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THE CHALLENGES OF EVALUATING EARTHQUAKE HAZARD IN COLORADO

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Key Terms: ***Earthquake hazard, earthquake risk, seismic hazard, seismic risk, tectonics, building codes, Quaternary faulting.***

ABSTRACT

In general, Colorado is not considered to be at risk from significant earthquake damage. The state is ranked 30th in the nation in terms of Annualized Earthquake Losses by the Federal Emergency Management Agency (FEMA) and Denver is rated by the U. S. Geological Survey (USGS) National Seismic Hazard maps as having about the same earthquake hazard as Montgomery, Alabama. However, a growing body of data suggests that Colorado may be at greater risk than previously recognized. Colorado has the second largest heat flow anomaly in the North American continent, fifty-eight peaks over 14,000 feet in elevation, and extensive Neogene deformation indicative of an active tectonic province. The catalog of Quaternary faults in Colorado has steadily increased from zero in 1960 to close to ninety in 1998 with many areas of the state unexamined. The strong 1882 earthquake has been definitively located in the northern Front Range. Studies of Quaternary faults in Colorado have resulted in 13 faults being assigned a "maximum credible earthquake" $\geq$ M 6.25 and as high as M 7.5. With Colorado's rapidly growing population (3rd fastest in the nation), substantially more research needs to be directed toward Colorado's earthquake hazard.

INTRODUCTION

Geotechnical workers face a difficult challenge in assessing earthquake risk in Colorado because, unlike many other states, there has not been a concentrated effort to gather data that can be used to evaluate the hazard. The official categorization of seismic design criteria in the International Building Code (IBC) is based on the USGS' National Seismic Hazard Maps. However, for a variety of reasons, Colorado has been relatively neglected in the gathering of the kind of data that is used in preparing the hazard maps. Because these crucial data sets are incomplete in Colorado, the maps may not reflect the true hazard. Consequently, the geotechnical consultant is commonly placed in the mode of recommending safety on the basis of incomplete data. In Colorado, "No evidence of Quaternary faulting" is *not* the same as "Evidence of no Quaternary faulting."

When one views the entire record of what is known in Colorado about faulting, tectonics, and earthquakes, one is led to the conclusion that caution must be used in blindly following the current hazard categories. Critical facilities should receive a rigorous analysis of the likelihood of a damaging earthquake during their lifetime. "Better safe than sorry", is probably not bad advice for critical-facility design in the western two-thirds of Colorado. However, even the eastern one-third of the state should not be treated lightly because the fault with one of the best-known records of earthquake recurrence in Colorado is located on the plains northeast of La Junta.

One source for information on seismic hazard in Colorado is the geotechnical reports prepared for critical facilities. Commonly, these studies determine a Maximum Credible Earthquake (MCE) for faults that might generate earthquakes affecting the site under study. A compilation of Maximum Credible Earthquakes (MCE) ≥ M 6.25 that were assigned to various faults in Colorado portrays a sobering picture (Figure 1).

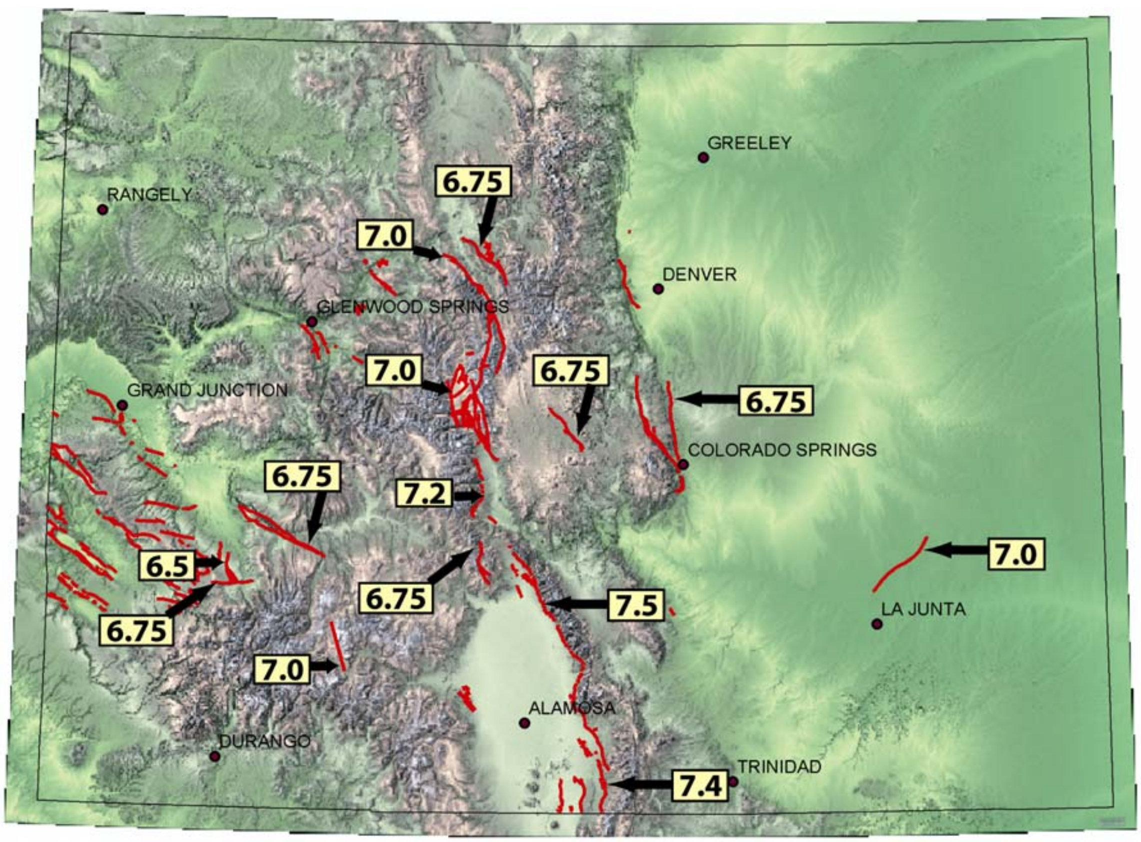


Figure 1: Known Colorado Quaternary Faults and Maximum Credible Earthquakes (MCE). The faults (red) and MCE values are from Widmann, and others (2002) and Frankel, and others (2002). MCE values exceeding M 6.25 were extracted from geotechnical reports and publications individually referenced in Widmann, and others (2002).

INTERMOUNTAIN WEST (IMW) SEISMIC AREA

Colorado is part of the InterMountain West (IMW) seismic area. In the IMW, an extensional tectonic environment began in the Miocene and continues today (Hamilton, 1989). All of the seven IMW states have evidence of Quaternary faulting (Frankel, and others, 2002) and all have experienced basaltic volcanism during the past 4,200 years. And, all but two (AZ & NM) have experienced earthquakes M > 6.0 within their borders during the last century and a half (Stover and Coffman, 1993).

The IMW is often compared to California when considering seismic activity, fault slip rates, GPS budget, and earthquake hazard. Obviously, the IMW states pale in these comparisons with ultra-active California (as do all other states with the possible exception of Alaska). However, when one compares the tectonic characteristics of the IMW to the Central and Eastern United States (CEUS) seismic area, the IMW characteristics do not seem nearly as insignificant as when compared to California. The eastern seaboard has been a passive margin since the opening of the Atlantic in the Triassic. Yet, South Carolina alone has a high-hazard area that is half the size of the high-hazard area in the six states of the IMW, even though the IMW is seventeen times as large as South Carolina (Figure 2).

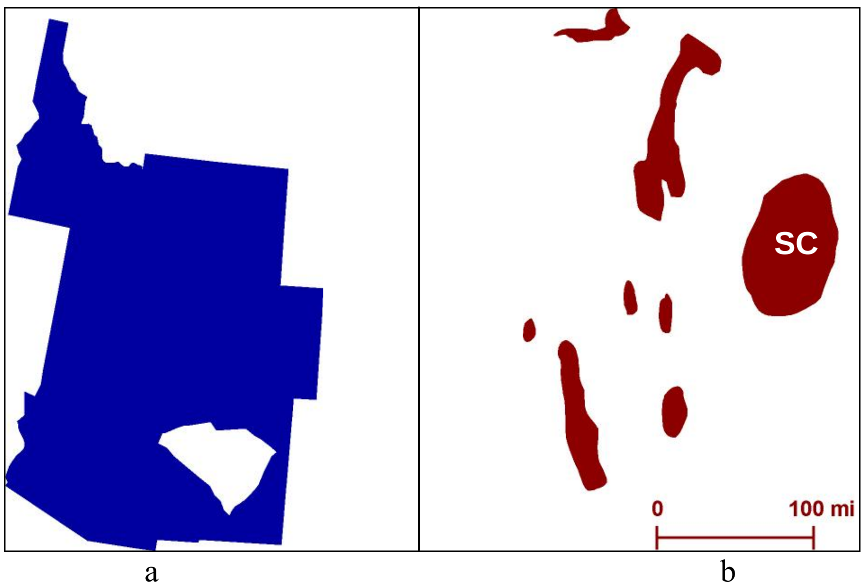


Figure 2: Comparison of earthquake hazard in the IMW and South Carolina. a.) Comparison showing that the area of the six IMW states is 17 times greater than the area of South Carolina [white inset] **b.)** The large blob on the right is the high-earthquake-hazard area in South Carolina and the other red blobs are the high-earthquake-hazard areas (Frankel, and others, 2002) in the six-state IMW (http://geohazards.cr.usgs.gov/eq/html/us2002oct.htm).

OFFICIAL CATEGORIZATION OF HAZARD AND RISK

Earthquake *hazard* maps relate to the probability of a particular site undergoing a given level of ground acceleration caused by an earthquake. *Risk* maps add the dimension of exposure of human life, as well as the design and value of buildings to the equation. An area could be considered to be a high, earthquake-hazard area, but a low risk because no one lives within the area. The epicenter of the 2002, M 7.9 Denali earthquake in Alaska is an excellent example of a high-hazard, low-risk area.

New York City, NY and Santa Rosa, CA provide excellent examples of the difference in hazard and risk. New York City's earthquake hazard (peak ground acceleration) is 15 times lower than Santa Rosa's hazard. But, New York has a higher population, higher building stock value, and lower earthquake-resistant design than Santa Rosa. Therefore, FEMA's calculation of earthquake risk gives New York City annualized earthquake losses of $56 million versus Santa Rosa's $51 million.

Two maps relate to earthquake hazards and risk in Colorado. The National Seismic Hazard Maps (Figure 3) created by the USGS form the underpinning for the risk maps (Figure 4) created by the FEMA. The hazard maps also provide data for calculations used in seismic-design formulae of the International Building Code (IBC).

2002 National Seismic Hazard Map (USGS)

National Seismic Hazard Maps are prepared by the USGS and updated every five years. The 2002 series are the most recent release and depict probabilistic ground motions. A team of USGS seismologists and geologists evaluate data throughout the United States (Frankel, and others, 2002). Regional workshops provide an opportunity for stakeholder input during the draft process. The currently posted maps depict peak ground acceleration and 0.2 sec and 1.0 spectral acceleration with 10% and 2% probabilities of exceedance (PE) in 50 years. Additional maps will eventually be posted.

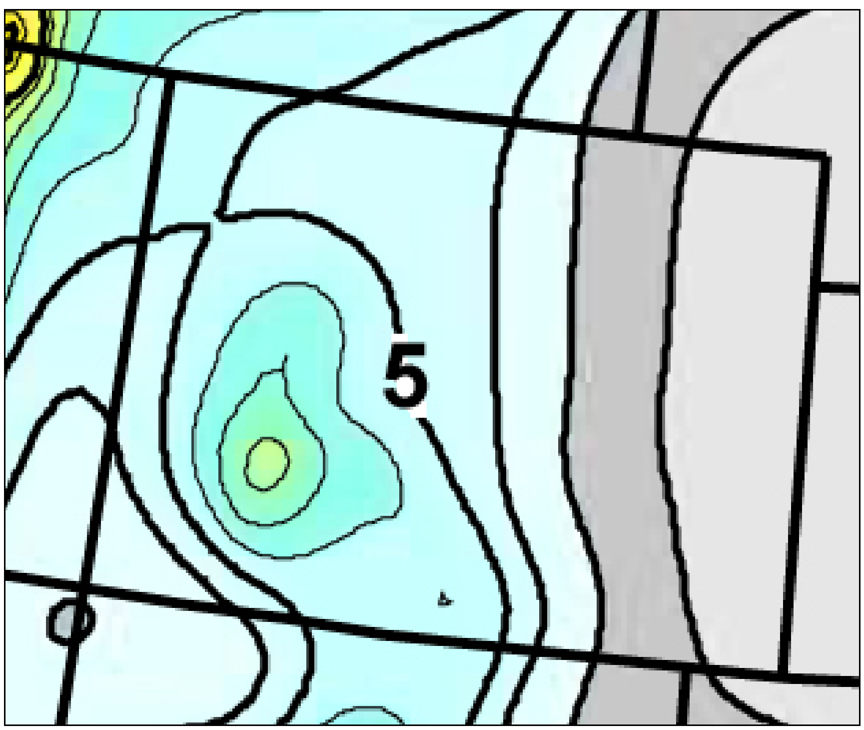


Figure 3: Colorado Seismic Hazard. Peak Acceleration (%g) with 10% Probability of Exceedance in 50 Years. Excerpted from the 2002 National Seismic Hazard Maps (USGS). The contour lines indicate the values of peak ground acceleration measured as a percent of the force of gravity (g). These maps indicate that peak ground accelerations of .08 to .09g are the maximum expected anywhere within the state at the 10% probability level during a 50 year period. Five additional maps at various probabilities and spectral and peak accelerations are available online at http://geohazards.cr.usgs.gov/eq/html/natlmap.html.

Factors that are considered in preparing the maps are:

- Historical seismicity— b value
- Faults slip rates— >0.2 mm/year.
- Quality factor (Q)— the ability of the lithosphere to attenuate seismic waves.
- Site amplification— firm rock or hard rock.

The results are presented in a variety of ways. Eventually a set of 12 maps of the U. S. will show contour lines depicting various levels of probabilities, ground acceleration, and spectral periods, e.g.:

Peak Acceleration (%g) with 10% Probability of Exceedance in 50 years
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 years
Peak Acceleration (%g) with 5% Probability of Exceedance in 50 years
0.2 sec Spectral Acceleration (%g) with 10% Probability of Exceedance in 50 years
0.2 sec Spectral Acceleration (%g) with 5% Probability of Exceedance in 50 years
0.2 sec Spectral Acceleration (%g) with 2% Probability of Exceedance in 50 years
0.3 sec Spectral Acceleration (%g) with 10% Probability of Exceedance in 50 years
0.3 sec Spectral Acceleration (%g) with 5% Probability of Exceedance in 50 years
0.3 sec Spectral Acceleration (%g) with 2% Probability of Exceedance in 50 years
1.0 sec Spectral Acceleration (%g) with 10% Probability of Exceedance in 50 years
1.0 sec Spectral Acceleration (%g) with 5% Probability of Exceedance in 50 years
1.0 sec Spectral Acceleration (%g) with 2% Probability of Exceedance in 50 years

2000 National Risk Assessment (FEMA)

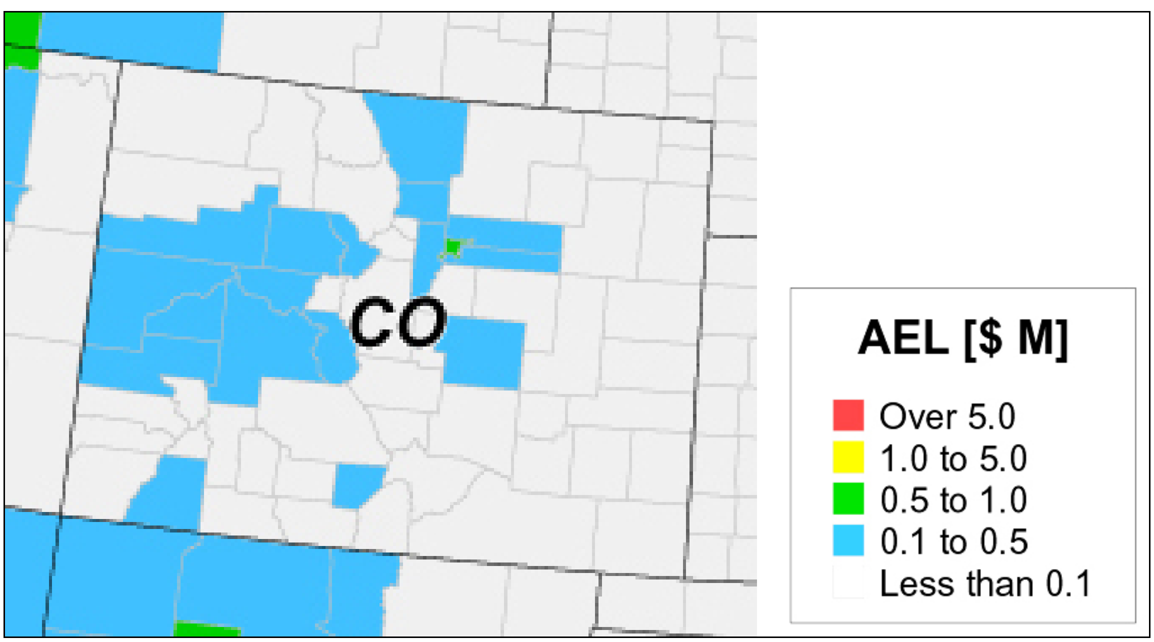


Figure 4: Annualized Earthquake Losses. The analysis of earthquake risk in Colorado performed by FEMA in HAZUS99 indicated Annualized Earthquake Losses (AEL) for the state of $5.8 million distributed by county as shown above. The full report is online at http://www.fema.gov/hazus/eq_ael.pdf .

In September of 2000, FEMA released a national study of earthquake risk using their risk analysis model, HAZUS99. The evaluation showed a risk of Annualized Earthquake Losses (AEL) of $4.4 billion for the nation and $5.8 million for Colorado. Colorado ranked 30th in the nation behind such states as Ohio, Virginia, North Carolina, Georgia, Delaware, Alabama, Pennsylvania, New Hampshire, Connecticut, and New Jersey.

In addition to these probabilistic evaluations, the model can also be used to conduct damage evaluations for deterministic earthquakes. According to FEMA, "Once the size and location (epicenter) of a hypothetical earthquake is selected, the HAZUS software, using a series of mathematical formulas, calculates the violence of ground shaking, the amount of damage, the number of casualties, the number of people displaced by damaged structures, and the disruption and economic losses caused by the earthquake. These formulas describe the relationship between earthquake magnitude, violence of ground shaking, building and utility system damage, cost of repair, and indirect economic impact. HAZUS allows for changing the size and location of the hypothetical earthquake to see the range of damage that may occur to the community."

In cooperation with FEMA's Region VIII, the Colorado Geological Survey (CGS) conducted two deterministic evaluations. The results indicate that a repeat of the 1882, M 6.6 earthquake north of Estes Park would cause $240 million in losses. An evaluation of the effects of a M 5.8 earthquake in the vicinity of the 2001 Trinidad earthquake swarm would result in $15 million in losses. HAZUS99 is a very effective tool for evaluating the potential losses from an earthquake of a given magnitude in a given location.

BUILDING CODES

Until the year 2000, those Colorado municipalities who chose to adopt a building code drew from the Uniform Building Code (UBC) that was updated every three years; most recently in 1997. In 2000, the International Building Code (IBC) replaced the UBC. Both the UBC and IBC have requirements of earthquake-resistant designs for buildings.

International Building Code (IBC)

Prior to 2000, at least three groups in the United States issued building codes. Denver used the 1997 UBC that divided the country into six Seismic Zones: 0, 1, 2A, 2B, 3 & 4 each with its own seismic-design criteria. [The higher the Zone number, the more stringent the seismic design criteria.] Most of Colorado was in Zone 1, requiring only minimal structural detailing requirements. The eastern 15 percent of the state was in Zone 0, on a par with Minnesota. The boundary between Zones 0 and 1 passed well east of the Front Range Urban Corridor, all of which was included in Zone 1. A small part of southern San Luis Valley was put in Zone 2B.

Recently, the three code councils merged into The International Code Council and now issue one combined code: the IBC. The IBC no longer issues the zone maps. Rather, the seismic design part of the IBC uses formulae to calculate required levels of design based on data from the USGS National Earthquake Hazard Maps that show contours for varying levels of ground acceleration at different periods and probabilities.

IBC versus UBC and Denver's Solution— A thorough review of the seismic-design implications of the IBC 2000 for Denver is given by Jackson (2001). He illustrates how the IBC 2000 actually reduces the seismic design criteria over the UBC 1997 for Front Range buildings founded on very dense soils and rock. And, he further illustrates how the determination of Seismic Design Category (SDC) varies up and down the Front Range. Following the IBC strictly would require Lakewood to have higher seismic-design criteria than the City of Denver. The ground acceleration map contours from the IBC generally decrease going east from the Front Range, so that communities such as Aurora, Greeley and most of Denver would be allowed to design buildings for Seismic Design Category A, using only 1% of gravity loads for the equivalent lateral earthquake force. This is significantly lower than the design of most Front Range buildings under previous codes.

Because the net effect of the IBC 2000 was to reduce the seismic-design criteria of the UBC 1997 for Denver, the City of Denver IBC 2000 Structural Sub-committee felt that it was imprudent to lower the seismic-design requirements. This committee, composed of City structural engineers and representatives from the Structural Engineers of Colorado recommended that the IBC 2000 adoption by Denver preclude the use of SDC A, thereby maintaining approximately the same seismic design criteria as provided for in prior codes. A general review of the 2000 IBC seismic provisions compared to the 1997 National Earthquake Hazard Reduction Program(NEHRP) provisions can be found online at http://www.skghoshassociates.com/Comparisons%20of%20seismic%20codes.htm.

Adoption of Building Codes— A first step in safe building practices is to get government jurisdictions to adopt modern building codes. In contrast to 40% of the states, Colorado does not have statewide building code requirements. Thus, adoption of building codes is spotty throughout the state. As of January 31, 2003, only six counties and 19 municipalities in Colorado have adopted the 2000 IBC (**http://www.icbo.org/**).

Building Code Enforcement— Adoption of a building code is only the first step. The code must then be enforced to be effective. Here again, Colorado is lacking in enforcement of even the minimal, seismic-design criteria in existence.

In addition to structural design criteria, the UBC and IBC require that non-structural mechanical and electrical systems (heating, ventilation, and air conditioning units, boilers, fans, cooling towers, and similar equipment) must be restrained in order to prevent being shaken loose or toppling over during a moderate earthquake. Bonkoski and others (2000) polled building inspectors along the Front Range to determine whether these provisions were being enforced. All of the responding inspectors indicated they were aware of this section of the code, but 80 percent of the respondents indicated that they do not enforce it, and 60 percent responded that they do not feel that this section of the code is necessary.

DATA PROBLEMS IN COLORADO

A variety of data deficiencies create a less-than-comforting situation for those charged with the responsibility of making evaluations of earthquake hazard in Colorado.

Earthquakes

Many factors contribute to concern about the validity of Colorado's earthquake record. The historical record is short. The lack of a modern seismometer network makes it difficult to locate and detect earthquakes. The lack of knowledge about attenuation of earthquakes in Colorado makes it difficult to predict the strength of ground acceleration. Additionally, the existence of induced earthquakes from fluid injection complicates the attempt to sort these from natural earthquakes.

Historical record of earthquake activity— One of the drawbacks with Colorado's seismic record is the same as that of most of the IMW states: a record of less than 175 years compared to 400 years in the CEUS. Since 1867, the historical record includes more than 500 earthquakes (Kirkham and Rogers, 2000 and online NEIC data through 2003). Charlie and others (2002) analyzed the earthquake catalogue and concluded that it contains 137 independent natural earthquakes between 1867 and 1996. They tested the completeness of the earthquake record and determined that their 137 independent earthquakes are complete for ML ≥ 4.0 between 1870 and 1950, ML ≥ 3.5 between 1950 and 1960, ML ≥ 3.0 between 1960 and 1970, and ML ≥ 2.5 since 1970. The record through 2002 includes fifteen earthquakes of intensity VI or greater. On average, earthquakes causing MM Intensity ≥ V occur about every four years (Figure 5). During a recent six-month period in 2001-02, Colorado experienced four earthquakes M ≥ 4.0.

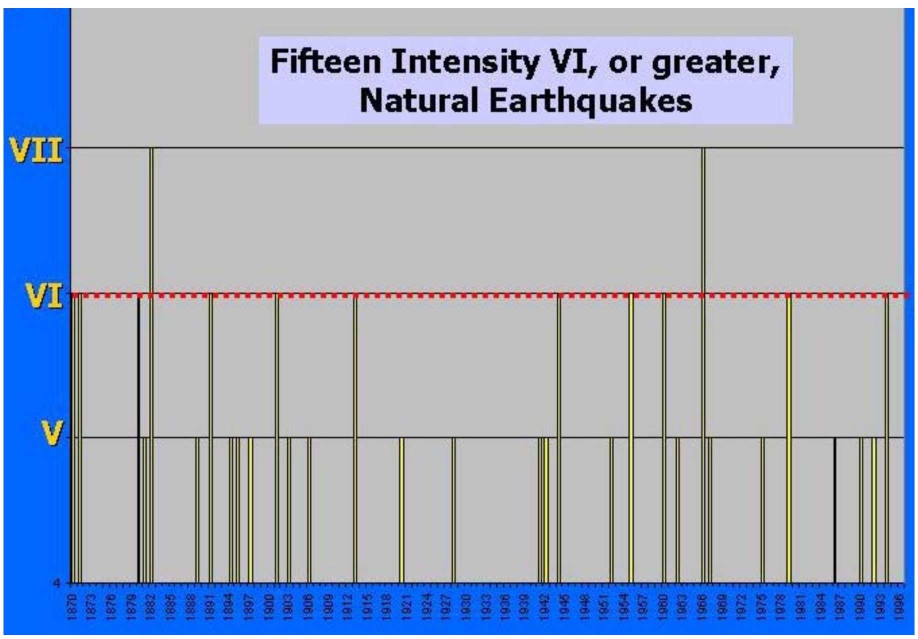


Figure 5: Naturally-occurring earthquakes of Modified Mercalli Intensity V in Colorado from 1870-1996. Intensity VI includes such effects as– People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. *Data from* Kirkham and Rogers, 2000.

The strongest earthquake in Colorado during the past century-and-a-half was M_w 6.6. This 1882 earthquake frightened people in Denver and other northern Front Range cities. It was so strong that the bolts holding the electric generators for Denver were snapped off and power was knocked out. The epicenter of the earthquake was uncertain for over a century. However, careful research by CGS scientists in 1986 determined that the earthquake was centered about ten miles north of Estes Park (Kirkham and Rogers, 1986). Research by USGS scientists (Spence, and others, 1996) confirmed this conclusion (Figure 6). Two other reviews affirmed that the location was in the northern Front Range (Stover and Coffman,1993; Bollinger,1994).

Evidence of stronger past earthquakes can be determined by offsets of recent geologic deposits in trenches across active faults. Study of deposits in Colorado show that magnitude 7.0 or higher earthquakes probably occurred on several faults since humans have been living here.

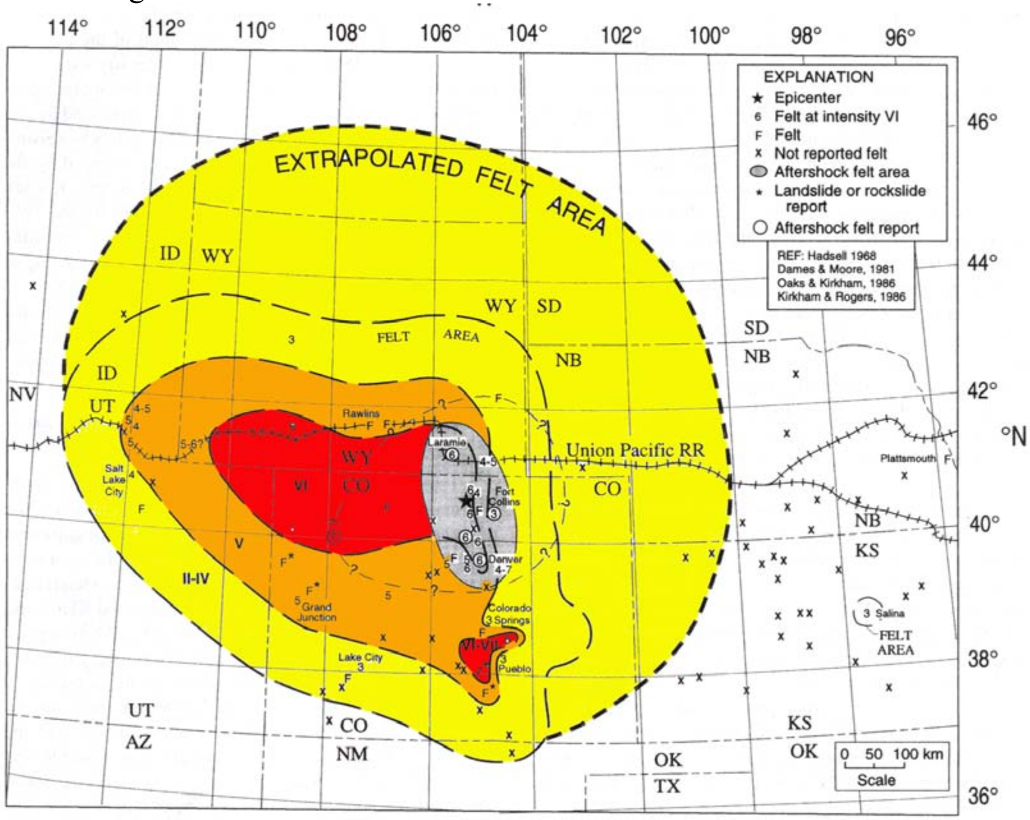
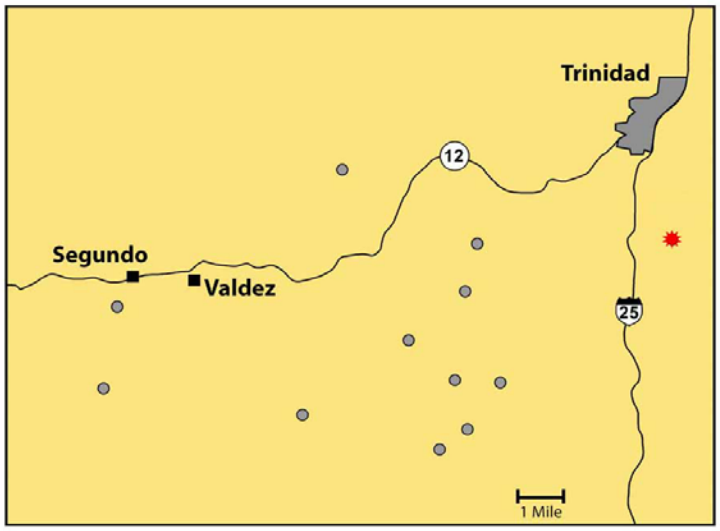


Figure 6: Isoseismal map of the 1882 Mw 6.6 =/-0.6 earthquake. Red contours show area of Modified Mercalli Intensity VI & VII. Gray shaded area shows felt area of aftershock. From Spence and others, (1996)

Difficulty in detecting and locating earthquakes— Until the summer of 2002, Colorado had only two seismographs as part of the National Earthquake Information Center (NEIC) network. Because they were so close together and one of them was in a very noisy location, we effectively had only one station within the state. This situation makes it difficult to detect and precisely locate smaller earthquakes.

The Trinidad swarm of 2001 vividly illustrates the problem of locating earthquakes (Figure 7). The largest earthquake of the swarm was a magnitude 4.6. Its location was initially reported as two miles south of Trinidad. However, Trinidad reported no damage. CGS geologists discovered Modified Mercalli Intensity VII damage in Segundo and Valdez, 11-12 miles west of the reported earthquake location. Pictures were thrown off walls, plaster was broken, bottles were emptied out of cabinets, and a chimney was broken and thrown into the street. The USGS quickly deployed a dense network of portable and temporary seismographs to better understand the earthquakes (Meremonte and others, 2002). Studies using the well-located earthquakes revealed that the largest earthquake was actually located under Segundo, more than ten miles west of the initial location report near Trinidad. Several lines of evidence also showed a good correlation of the earthquakes with the projection of a fault exposed at the surface (Matthews and Morgan, in preparation).



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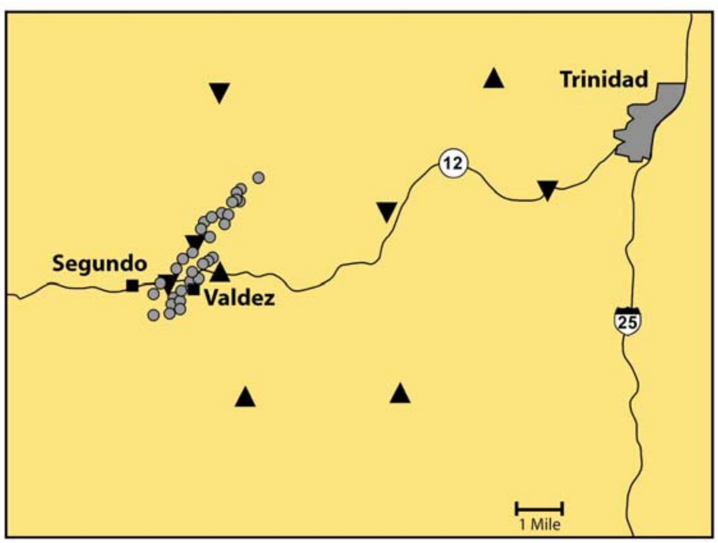

b.

Figure 7: Epicenters of the 2001 Trinidad Earthquake Swarm. a.) Locations of earthquakes reported by the NEIC prior to installation of the local network. The earthquakes appear to be random and are scattered over 75 square miles. The largest earthquake, M 4.6, was calculated to be two miles south of Trinidad (red dot). b. Tight northeast-southwest cluster of earthquake locations determined with the USGS local network. Portable seismographs shown by triangles, earthquakes shown by circles. *Modified from* Meremonte and others, 2002.

Fortunately, the USGS has recognized the problem of accurately locating earthquakes in Colorado and has funded the installation of two permanent, modern seismographs in the state that will be part of the ANSS national network. One went online at the Great Sand Dunes National Park in July of 2002. The second is scheduled for Kit Carson County. This is an important step toward a better understanding of which faults in Colorado are currently generating earthquakes. Also, an analysis for local earthquake events in the PASCAL data set was recently funded by NEHRP and is currently underway by Dr. Anne Sheehan at the University of Colorado.

Attenuation of Earthquakes— The Quality Factor (Q) indicates how an area dampens seismic waves; higher Q values dampen less, lower Q values dampen more. The CEUS seismic area has a higher Q value relative to California's. Therefore, earthquake waves are considered to be reduced less in the CEUS causing shaking over a wider area than a similar-sized earthquake in California would cause.

The Q value for Colorado is unknown. In the National Seismic Hazard Maps an assumed Q is used. The CEUS Q value was assumed for most of Colorado in the 2002 hazard maps, except for the San Luis Valley where the attenuation value for the Western United States (WUS) was used. In the hazard maps, the Q for a given earthquake is assigned according to which attenuation area the earthquake epicenter is located. Because the boundary between the CEUS and WUS attenuation zones enters Colorado, an interesting dilemma arises.

The San Luis Valley is bounded on the east by the Holocene, Sangre de Cristo fault (McCalpin, 1982) and is the only part of Colorado in the WUS attenuation zone. Therefore, although the Q between Denver and the Sangre de Cristo fault is the higher CEUS value, a lower WUS value would be assigned to an earthquake occurring on the Sangre de Cristo fault because it originated barely within the WUS attenuation boundary. This has the effect of lowering the forecast shaking in Denver from a strong earthquake on that active fault.

Correlation of microseismicity with faults— Several studies have shown clustering of microseismicity on specific faults in Colorado (Sheehan, 2000; Sheehan, 2003, this volume; Godchaux, 2000; Matthews and Morgan, in preparation). However, this relationship is still poorly understood throughout much of the state because of the absence of a complete fault catalogue. At this point in the state of our knowledge, it is probably imprudent to assert that microseismicity in Colorado is not related to specific faults.

Induced versus natural seismicity— Many earthquakes catalogued in Colorado (Kirkham and Rogers, 2000) are considered to be induced by fluid injection at either the Rocky Mountain Arsenal, Rangely Oil Field, or in the Paradox Valley (Charlie and others, 2002). Determining whether earthquakes are natural or human-induced can be problematic such as in the Trinidad swarm (Meremonte, and others, 2002; Matthews, 2002) and at the Rocky Mountain Arsenal (Frankel and others, 2002). Construction or mine blasts are much easier to sort out because of their unique first-motion patterns.

Paleoliquefaction

Paleoliquefaction features (seismites) provide important information for the National Seismic Hazard Maps in areas such as South Carolina, Illinois, Missouri, Washington, and California. Liquefaction seems more likely to occur in humid environments than arid or semi-arid environments such as Colorado's. However, paleoliquefaction features have been described in arid Death Valley. A concentrated search for paleoliquefaction features has not been made in Colorado, but suspicious features are beginning to turn up. Many areas in Colorado have been identified that contain conditions suitable for liquefaction, i.e., groundwater table < 40 feet and unconsolidated sediments.

Faults

Recognizing faults and dating their movement in Colorado is particularly challenging. Colorado's claim to one of the largest expanses of Precambrian crystalline rock (Noe and Matthews, this volume) in the Western U.S. makes dating movement on faults in the mountainous areas exceedingly difficult. Young strata are commonly stripped by erosion from these areas leaving only rocks that are more than a billion years old on each side of a fault. Obtaining slip rates on faults in environments that are not particularly amenable to creating and/or preserving datable strata is also difficult. Because of the uncertainty involved in dating movement on these faults and because of the lingering skepticism about the level of seismicity in Colorado, a higher standard of proof is sometimes applied than in areas such as California and Washington.

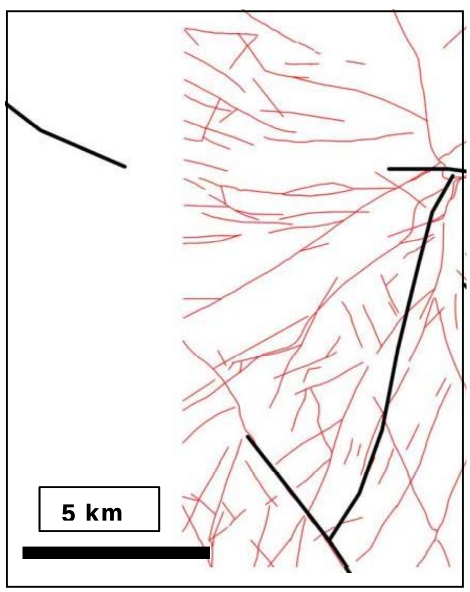

Figure 8: **Comparison of faulting at different scales**. This map shows published faulting along the eastern flank of the Front Range from Morgan, 2003. Red faults are from 1:24,000 mapping and black faults are from 1:250,000 mapping. The vertical line where the red faults appear cut off are 7.5 minute quadrangle boundaries. Note that there is only one fault from the 1:250,000 map shown west of that line. Yet the true density of faulting west of that cutoff is probably the same as mapped in the east.

Recognizing the existence of faults— Much of Colorado's tectonically active terrane exposes Precambrian crystalline rock. Published mapping of faults in these areas is irregular. Morgan (2003) digitally compiled all of the published faults in the Front Range. His maps clearly illustrate that adjacent maps have vastly different patterns and intensity of faulting depicted (Figure 8). Geotechnical workers must be wary of relying on published maps to define the faults in an area.

Quaternary Faulting— The current catalogue of Quaternary faults and folds in Colorado includes 92 faults and 6 folds (Figure 9). However, the National Earthquake Hazard Maps include only four of these faults in their calculations. More of Colorado's faults are not included because they lack published evidence of slip rates > 0.2mm per year. Some faults that do have published slip rates > 0.2 mm were not included in the newest hazard maps because USGS and CGS geologists concurred that further documentation was required before making a decision on whether to include them in the calculations of hazard.

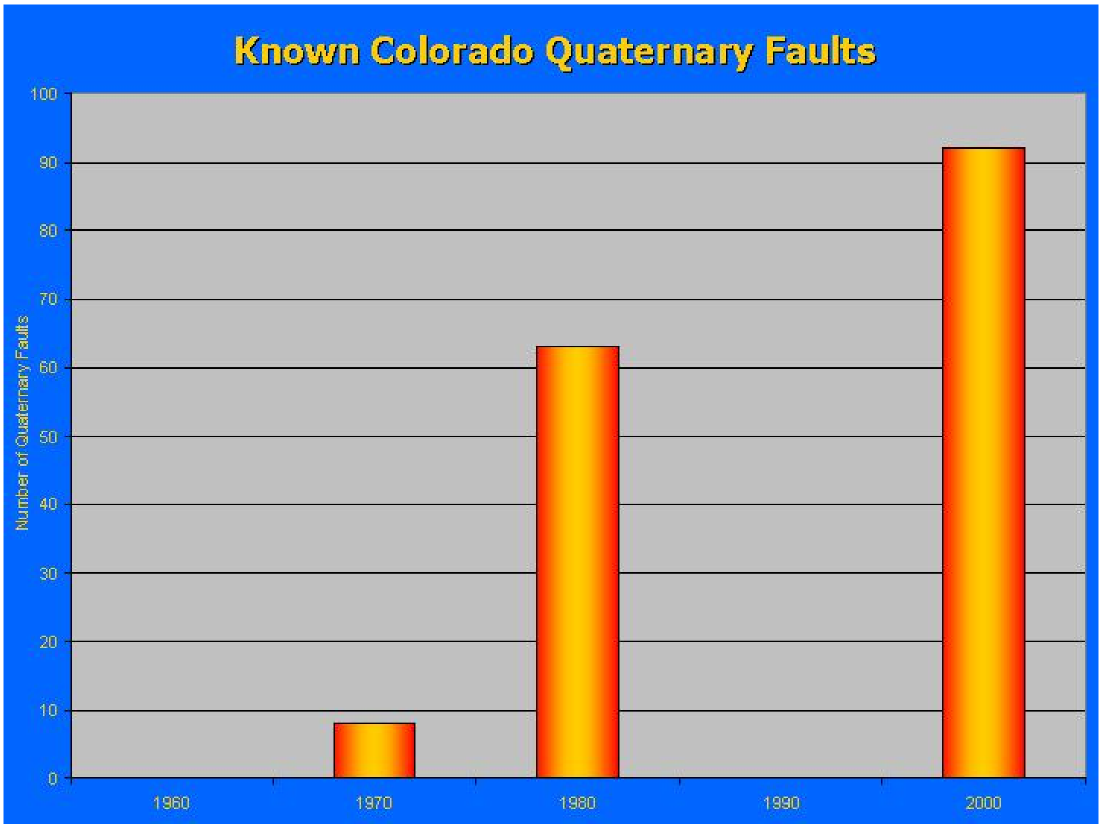

Figure 9: Growth in the Number of Known Quaternary Faults. In 1970 our catalogue of Quaternary faults totaled eight (Scott, 1970). By 1980 the number of identified Quaternary faults increased to more than 60 (Kirkham and Rogers, 1981). The most recent catalogue of Quaternary faults totals 92 (Widmann and others, 1998)

Dating fault movement— Much of the mountainous terrane in Colorado is composed of Precambrian crystalline rocks in excess of one billion years in age. Dating a fault in this terrane is problematic for determining earthquake hazard. All that is immediately obvious is that the fault has moved sometime since the Precambrian rocks cooled. If the topography appears to be at different elevations on either side of the fault, it is probably justified to try and determine whether there is evidence that can rule out the possibility that it has moved in recent geologic time. Because the catalogue of young faulting in

Colorado continues to grow, it becomes questionable whether one can pronounce a fault safe to build upon in the absence of defensible evidence. In the absence of evidence that a fault has not moved in the Quaternary, should one declare that it is safe to build on? This question is further discussed in the section below on Colorado: An Active Tectonic Area.

Recurrence Intervals and slip rates— Even where evidence of displacement of Quaternary strata is present, it is difficult to get the data required for slip rates or return periods for large earthquakes. Defensible slip rates require an exposure (natural or mechanically trenched) that shows faulted strata that are correlateable and dateable. Such data are hard to obtain in Colorado.

The Cheraw fault northeast of La Junta has one of the better records of recurrence found to date in Colorado. Yet, even it is somewhat of a fluke. The Cheraw fault trends northeast-southwest and has a subtle scarp facing northwest opposing the regional drainage gradient to the southeast. As a result, ponding occurs at the base of the northwest-facing scarp. These ponds create organic rich sediments that can be correlated and can be dated with radiocarbon methods. Crone and others (1997), trenched the fault and determined that three strong earthquakes occurred on this fault during the past 22,000 years. The results gleaned from this study met the criteria for the hazard maps and the fault was included in the 2002 National Seismic Hazard Maps. However, workers who have studied this fault believe that if the fault dipped to the southeast rather than the northwest, the a scarp would probably not be preserved and the fault would most likely never be discovered. In the unlikely event that such a fault were discovered and trenched, there probably would be no correlative and dateable strata because conditions would not exist to create the ponding and associated dateable, organic sediments.

Because Colorado is such an active area, erosion is more common than deposition in the mountainous areas. This creates a paucity of young deposits useful for evaluating earthquake hazards. As Steven (2002) states, "… erosion has been the dominant geologic process acting on the Southern Rocky Mountains during the late Cenozoic, and by its nature, erosion progressively destroys the history of its own evolution". Many of the young deposits that do exist, are coarse clastics that don't make for easy correlation and dating when they are faulted. As a result, very few slip rates have been obtained for Quaternary faults in Colorado and the few that have been reported are often challenged as not being sufficiently definitive. Documentation of recurrent faulting has been achieved on the southern Sawatch fault (Ostenaa, and others, 1981) and on the Sangre de Cristo fault (McCalpin, 1982) which qualifies them to also be included in the 2002 National Seismic Hazard Maps.

Default Soil Classification

Another problem with assessing earthquake risk through HAZUS99 modeling in Colorado is the lack of good compilations of soil types. Because of this lack of data which states like California have gathered, HAZUS just assumes a default soil type in

Colorado. Data on soil types must be compiled before useful "shake maps" can be generated and before the most meaningful results can be obtained from HAZUS..

COLORADO: AN ACTIVE TECTONIC AREA

The dogma being taught in most Colorado universities until the early 1970s was that all of the most recent faulting occurred during Laramide mountain building (~80 to 40 m.y.a.). The only post Laramide activity was considered to be broad regional warping with no faulting, i.e. "the faults have all been dead for 40 million years." Research presented in the early 1970s (Curtis, 1975) set that notion on its ear by documenting significant and widespread post-Laramide faulting.

It is somewhat naive to suggest that a state with 58 peaks over 14,000 feet high, and the highest average elevation in the country (6800 feet above sea level), does not have active mountain building going on. The notion that these mountains are just unroofed remnants of the Laramide mountains, or are only gently upwarped over a broad area, is not substantiated by the data. Rather, they were uplifted by thousands of feet of movement along faults in the past 25 million years, much of it in the past five million years (Steven (2002). Holocene faulting and volcanism, high heat flow, earthquakes, and rugged, challenging mountains indicate that this activity continues today.

Heat flow and volcanism— Heat flow is one common indicator of active tectonism. Colorado has the second-largest, high-heat-flow anomaly in North America (Blackwell and Steele, 2000). The state has 93 large hot springs with hundreds of smaller, hot springs (George, 2000). Central Colorado is also underlain by low-velocity, mantle material (Lerner-Lam, and others, 1998; Duecker, and others, 2001) indicating some sort of upwelling forces at work.

Basaltic volcanism is another indicator of active, extensional tectonism. Late Cenozoic basalt flows abound in the state and Quaternary basalts are found in four places (Tweto, 1979). The Dotsero volcano erupted only 4,150 years ago (Giegengack, 1962).

Neogene faulting— Since Curtis (1975) first documented widespread, post-Laramide deformation in Colorado, the body of evidence continues to grow that active uplift and faulting is a dominant imprint on late Cenozoic geologic history. Late Cenozoic faults are common in the western two-thirds of Colorado (Figure 10). Steven (2002) concluded that major deformation took place in Colorado during latest Miocene and Pliocene time and continued into the Quaternary.

Apatite fission-track data from north-central Colorado demonstrate significant, post-Laramide uplift (Naeser, and others, 2002). They report that 4.0 km of material was removed from the Gore Range since middle Tertiary time.

Fault studies show large, vertical offsets of late Cenozoic rock units throughout central Colorado. For instance, geologic mapping in Rocky Mountain National Park (Braddock and Cole, 1990) shows two kilometers of post-Oligocene vertical displacement of volcanic rocks in Specimen Mountain; Geismann and others (1992) demonstrated 2.3 km of vertical offset of the ore body at Red Mountain; coreholes at Climax verify 3.0 km of vertical displacement on the Mosquito fault (Wallace and others, 1968); Limbach (1975) reports 3.0 km vertical displacement of the Sawatch Range; and Lindsey, and others, (1986) report 4 km of vertical displacement of the Sangre de Cristo Range. These large faults span 150+ miles in central Colorado. With documented displacements of this magnitude and distribution, it is questionable whether one can safely make the assumption that a fault in Precambrian rock has not moved since the Laramide without strong evidence to that effect.

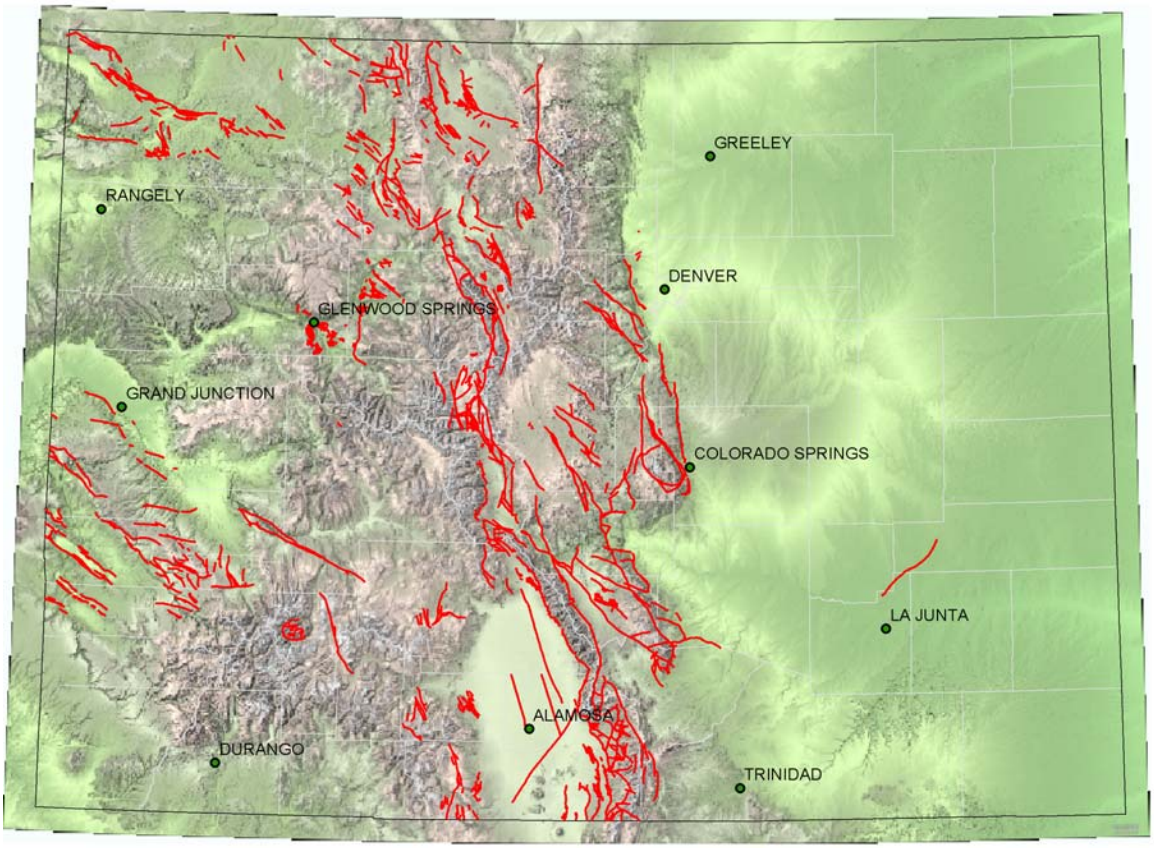

Figure 10: Known Late Cenozoic Faults in Colorado. These faults include Quaternary faults shown separately in Figure 1. The widespread Late Cenozoic faults (Miocene or younger) suggest that more Quaternary faults remain undetected. *from* Widmann and others (2002).

REASONS WHY COLORADO'S EARTHQUAKE INFORMATION IS LACKING

Colorado's database of information relative to earthquake hazard seems to be lacking for several reasons:

- A general perception among decision-makers that Colorado does not have an earthquake problem.
- Original uncertainty about the location of Colorado's 1882 Mw 6.6 earthquake.

- Difficulty in obtaining slip rates on Colorado's Holocene and Quaternary faults.
- Lack of statewide seismograph coverage making it difficult to accurately locate earthquakes and to detect smaller earthquakes.
- Short record of historic seismicity; approximately175 years versus 450 years in parts of the CEUS.
- Past research was not focused in Colorado because of higher priorities in other parts of the country.

CGS RESOURCES RELATIVE TO EARTHQUAKES AND FAULTING IN COLORADO

The Colorado Geological Survey has a number of resources that geotechnical practitioners might find useful in studying the earthquake hazard in Colorado:

OFR-03-4, "Published faults of the Colorado Front Range": Map plate and CD-rom contains faults published at a variety of scales (Morgan, 2003). This compilation vividly illustrates the incompleteness of our knowledge of the location and extent of faulting in the Front Range. It also is probably a good indicator of the lack of knowledge about faulting in other areas of the state.

Bulletin 52, "Colorado Earthquake Information, 1867-1996" CD-ROM (kirkham and Rogers, 2000). This publication received the 2001 "Excellence in the Use of New Technology Award" from the Western States Seismic Policy Council.

Earthquake Reference Collection: More than 500 papers on earthquakes and faulting relative to Colorado are available for review in the CGS offices. The collection includes many obscure studies and unpublished geotechnical reports. An online bibliography is at http://geosurvey.state.us.

Late Cenozoic Fault and Fold Database and Internet Map Server (Widmann and others (2002): This online publication (http://geosurvey.state.co.us/pubs/ceno/index.htm) is useful to quickly gain information about known faults that offset Late-Cenozoic (<23m.y.a) deposits in Colorado. Faults on the map server are color-coded by age of youngest known movement. Double clicking on a given fault brings up a data sheet containing a variety of information about the fault, e.g. length, sense of movement, geomorphic expression, age of faulted deposits, slip rate, and references.

SUMMARY AND CONCLUSIONS

Former Colorado State Geologist, Vicki Cowart, succinctly summed up our current state of knowledge about the earthquake hazard in Colorado, "We know enough, to *know*, that we *need* to know, a *lot* more."

The Colorado Earthquake Hazard Mitigation Council composed of seismologists; geologists; geotechnical, structural, and civil engineers; emergency managers; federal, state, and academic scientists; and insurance industry representatives issued the following consensus statement in 1999:

> "Based on the historical earthquake record and geologic studies in Colorado, an event of magnitude 6½ to 7¼ could occur somewhere in the state. Scientists are unable to accurately predict when the next major earthquake will occur in Colorado, only that one will occur. The major factor preventing the precise identification of the time or location of the next damaging earthquake is the limited knowledge of potentially active faults. Given Colorado's continuing active economic growth and the accompanying expansion of population and infrastructure, it is prudent to continue the study and analysis of earthquake hazards. Existing knowledge should be used to incorporate appropriate levels of seismic safety in building codes and practices. The continued and expanded use of seismic safety provisions in critical and vulnerable structures and in emergency planning statewide is also recommended. Concurrently, we should expand earthquake monitoring, geological and geophysical research, and mitigation planning."

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REFERENCES

Blackwell, D.D. and J.L. Steele, Geothermal Map of North America: Decade of North American Geology (DNAG), Geological Society of America, Boulder, CO

Bollinger, G.A., 1994, Reevaluation of the epicenter and magnitude for the 1882 Colorado earthquake: Appendix C *in* Risk Engineering, Inc.; Seismic hazard analysis for Rocky Flats Plant: unpublished report prepared for EG&G Rocky Flats, Inc., Golden, Colorado.

Bonkoski, M., Carsten, J., Hansuld, B., Hochnadel, J., and Ryman, D., 2000, Seismic restraint of mechanical and electrical systems: Unpublished Report, Colorado School of Mines EPICS Team Report.

Braddock, W.A., and Cole, J.C., 1990, Geologic map of Rocky Mountain National Park and vicinity,Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1973.

Charlie, W.A., Battalora, R.J., Siller, T.J., and Doehring, D.O., 2002, Magnitude recurrence relations for Colorado earthquakes, Earthquake Spectra, v. 18, p. 233-250.

Crone, A.J., Machette, M.N., Bradley, L.A., and Mahan, S.A., 1997, Late Quaternary surface faulting on the Cheraw fault, southeastern Colorado: U.S. Geological Survey Geological Investigations Map I-2591.

Curtis, B.F., 1975, ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, 279 p.

Dueker, K.G, H. Yuan, and B. Zurek, 2001, Thick-Structured Proterozoic Lithosphere of the Rocky Mountain Region, GSA Today, December, pp 4-10

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheller, R.L., Leyendecker, E.V., Wesson, R. L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: USGS Open File Report 02-420.

Geismann, J.W., L.W. Snee, G.W. Graaskamp, R.B. Carten, and E.P. Geraghty, 1992, Deformation and age of the Red Mountain intrusive system (Urad-Henderson molybdenum deposits), Colorado: Evidence from paleomagnetic and 40AR/39Ar data: Geological Society of America Bulletin, v. 104, p. 1031-1047.

George, D.F., 2000, Colorado's hot springs: Pruett Publishing Company, Boulder, CO, 165 p.

Giegengack, R.F., Jr., 1962, Recent volcanism near Dotsero, Colorado: Boulder, Colorado, University of Colorado, unpublished MS thesis, 69 p.

Godchaux, J.D., 2000, A microseismic survey of the northern Colorado Front Range: San Antonio, Texas, Trinity University, Honors Thesis, 27 p.

Hamilton, W.B., 1989, Crustal geologic processes of the United States, *in* Pakiser, L.C., and Mooney, W.D., Geophysical framework of the continental United states: Boulder, Colorado, Geological Society of America Memoir 172

Jackson, R., 2001, Seismic Risk Hazards Analysis and the IBC 2000 for Denver and the Front Range: Unpublished Report, 13 p, 7 Appendices.

Kirkham, R.M., and Rogers, W.P., 2000, Colorado Earthquake Information, 1867-1996: Colorado Geological Survey Bulletin 52, CD-ROM.

Kirkham, R.M., and Rogers, W.P., 1986, An interpretation of the November 7, 1882 earthquake, in Rogers, W.P. and Kirkham, R.M., eds., Contributions to Colorado tectonics and seismicity - A 1986 update: Colorado Geological Survey Special Publication 28, p. 122-144.

Kirkham, R.M., and Rogers, W.P., 1981, Earthquake potential in Colorado: Colorado Geological Survey Bulletin 43, 171 p.

Lerner-Lam, A.L., Sheehan, A.F, Grand, S., Humphreys, E., Dueker, K., Hessler, E., Guo, H., Lee, D., and Savage, M., 1998, Deep structure beneath the Southern Rocky Mountains from the Rocky Mountain Front Broadband Seismic Experiment: Rocky Mountain Geology, v. 33, no. 2, p. 199-216.

Limbach, F.W., 1975, The geology of the Buena Vista area, Chaffee County, Colorado: Golden, Colorado, Colorado School of Mines, M.S. thesis T-1692, 98 p.

Lindsey, D.A., Andriessen, P.A.M., and Wardlaw, B.R., 1986, Heating, cooling, and uplift during Tertiary time, northern Sangre de Cristo Range, Colorado: Geological Society of America Bulletin, v. 97, no. 9, p. 1133-1143.

Matthews, V., 2002, We don't have earthquakes in Colorado, do we?: RockTalk, Colorado Geological Survey, v. 5, no. 2, 12 p.

Matthews, V. and Morgan, M.L., in preparation, Trinidad earthquake swarm of 2010: Colorado Geological Survey Open File Report.

McCalpin, J.P., 1982, Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, south-central Colorado: Colorado School of Mines Quarterly, v. 77, no. 3, 97 p.

Meremonte, Mark E., John C. Lahr, Arthur D. Frankel, James W. Dewey, Anthony J. Crone, Dee E. Overturf, David L. Carver, W. Thomas Bice, and Nancy C. Dickman, 2002, Investigation of an earthquake swarm near Trinidad, Colorado, August-October, 2001: USGS Open File Report 02-0073.

Morgan, M.L., 2003, Published faults of the Colorado Front Range: Colorado Geological Survey Open-file Report 03-04.

Naeser, C.W., B. Bryant, M.J. Kunk, K. Kellogg, R.A. Donelick, and W.J. Perry, 2002, Tertiary cooling and tectonic history of the White River uplift, Gore range, and western Front range, central Colorado: evidence from fission-track and 39Ar/40Ar ages: *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W. eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Boulder, Colorado, Geological society of America Special Paper 366, p.31-53.

Ostenaa, D.A., Losh, S.L., and Nelson, A.R., 1981, Evidence for recurrent late Quaternary faulting, Sawatch fault, upper Arkansas Valley, Colorado, 'in' Junge, W.R., ed., Colorado tectonics, seismicity and earthquake hazards: Proceedings and field trip guide: Colorado Geological Survey Special Publication 19, p. 27-29.

Scott, G.R., 1970, Quaternary faulting and potential earthquakes in east-central Colorado, in Geological Survey research 1970, chapter C: U.S. Geological Survey Professional Paper 700-C, p. C11-C18.

Sheehan, A.F., 2000, Microearthquake study of the Colorado Front Range, combining research and teaching in seismology: Seismological Research Letters, v. 71, no. 2, p. 175-179.

Spence W., Langer, C.J., and Choy, G.L., 1996, Rare, large earthquakes at the Laramide deformation front-Colorado (1882) and Wyoming (1984): Seismological Society of America Bulletin, v. 86, no. 6, p. 1804-1819.

Steven, T.A., 2002, Late Cenozoic tectonic and geomorphic framework surrounding the evaporite dissolution area in west-central Colorado, *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W. eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Boulder, Colorado, Geological society of America Special Paper 366, p.15-30.

Stover, C.W., and Coffman, J.L., 1993, Seismicity of the United States, 1568-1989 (revised): U.S. Geological Survey Professional Paper 1527, 418 p.

Tweto, Ogden, 1979b, Geologic map of Colorado: U.S. Geological Survey Special Map

Wallace, S.R., N.K. Muncaster, D.C. Jonson, W.B. Mackenzie, A.A. Bookstrom, and V.E. Surface, 1968, Multiple intrusion and mineralization at Climax, Colorado: *in* Ridge, ed., Ore Deposits of the United States, 1933-1967, American Institute of mining. Metallurgical, and Petroleum Engineers, New York, v. 1, 991 p.

Widmann, B. L., Kirkham, R. M., Morgan, M. L., and Rogers, W. P., *with contributions by* Crone, A. J., Personius, S. F., and Kelson, K. I., *and GIS and Web design by* Morgan, K. S., Pattyn, G. R., and Phillips, R. C., 2002, Colorado Late Cenozoic Fault and Fold Database and Internet Map Server: Colorado Geological Survey Information Series 60a, http://geosurvey.state.co.us/pubs/ceno/.

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- Report 98-8, 331 p.