as epicenter location, hypocentral depth, seismogram characteristics, and event magnitude can be used to separate man-made events from natural earthquakes. In Figure 2a the events are colored by the time-of-day at which they occur. The figure shows two major clusters, one in the Craig / Steamboat Springs area (near the northwestern corner of Colorado) and one in the Montrose area (southwest Colorado), both of which have been identified by the USGS as mining seismicity source regions (U.S. Geological Survey, 2007). Events occurring at 4 pm ± 12 minutes MST (in pink) are very localized within the cluster in the northwestern corner of Colorado, so they are most likely mining blasts. Blasting tends to occur at the end of the workday (e.g. 4 p.m. local time) to allow settling of dust and rock before the next workday. Events with hypocentral depths greater than about 8 km are not likely to be man-made. Waveform characteristics can also be used to discriminate between blasts and earthquakes. Generally, local earthquakes have an impulsive P-arrival and a distinct S-arrival a few seconds later (Figure 3a). The long ripple fire technique used for blasting can cause an emergent P-arrival and the S-arrival is usually difficult to identify (Figure 3b) (Harder and Keller, 2000, Stump et al., 2002; Louie et al., 2004, U.S. Geological Survey, 2007). Localization of similar magnitude events can also indicate regions of routine blasting.

The objective of removing the events characterized as blasts was to identify natural (tectonic) sources of seismicity in the region. After blast-removal using the criteria described above, only 24 seismic events remained, meaning that about 80% of the events in the catalog were man-made blasts, in agreement with the predictions from Schuster's Method. Table 2 lists earthquake parameters of the events after removing the man-made explosions. Figure 4 shows their locations in map view.

The resulting set of 24 events after removing the blasts most likely consists of tectonic earthquakes and rock bursts related to mining. Half of these events were located in the Craig / Steamboat Springs area; and excluding two events with depths greater than 10 km, they are probably still related to mining activity in the area. Six of those events occurred in the Montrose area, where Quaternary faults with assigned Maximum Credible Earthquakes greater than magnitude 6.5 have been reported (Widmann et al., 1998); however, these six earthquakes occurred within a period of 12 days in a region of intense mining activity, so we think that they are most likely mining-related. The rest of the events (only 6 remaining events) are probably tectonic earthquakes, some of them have nearby Quaternary faults (Widmann et al., 1998, Figure 4).

Date	Time (UT)	Latitude	Longitude	Depth (km)	Mdur	Ex (km)	Ey (km)	Ez (km)	Et (s)
5/28/1992	14:07:55.6	40.709	-108.242	18.2	3.26	0.91	1.11	0.8	1.0
6/02/1992	7:57:36.2	38.018	-107.772	0.0	2.47	0.32	0.72	1.1	1.7
6/02/1992	8:05:35.2	38.053	-107.892	0.0	2.59	0.32	1.13	0.9	1.2
6/02/1992	9:54:08.3	37.986	-107.592	12.4	2.34	0.14	0.19	2.3	0.5
6/06/1992	9:46:13.9	38.230	-107.871	2.5	2.61	0.53	0.73	0.4	0.9
6/06/1992	13:08:08.0	38.006	-107.841	0.0	1.31	0.20	0.49	1.8	2.5
6/10/1992	17:26:46.6	39.000	-104.632	8.7	2.05	0.39	1.12	1.4	1.1
6/12/1992	1:00:49.3	40.717	-108.275	0.0	3.20	0.22	1.04	0.4	0.7
6/14/1992	7:27:10.1	38.897	-105.574	0.0	2.63	2.02	2.01	2.7	2.0
6/19/1992	7:20:32.2	40.344	-107.150	0.0	2.63	0.26	0.09	0.2	0.7
7/02/1992	11:31:21.5	38.604	-107.381	0.0	1.50	0.64	1.62	1.1	1.8
7/14/1992	17:42:39.1	40.326	-107.300	5.6	1.97	0.72	1.00	1.2	1.1
7/17/1992	19:30:56.4	40.365	-107.668	11.6	2.21	0.87	0.82	1.2	1.1
9/01/1992	20:39:09.4	40.324	-107.134	0.0	2.53	1.04	0.59	1.7	1.5
9/04/1992	17:55:52.0	40.319	-107.121	1.6	2.27	1.25	1.56	0.4	0.1
9/09/1992	11:20:48.8	37.278	-103.031	13.8	2.17	0.13	0.72	0.9	0.7
9/10/1992	6:46:16.2	40.356	-107.064	0.0	1.79	0.41	0.55	0.8	1.1
9/11/1992	2:56:52.3	40.342	-107.104	0.5	2.17	0.76	2.27	0.3	0.5
9/11/1992	14:57:34.3	40.343	-107.075	0.0	2.37	0.56	1.03	0.9	1.7
9/11/1992	22:55:46.0	40.352	-107.083	2.4	2.88	1.04	0.96	1.0	1.5
9/13/1992	7:22:43.1	40.358	-107.081	0.0	2.82	0.89	1.04	1.2	1.7
9/24/1992	3:54:08.6	40.213	-106.097	3.2	2.62	0.70	0.59	1.2	1.5
9/28/1992	5:19:45.0	40.243	-106.082	8.5	2.59	0.74	0.79	1.2	1.2
10/09/1992	20:14:04.6	38.086	-103.772	2.3	2.35	1.88	0.55	1.1	0.9

Table 2: List of events classified as earthquakes recorded by the RMF network between May and December of 1992. Event depth is given in kilometers below sea level.

Earthquake recurrence in Colorado

The RMF array sensitivity was assessed using a magnitude frequency curve (Figure 5). Magnitude was plotted against the cumulative number of events of that magnitude and higher (blasts removed), taking into account the spatial area of the network (the state of Colorado) and the time frame of data acquisition. These factors are used to normalize the curve in order to compare it to other catalogs. Catalogs of events in Colorado from the National Earthquake Information Center (NEIC) and the Microgeophysics Corporation (MGC) are also plotted with the RMF events to compare network sensitivity. Where the curve levels out at small magnitudes, it is interpreted that the network is not detecting smaller events, and the break in slope represents the lower limit of seismic sensitivity. Figure 5 shows the RMF sensitivity limit to be about magnitude 2.5. It also reveals that the RMF array is more sensitive than the NEIC catalog, yet less sensitive than the MGC catalog. This is not surprising given the differences in station spacing of these various networks. The NEIC and MGC catalogs are not adequate to evaluate the statewide seismicity: NEIC coverage in the region is too sparse, with locations mainly constrained by arrival times at stations in different states, so that detection of small events is difficult; the MGC network had a dense station spacing but was limited to parts of the Colorado Front Range.

Figure 6 shows the Colorado seismicity rate deduced from our experiment results (thicker line): it suggests that a magnitude 6 earthquake occurs once every thousand years in the state. This extrapolation of observations from a short duration deployment should be interpreted with caution, and our inferences about the long term Colorado seismicity are tenuous. These results suggest a smaller rate of seismicity than similar calculations by Sheehan et al. (2003) (Figure 6, thinner line); however, the 2003 study only considered a small area of the state of Colorado (around Boulder, Colorado) and was likewise from a short duration temporary deployment. Our results indicate a lower rate of seismicity than that obtained by Charlie et al. (2002), who deduced a recurrence mean interval of 420 years for a 6.5 ML earthquake in Colorado, based on an earthquake catalog (Kirkham and Rogers, 2000) that included instrumentally recorded events and historical earthquakes. Combining this patchwork of results from temporary networks is the best we can do given the absence of long-term monitoring in the region. The USArray experiment will provide another two years of ground motion recording in the region, which in combination with these previous results will contribute to improved understanding of the regional seismicity.

Conclusion

Analysis of data from the 1992 Rocky Mountain Front seismic experiment provides a 6 month catalog of regional seismicity, which combined with additional temporary deployments contributes to improved understanding of Colorado seismicity. Though the majority of the events detected during the six-month deployment were classified as mining blasts (about 80%), the remaining events reveal a six-month snapshot of seismicity in the state. Twenty-four events characterized as earthquakes were recorded during the six-month deployment. Extrapolation of our small sample of seismicity to higher magnitudes indicates that an earthquake of magnitude 6 is expected to occur once every thousand years, suggesting a lower rate of seismicity than estimated in several prior studies. However, the validity of the extrapolation of results based on a small data set is tenuous. A long-term uniform seismic network would give a better representation of the seismicity of Colorado, and further analysis will be advanced through the upcoming EarthScope USArray deployment.

Bibliography

Agnew, D.C., 1990, The use of time-of-day seismicity maps for earthquake-explosion discrimination by local networks with an application to the seismicity of San Diego County: Bull. Seismol. Soc. Am., 80, pp. 747-750.
Bott, J.D.J., and Wong, I.G., 1995, The 1986 Crested Butte earthquake swarm and its implications for seismogenesis in Colorado: Bull. Seismol. Soc. Am., 85, pp. 1,495-1,500.
Bott, J.D.J., Wong, I.G., and Ake, J., 2003, Contemporary seismicity, 1983-1993, and its implications to seismic hazard in the Central Front Range, Colorado, in Engineering Geology in Colorado: Contributions, Trends, and Case Histories, edited by D. Boyer, P. Santi, and W. Rogers, Association of Engineering Geologists Special Publication No. 15, Colorado Geological Survey Special Publication 55, pp. 1-18.
Charlie, W.A., Battalora, R.J., Siller, T.J., and Doehring, D.O., 2002, Magnitude recurrence relations for Colorado earthquakes: Earthquake Spectra, 18, pp. 233-250.
Dewey, J.W., 1998, Monitoring mine explosions in the conterminous U.S. (abs.): Seismol. Res. Lett., 69, 176 p.
Evans, D. M., 1966, The Denver area earthquakes and the Rocky Mountain disposal well: The Mountain Geologist, 3, pp. 23-26.
Gibbs, J. F., Healy, J. H., Raleigh, C. B., and Coakley, J., 1973, Seismicity in the Rangely, Colorado, area: 1962-1970: Bull. Seism. Soc. America, 63, pp. 1557-1570.
Godchaux, J.D., 2000, A microseismic study of the northern Colorado Front Range, Undergraduate honors thesis, Trinity University, 27 p.
Goter, S.K., and Presgrave, B.W., 1986, Preliminary results of the Carbondale, Colorado earthquake field study: Contributions to Colorado Seismicity and Tectonics – A 1986 update, Colorado Geological Survey Special Publication, 28, pp. 162-163.
Harder, S., and Keller, G.R., 2000, Crustal structure determined from a new wide-angle seismic profile in southwestern New Mexico: New Mexico Geol. Soc. Guidebook, 51st Field Conf., Southwest Passage – a trip through the Phanerozoic, pp. 75-78.
Healy, J. H., Rubey, W. W., Griggs, D. T., and Raleigh, C. B., 1968, The Denver earthquakes: Science, 161, pp. 1301-1310.
Herrmann, R. B., Park, S. K., and Wang, C. Y., 1981, The Denver earthquakes of 1967-1968: Bull. Seism. Soc. Am., 71, pp. 731-745.
Keller, G.R., and Adams, H.E., 1975, A reconnaissance microearthquake survey of the San Luis Valley, Southern Colorado: Bull. Seism. Soc. Amer., pp. 345-347.
Kirkham, R.M. and Rogers, W.P., 1981, Earthquake potential in Colorado: Colorado Geological Survey Bulletin, 43, 171 p.
Kirkham, R.M., and Rogers, W.P., 1986, An interpretation of the November 7, 1882 Colorado Earthquake: Contributions to Colorado Seismicity and Tectonics - A 1986 update, Colorado Geological Survey Special Publication, 28, pp. 122-144.
Kirkham, R.M., and Rogers, W.P., 2000, Colorado Earthquake Information, 1867-1996, Bulletin 52: Colorado Geological Survey, CD-ROM format, Department of Natural Resources, State of Colorado, Denver, CO.
Lee, W.H.K., and Stewart, S.W., 1981, Principles and applications of microearthquake networks, in Advances in Geophysics, Supplement 2, Academic Press.
Lee, D.K., and Grand, S.P., 1996, Upper mantle shear structure beneath the Colorado Rocky Mountains: Journal of Geophysical Research, v. 101, p. 22,233–22,244.
Lerner-Lam,W., Sheehan, A., Humpreys, E., 1998, Mantle structure at the edge of a craton: Seismological studies of the crust and upper mantle at the transition between the southern Rockies and the Great Plains: Rocky Mountain Geology, 33, pp. 199-216.

Louie, J.N., Weston Thelen, T., Smith, S.B., Scott, J.B., and Clark, M., 2004, The northern Walker lane refraction experiment: Pn arrivals and the Northern Sierra Nevada root: Tectonophysics, 388, pp. 253-269.
Matthews, V., 2003, The challenges of evaluating earthquake hazard in Colorado, in Engineering Geology in Colorado: Contributions, Trends, and Case Histories, edited by D. Boyer, P. Santi, and W. Rogers, Association of Engineering Geologists Special Publication No. 15, Colorado Geological Survey Special Publication 55, pp 1-22.
McCalpin, J., 1986, Quaternary tectonics of the Sangre de Cristo and Villa Grove fault zones: Contributions to Colorado Seismicity and Tectonics - A 1986 Update, Colorado Geological Survey Special Publication 28, pp. 59-64.
McGuire, R. K., Krusi, A., and Oaks, S. D., 1982, The Colorado earthquake of November 7, 1882: Size, epicentral location, intensities and possible causative fault: The Mountain Geologist, 19, pp. 11-23.
Meremonte, M. E., Lahr, J. C., Frankel, A. D., Dewey, J. W., Crone, A. J., Overturf, D. E., Carver, D. L., and Bice, W. T., 2002, The Investigation of an Earthquake Swarm near Trinidad, Colorado, August-October 2001: USGS Open-File Report 02-0073.
Pavlis, G.L., Vernon, F., Harvey, D., and Quinlan, D., 2004, The generalized earthquake-location (GENLOC) package: an earthquake location library: Computers and Geosciences, 30, pp. 1,079-1,091.
Rydelek, P.A., and Hass, L., 1994, On estimating the amount of blasts in seismic catalogs with Schuster's method: Bull. Seismol. Soc. Am., 84, pp. 1,256-1,259.
Sheehan, A.F., 2000, Microearthquake study of the Colorado Front Range: Combining research and teaching in seismology: Seismol. Res. Lett., 71, pp.175-179.
Sheehan, A.F., Abers, G.A., Lerner-Lam, A.L., and Jones, C.H., 1995, Crustal thickness variations across the Colorado Rocky Mountains from teleseismic receiver functions, J. Geophys. Res., 100, pp. 20,391-20,404.
Sheehan, A.F., Godchaux, J.D., Hughes, N., 2003, Colorado Front Range Seismicity and Seismic Hazard, in Engineering Geology in Colorado: Contributions, Trends, and Case Histories, edited by D. Boyer, P. Santi, and W. Rogers, Association of Engineering Geologists Special Publication No. 15, Colorado Geological Survey Special Publication 55, pp 1-21.
Snelson, C.M., Keller, G.R., Miller, K.C., Rumpel, H.M., and Prodehl, C., 2005, Regional crustal structure derived from the CD-ROM 99 Seismic Refraction / Wide-Angle Reflection profile: The lower crust and upper mantle, in, The Rocky Mountain Region: An Evolving Lithosphere, edited by Karlstrom, K.E., and Keller, G.R., Geophysical Monograph Series 154, American Geophysical Union, Washington, DC, 10.1029/154GM30, pp.271-291.
Spence, W., Langer, C.J. and Choy, G.L., 1996, Rare, large earthquakes at the Laramide Deformation Front – Colorado (1882) and Wyoming (1984): Bull. Seismol. Soc. Am., 86, pp. 1804-1819.
Stump, B. W., Hedlin, M.A.H., Pearson, D.C., and Hsu, v., 2002, Characterization of mining explosions at regional distances: Implications with the International Monitoring System, Reviews of Geophysics, 40, 4, pp. 2-1 - 2-46, doi:10.1029/1998RG00048.
Talley, H.C. and Cloud, W.K., 1962, United States earthquakes 1960: U.S. Coast and Geodetic Survey, 90 p.
U.S. Geological Survey (NEIC web team), September 27, 2007, Routine United States Mining Seismicity, URL: http://neic.usgs.gov/neis/mineblast/ (October 23, 2007).
Widmann, B.L., Kirkham, R.M., and Rogers, W.P., 1998, Preliminary quaternary fault and fold map and database of Colorado: Colorado Geological Survey Open-File Report 98-8, 331 p.
Wong, I.G., 1986, Tectonic stresses in Colorado and their implications to seismicity: Contributions to Colorado Seismicity and Tectonics - A 1986 update, Colorado Geological Survey Special Publication, 28, pp. 17-27.

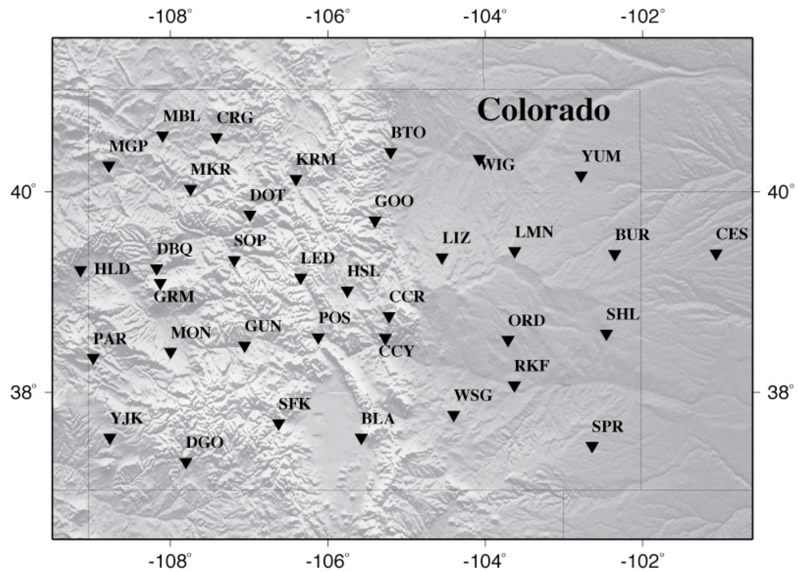

Figure 1: The RMF station network. Locations (inverted triangles) and a three-letter identification code for each station are shown.

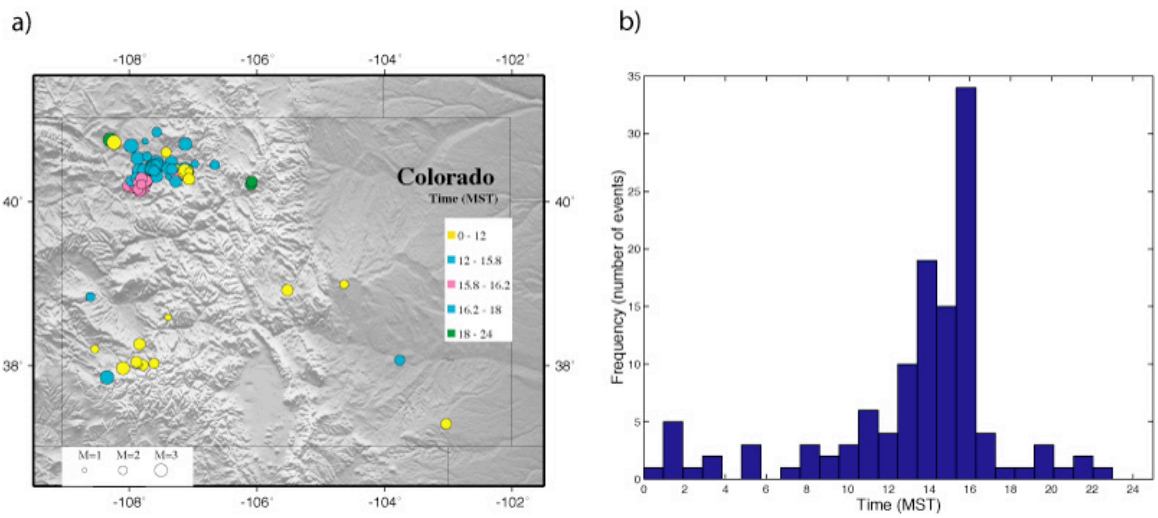

Figure 2: Seismic events (including suspected mine blasts) recorded by the RMF network between May and December 1992. a) Seismicity map with symbol size scaled by event magnitude and colored by event origin time-of-day. Note the predominance of afternoon events (hours 12 – 18 MST). b) Time of day histogram of events. Note the peaks at afternoon hours (hours 12 – 18 MST).

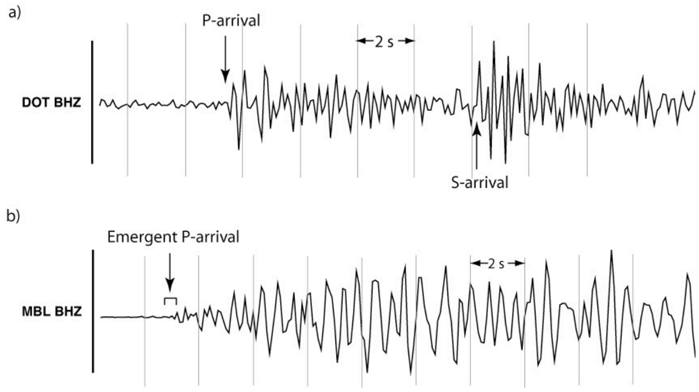

Figure 3: Examples of seismograms for (a) a local earthquake event (event-station distance ~ 65 km), and (b) a mine blast (event-station distance ~ 34 km). Seismograms are band-pass filtered from 1-5 hz.

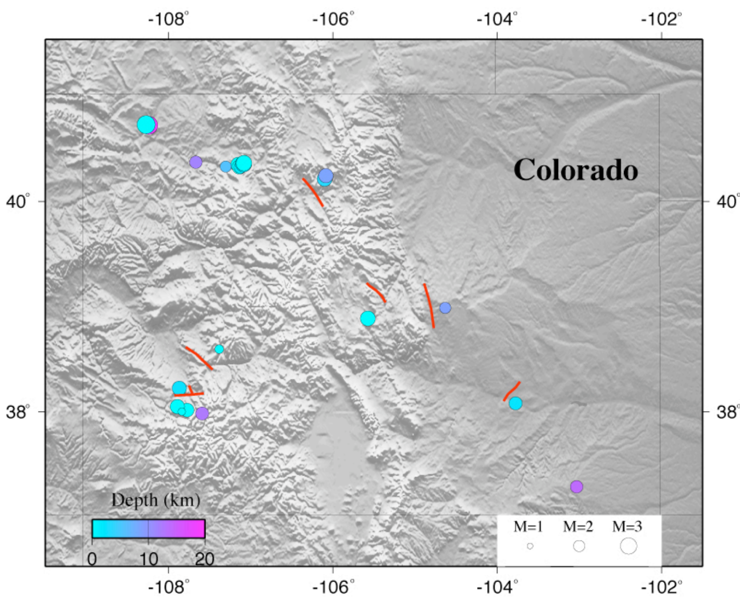

Figure 4: Earthquakes after removal of man-made explosions. Symbol size scaled with magnitude and colored by depth. Red lines denote Quaternary faults from database of Widmann et al. (1998) near event
epicenters.

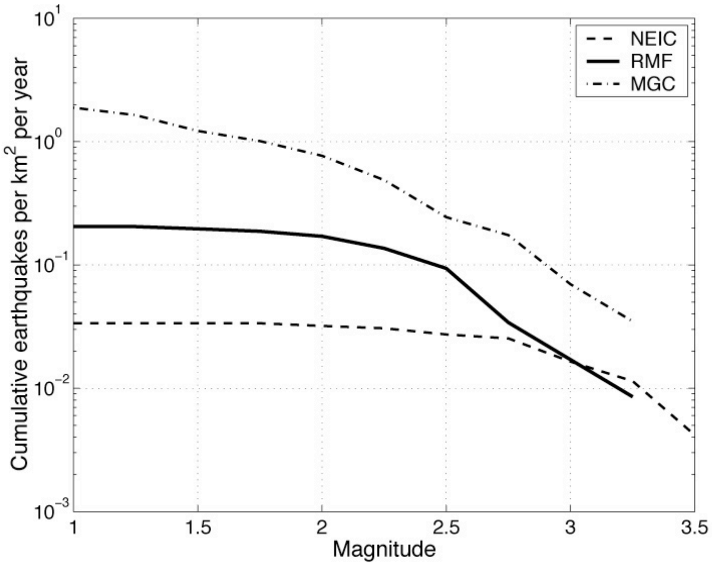

Figure 5: Array sensitivity (b-value plots) of NEIC, RMF (this study), and MGC catalogs.

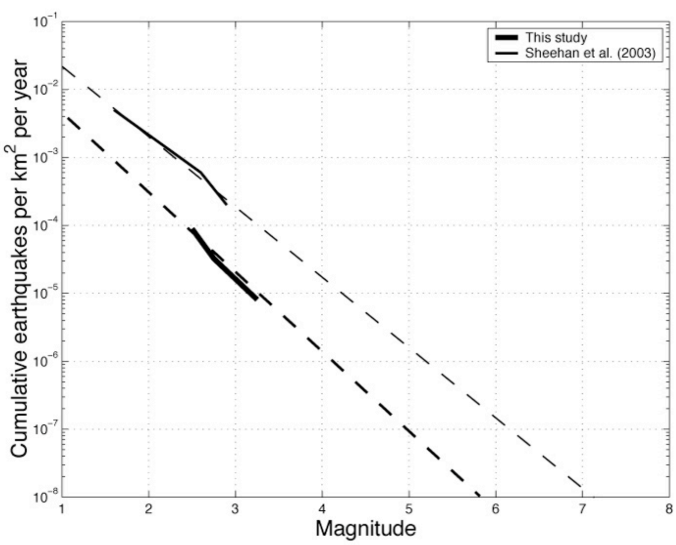

Figure 6: Extrapolated Colorado seismicity rate deduced from this experiment (thicker lines) and from Sheehan et al. (2003) (thinner lines).

NEHRP Project Results

Results include writing 20 Gb of broadband seismic data from a six-month temporary seismic deployment to archival SEED format, for submission to the IRIS Data Management Center, analysis of all of the data for local earthquakes, developing a local earthquake catalog for the 6 month duration of the seismic experiment, and preparation of a paper for publication.

Reports published/Professional presentations:

Bensen, G., C. Meertens, and A. Sheehan, Information technology developments for geophysical data, *Geol. Soc. Am. Annual Meeting*, Denver, November 2004.

Bensen, G., C. Meertens, and A. Sheehan, Information technology developments for geodynamics, American Geophysical Union, Fall Meeting 2004.

Bensen, G., C. Meertens, and A. Sheehan, Colorado seismicity, data visualization and IT research at UNAVCO, *Rocky Mountain Earthscope Workshop I, Sevilleta National Wildlife Refuge and Long Term Ecological Research Facility*, Socorro, New Mexico, September 15-17, 2004.

Viviano, C., G. Monsalve, A. Sheehan, and G. Bensen (2005), Determining Rocky Mountain Front seismicity: A Colorado case study, Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract S51B-1013.

Monsalve, Viviano, and Sheehan, An assessment of Colorado Seismicity from a statewide temporary seismic station network, submitted to Seismological Research Letters, January 2008.

Data products

20 Gb of broadband seismic waveform data from a 30 station, 6 month temporary deployment of broadband seismometers throughout Colorado. The data are in SEED format. All seismic data were submitted to the IRIS Data Management Center in early Spring 2005 and are available through the IRIS DMC. The data can be found at IRIS as data set 'XG92 Rocky Mountain Front' http://www.iris.edu/mda/XG.The seismic data have been analyzed for local earthquakes and a paper summarizing this results is under review in Seismological Research Letters (Spring 2008). A catalog of 24 Colorado earthquakes was constructed and is in the paper and also presented in this technical report.