

QUANTIFYING SEISMIC HAZARD IN THE SOUTHERN ROCKY MOUNTAINS THROUGH GPS MEASUREMENTS OF CRUSTAL DEFORMATION

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ABSTRACT

Using repeated high precision GPS measurements on existing monuments, we hope to accurately determine the present day crustal strain rates in the State of Colorado on a regional and/or local scale. We will provide the first modern, space-based crustal strain and surface velocity estimates for the southern Rocky Mountain region, including the Front Range and Rio Grande Rift. In addition, this work will provide a critical set of measurements to which to refer future project measurements. Thus, if a future moderate or large earthquake were to occur in Colorado, the earthquake size and faulting geometry might be accurately determined by a second set of measurements.

INTRODUCTION

The Colorado Front Range and the Rio Grande Rift have experienced moderate seismic activity in recent times. The largest known historical earthquake in Colorado was the November 8, 1882 earthquake, with an estimated Richter magnitude of $6.2 < M_L < 6.6$, and located in north-central Colorado [Spence et al., 1996]. Among the best documented earthquakes in Colorado is the 2001 Trinidad swarm [Meremonte et al, 2002], and other thoroughly studied events include 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]. The largest instrumentally recorded natural earthquake in Colorado was a magnitude 5.5 event in 1960 which occurred near Ridgeway in southwest Colorado [Talley and Cloud, 1962]. Fault-scarp data on Sangre de Cristo Fault Zone in south-central Colorado suggests past earthquakes of magnitude 7 to 7.3 [McCalpin, 1986]. The base map (Figure 1) of Quaternary faults in Colorado [after Widmann et al, 1998] documents 92 different faults with Quaternary offset, including 8 major faults with Holocene displacement. One of these Holocene faults, the Williams Fork Mountains Fault, is just 50 mi west of the Denver metropolitan area and is capable of producing a moment magnitude 6.75 earthquake [Unruh et al., 1993]. Indeed, a significant swarm of seismicity of magnitudes 2.8 - 4.6 took place during a 3 1/2 week period during our survey in September of 2001 southwest of Trinidad, CO [Meremonte et al, 2002], which has in part led to a major resurgence of interest in the seismic hazard of the region.

Despite this evidence for past and present earthquake activity, the nature and rates of the tectonic processes responsible for creating this seismic hazard are not well understood. The contemporary

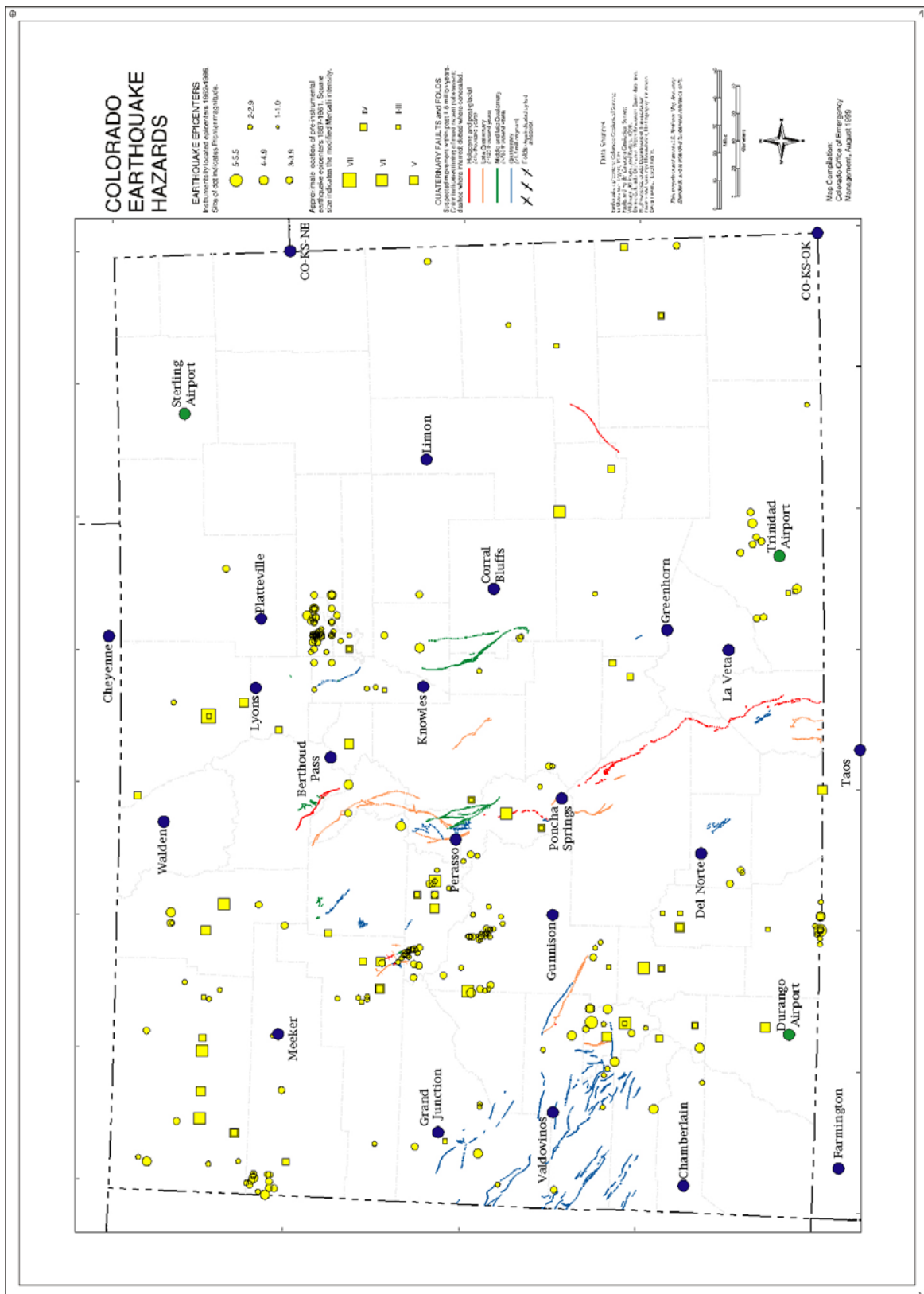


Figure 1. Location of 2001 GPS Measurements (Fault Data after Widmann et al, 1998).

crustal stress regime in Colorado includes extension along a roughly northeast-oriented axis [Bott and Wong, 1995]. A possible mechanism for seismogenesis in the area is reactivation of existing faults, which are oriented favorably to the contemporary stress field, i.e. oriented west-northwest to northwest. Focal mechanisms of two of the earthquakes related to the Rocky Mountain Arsenal fluid injection have indicated normal (or extensional) fault movement locally in the northern Front Range region [Wong, 1986]. In the Rio Grande Rift zone, recent VLBI results [Argus and Gordon, 1996] indicate larger rate than geologic and ground geodetic measurements. Their estimates are on the order of 4-5 mm/yr, whereas estimates from the geology of the Albuquerque basin [Woodward, 1977] are on the order of 0.3 mm/yr, extension estimates from Cordell [1982] are 0.5 to 1 mm/yr, and trilateration data yields 1 mm/yr (Savage et al., 1980). The large variations in estimated rate result in wide uncertainties in estimating recurrence rates for earthquakes in the region. No modern deformation rates have been measured for the Front Range area. Knowledge of the nature and orientation of tectonic stress regimes within the southern Rockies will provide a basis for assessing the capability of faults to slip seismically and produce earthquakes and is a useful tool to evaluate potential seismic hazard in the region.

We are seeking to answer fundamental questions about the mountains in our back yard: Are they a dead mountain range? Alternatively, are the Rockies currently undergoing tectonic uplift, or subsidence and extension? Are the numerous Quaternary faults in Colorado a significant source of seismic hazard? Seismic tomography work [Sheehan et. al, 1995] shows anomalously slow seismic velocities in the upper mantle beneath the Rockies, consistent with the northward propagation of the Rio Grande Rift. Our results will allow us to test this hypothesis and better determine any surface expression of these mantle anomalies.

BODY OF PAPER

Outline of the Method

One way of obtaining crustal deformation rates is by comparing two sets of high-precision GPS measurements taken at the same network of points at two different times. The total errors in the two sets of measurements must be small enough so that the accumulated movement within the network during the intervening time period can overcome the noise. Our aims were two-fold: to acquire a new set of measurements statewide in 2001 that are of the highest possible precision using state of the art acquisition and processing techniques using a previously established set of control points: and to reprocess data measured on these points 10 years earlier to high enough precision to obtain an estimate of crustal strain without requiring a future remeasurement. The level of precision necessary to use GPS for tectonic studies can only be obtained by extensive post-processing of data that were obtained using proper field procedures, and if the GPS satellite orbits can be post-processed to a high level of precision using a global tracking network. This tracking network has been in place and orbits calculated by the International GPS Service since 1992, but as the original measurements were done in 1991, we are trying to devise our own strategy to improve the accuracy of the satellite orbits. Furthermore, the 1991 data were acquired by the National Geodetic Survey for geodetic data definition and not tectonic studies, so the potential accuracy of the reprocessed results is reduced even further, adding to the challenge

of obtaining an immediate result. Given the anticipated low rates of strain in the region, we must reduce the present errors in the reprocessed data by two orders of magnitude from its current levels if a meaningful result is to be calculated.

2001 Field Measurements and Processing

Twenty-six control points of the National Geodetic Survey's High Accuracy Reference Network, HARN, were occupied in August and September of 2001 using Trimble and Ashtech geodetic quality GPS receivers. These points were chosen on the basis of their geographic distribution, their physical stability and potential longevity, their security during extended multi-day and night recording sessions, and the availability of data recorded at these sites in 1991. The data were acquired by personnel from CIRES, the National Geodetic Survey, the Colorado Department of Transportation, and the Bureau of Land Management under our direction. Three stations (Sterling, Trinidad, and Durango Airports) were operated continuously, while the others were operated for between 36 and 72 hours. Specially designed low profile, low eccentricity antenna mounts were used wherever conditions permitted, and antenna positioning was carefully monitored to millimeter precision to assure stability during the sessions.

Processing was done using Bernese version 4.2 software [Rothacher and Mervart, 2001], using high-precision satellite orbits recalculated by the International GPS Service to 20 centimeter precision and carrier phase double-differencing ambiguity resolution. Ionospheric delays are calculated using dual frequencies, earth tides and pole positions are precisely accounted for, and tropospheric effects are statistically modeled. Positions are calculated with respect to four permanent tracking stations (Colorado Springs, central New Mexico, Southern California, and western Canada) operated by the International GPS Service (IGS), in order to tie into the ITRF97 global reference frame.

The resulting coordinates for the network and their estimated errors are shown in Table 1, and the geographical locations are shown in Figure 1 along with the Colorado Earthquake Hazards Map [Colorado Office of Emergency Management, 1999]. The errors, currently on the order of 1 centimeter, will require at least 5 years before a remeasurement of the network can yield an accurate crustal strain rate with errors $< 2\text{mm/yr}$. Efforts are ongoing to reduce the errors by manual identification of outliers and cycle-slips, and we expect to reduce the overall uncertainty by a factor of 2 or more in the near future.

Use of 1991 GPS Measurements to Determine Regional Seismogenic Strain

HARN (High Accuracy Regional Network) was established in 1991 for the purpose of adjusting the geodetic mapping datum of North America to a space-based standard. There are 165 of these benchmarks installed in Colorado using various high-stability monumentation techniques depending on local geology. Per standard NGS practice, the 1991 measurements consist of relatively short 3-6 hour sessions, resulting in a roughly 15 cm precision level, more than adequate for their purpose of continental scale mapping datum adjustment. Unfortunately, the International GPS Service was not established until 1992, and therefore precise reprocessed satellite orbits are unavailable for reprocessing of the 1991 data. The use of broadcast orbits introduces an uncertainty of 20 meters into the satellite positions which maps into

uncertainties of tens of centimeters in carrier phase reprocessed positions. We are currently experimenting with techniques to improve the 1991 satellite orbits, which, when combined with state-of-the-art point positioning algorithms may yield results of sufficient precision to calculate strain rates given the 10 year period between the two measurements. However, it is likely that even if we are successful, the errors in the 1991 positions will be at least 5 cm., which will obscure any tectonic signal of less than 7 mm/year. Given the anticipated extension rates are less than 5 mm/year, it is unlikely that we will be able to definitively determine any local effects, although some regional results may be possible due to some extended measurements taken at a few stations in 1991.

SUMMARY AND CONCLUSION

Currently we only have obtained one set of GPS measurements of sufficient precision for use in calculating crustal strain. Reprocessing of both the 2001 and 1991 is ongoing in an attempt to reduce the position errors in order to resolve low levels of crustal strain postulated to exist in the southern Rockies without a future remeasurement of the 2001 network. Errors (Table 1) in the processed data are currently on the order of 1-2 cm., which given the smaller than 5 mm/yr deformation rates we must resolve, will require a 10 year remeasurement interval to obtain a meaningful strain rate if no improvement in the 2001 positions is obtained. In any case, repeating the 2001 measurements in five to ten years time will likely provide a precise calculation of the strain field in Colorado and quantify seismic hazard in the area.

The establishment of dense networks of new monumentation in areas of higher seismic hazard, such as the Rio Grande Rift or Trinidad would be of high value in addressing local hazard and tectonic concerns. These networks could be occupied periodically, in campaign style, or continuously if the means were provided

Further analysis of archived continuous IGS and other GPS data in the Rockies may be useful on a regional level. The IGS network was being continuously densified during the late 1990's and sufficient continuous data may exist to determine regional strain rates over the last 4 – 6 years. Other potential sources of continuous GPS data such as the NGS and UNAVCO (University NAVSTAR Consortium) have been identified and we are currently evaluating the suitability of the data for use.

A new project for seismic hazard evaluation using archived seismological data in the Rocky Mountains has been funded by the National Earthquake Hazard Reduction Program and work is in the initial stages. We hope to use these data, acquired during the Rocky Mountain Front Experiment [Lerner-Lam et al, 1998] in 1992 using broadband seismometers, will be reevaluated to determine magnitudes and locations for all seismic events of $M_b > 2.0$ and source parameters for events of $M_b > 3.5$ during the experiment. This will allow us to characterize existing and newly identified faults in proximity to the very densely urbanized Front Range corridor of Colorado (Denver/Colorado Springs/Ft. Collins). We will produce a database available for crustal attenuation studies to help assess wave amplitudes and seismic hazard, and input parameters for the National Seismic Hazard and Risk Maps including seismicity and source parameters (focal mechanisms, stress drop).

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Table 1. Processed 2001 GPS HARN Control Point Coordinates and Precisions

<u>Site</u>	<u>Session Length</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Height (m)</u>	<u>Nσ (cm)</u>	<u>Eσ (cm)</u>	<u>Uσ (cm)</u>
STERLING AIRP.	Continuous	40.6216	-103.2666	1208.938	0.60	1.14	1.48
TRINIDAD AIRP.	Continuous	37.2609	-104.3377	1732.143	0.56	1.20	1.92
DURANGO AIRP.	Continuous	37.1588	-107.7528	2013.348	0.44	0.60	0.98
DEL NORTE	36 Hours	37.6828	-106.4988	2439.448	1.28	3.14	6.74
LAVETA AIRP.	36 Hours	37.5248	-105.0016	2138.670	1.00	2.36	4.78
KNOWLES	36 Hours	39.2522	-105.2392	1990.856	1.54	3.92	7.54
PERASSO	36 Hours	39.0838	-106.3060	2797.794	2.38	6.44	12.64
TAOS AIRPORT	72 Hours	36.4603	-105.6690	2137.716	1.16	2.90	6.18
GREENHORN	36 Hours	37.8889	-104.8560	1864.335	1.66	4.02	8.26
PONCHA SPRINGS	36 Hours	38.5170	-106.0712	2261.234	2.78	6.86	14.22
LIMON AIRPORT	36 Hours	39.2684	-103.6641	1609.166	1.22	2.94	5.94
CORRAL BLUFFS	72 Hours	38.8698	-104.5934	2051.130	1.00	2.42	4.86
CLAYTON AIRP	24 Hours	36.4451	-103.1560	1491.375	2.46	6.86	14.16
BERTHOUD PASS	36 Hours	39.7989	-105.7778	3436.839	1.62	3.80	8.00
GUNNISON	36 Hours	38.5388	-106.9267	2325.805	1.98	5.14	10.64
CO-KS-NE Boundary	36 Hours	40.0032	-102.0518	1026.168	2.30	5.32	12.18
FARMINGTON AIRP	24 Hours	36.7400	-108.2195	1654.654	2.08	5.46	10.84
GRAND JCT AIRP	48 Hours	39.1063	-108.5337	1435.100	1.02	2.50	4.10
MEEKER AIRPORT	72 Hours	40.0420	-107.8929	1920.077	0.78	1.12	2.14
CHEYENNE							
GPSBASE	72 Hours	41.1341	-104.8672	1867.411	0.74	0.60	1.46
CHAMBERLAIN	36 Hours	37.7183	-108.8531	2004.180	1.24	3.38	6.94
VALDOVINOS	36 Hours	38.4959	-108.3515	2496.140	1.28	3.36	6.48
LYONS	36 Hours	40.2283	-105.2689	1655.603	1.16	2.52	4.96
PLATTEVILLE	72 Hours	40.1828	-104.7263	1501.276	0.92	1.96	3.58
WALDEN AIRP.	36 Hours	40.7440	-106.2805	2471.924	1.36	2.52	5.52
CO-OK-KS Boundary	36 Hours	36.9931	-102.0421	1098.001	4.02	9.06	18.90
PIETOWN IGS	Continuous	34.3015	-108.1189	2347.778	0.44	0.44	0.62
PINYON #1 IGS	Continuous	33.6122	-116.4582	1256.163	0.44	0.48	0.26
SCHREIVER IGS	Continuous	38.8031	-104.5246	1911.303	0.46	0.98	0.56
YELLOWKNIFE IGS	Continuous	62.4809	-114.4807	1208.938	0.22	0.80	0.22

APPENDIX I: SUPPLEMENTAL READING LIST

Listed below are additional references that were not cited in the text:

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