THE STATE OF COLORADO FIVE-YEAR EARTHQUAKE AND RELATED HAZARDS PLAN

State of Colorado
Division of Local Government

Tommy Grier, Director
Bryan Sage, Earthquake Project Manager
15075 South Golden Road
Golden, Colorado 80401-3979
TEL: (303) 273-1622
FAX: (303) 273-1795

EXECUTIVE SUMMARY

The state of Colorado's residential and business communities are growing at a rapid pace. In some cases, this population growth is taking place without thorough consideration of the risks associated with natural hazards. For example, earthquake hazards vary throughout the state, depending on the closeness of residents and businesses to active faults, the types of soil structures are built on, the potential for ground failure in a particular areas, and the age and design of each structure.

The purpose of this plan is to formulate a comprehensive strategy, to be implemented over the next five years, to help minimize the impact of earthquakes on the residents and visitors of Colorado. The five-year plan lays out the particulars leading to a more thorough assessment of the earthquake hazards that exist in Colorado and the possible effects of these hazards; it addresses the educational and training needs necessary to help prepare the people of Colorado for future earthquakes and the secondary hazards associated with quakes; and it identifies risk reduction measures that need to be accomplished to help mitigate the threat.

The information for this paper was obtained from several sources. Numerous interviews and discussions were held with professionals from local colleges and universities, consultants, and officials from local, state and federal organizations. Documents from the United States Geological Survey, the Colorado Geological Survey, the National Earthquake Information Center, the Federal Emergency Management Agency, and the states of Utah and California were consulted and used in preparing the plan.

Earthquake disasters, whether small or large, can be devastating. It is common for lives to be lost, property to be damaged or destroyed, and the normal routine of individuals, businesses and institutions disrupted for lengthy periods of time. The state however, is not entirely at the mercy of this hazard. Much of what needs to be done to lessen earthquake hazards and to manage earthquake risk is presently understood and simply needs to be put into effect. The citizens of Colorado can reduce earthquake damage by working together to implement cost-effective actions that save lives, prevent injuries, protect property and reduce economic and social chaos.

We cannot predict when or where the next earthquake will take place, nor can we control the magnitude of the event. But, if the majority of the goals programmed for accomplishment in this plan are achieved, the state of Colorado will significantly reduce the damage and disruption that result from the hazard. The section of this report titled, "The Five Year Plan" summarizes last year's accomplishments and the earthquake and related hazards goals for the next five years.

TABLE OF CONTENTS

EXECUTIVE SUMMARY ii

I. EARTHQUAKE PHENOMENON and MITIGATION TECHNIQUES 1
- A. Phenomenology 1
- B. Mitigation 2

II. THE EARTHQUAKE THREAT IN COLORADO 3
- A. The Geologic Record for the State 5
- B. Colorado Earthquakes Induced by Human Activity 6
- C. Colorado Population and Facilities at Risk 7
- D. Additional Hazards Resulting from Earthquakes 8

III. THE FEDERAL AND STATE PARTNERSHIP 9
- A. The National Earthquake Program 9
- B. The National Earthquake Hazards Reduction Program 10
- C. The Colorado Earthquake Project 10

IV. THE FIVE-YEAR PLAN 11
- A. Last Year's Accomplishments 11
  1. Assess Earthquake Risk 11
  2. Increase Earthquake Awareness 13
  3. Enhance Seismic Safety 14
- B. Future Earthquake Goals 16
  1. Assess Earthquake Risk 16
  2. Increase Earthquake Awareness 17
  3. Enhance Seismic Safety 18

V. CONCLUSION 20

VI. BIBLIOGRAPHY 21

APPENDICES
- A. Magnitude and Intensity Scales 23
- B. Maximum Historical Earthquake Intensities in Colorado 24
- C. Seismotectonic Provinces in Colorado 25
- D. Seismology Glossary of Terms 26
- E. Earthquake History of Colorado 30
- F. Colorado Earthquake Information 34

ILLUSTRATIONS
- Figure 1. Seismic Waves Generated by Fault Rupture 1
- Figure 2. Seismicity of Colorado and Surrounding Areas 3
- Figure 3. Magnitude of Selected Earthquakes 4
- Figure 4. Significant Colorado Earthquakes 5
- Figure 5. Earthquakes at the Rocky Mountain Arsenal 7

I. EARTHQUAKE PHENOMENON and MITIGATION TECHNIQUES

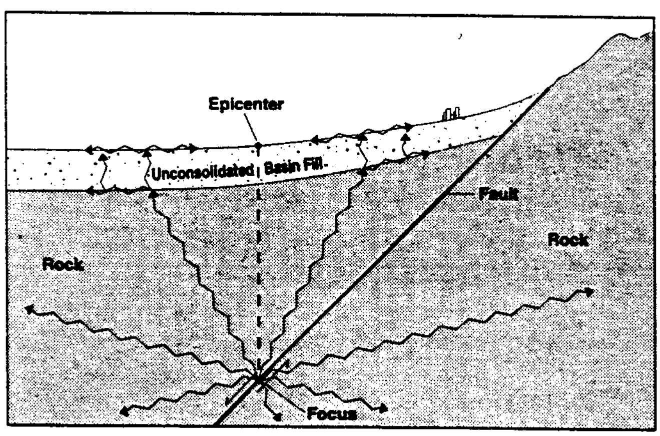
The purpose of this plan is to reduce the risk of loss of life and property to earthquakes. In order to do that the citizens of Colorado must understand the threat in realistic terms and know the reasonable mitigation techniques that might be applicable. This plan lays out a framework for accomplishing those two objectives. But first, the public must understand the nature of earthquakes.

A. Phenomenology

Geologists believe the earth's surface is made up of dozens of large plates, most of which cover millions of square miles and each of which is several miles thick. These plates are in continual motion and this sliding motion is neither smooth nor constant. A fault is a thin zone of crushed rock between the large plates and can be any length, from a few inches to thousands of feet. The movement of the plates deforms or strains the rocks along the plate boundaries until the rocks can no longer withstand the strain. The result is an earthquake; a rapid slip along the fault. The fault surface can be horizontal, vertical, or at some angle to the surface of the earth. The slip direction can also be at any angle.

The slip of one plate over another releases energy that causes the ground to vibrate. In turn, this vibration pushes adjoining ground areas causing additional vibration in the adjoining areas. The energy from this action is released in all directions and travels in waves. Figure 1 depicts the generation of seismic waves by fault rupture.. In the figure the focus or hypocenter is the location on the fault where the rupture begins. The point on the surface directly above the focus is the epicenter.

Figure 1: Seismic Waves Generated by Fault Rupture



(From "A Strategic Plan for Earthquake Safety in Utah")

The energy released from an earthquake can cause ground shaking, surface fault rupture, or liquefaction. Liquefaction is defined as the temporary transformation of sandy water-saturated soils from a solid to a liquid state due to the earthquake shaking. The energy released during the earthquake can also cause regional subsidence, landslides, rock falls, snow avalanches and various types of flooding.

B. Mitigation

Many of our Colorado residents are unaware of the variety of secondary hazards associated with earthquakes that can pose a significant threat to life and property. One reason for this lack of knowledge is that disastrous earthquakes occur relatively infrequently in Colorado; therefore, the hazards tend to be downplayed. Another reason is that citizens have a tendency to only plan for the immediate future, overestimate their ability to manage a disaster when it does strike and then expect State or local emergency relief organizations to come to their rescue. In addition, many citizens feel the destruction caused by earthquakes is unavoidable. This belief of course is not true. Earthquake damage can be significantly reduced through proper planning and preparation. Many citizens also believe that the majority of the damage during an earthquake comes from collapsing structures. Again, this is not true, especially here in Colorado. Nonstructural damage will often equal or exceed structural damage.

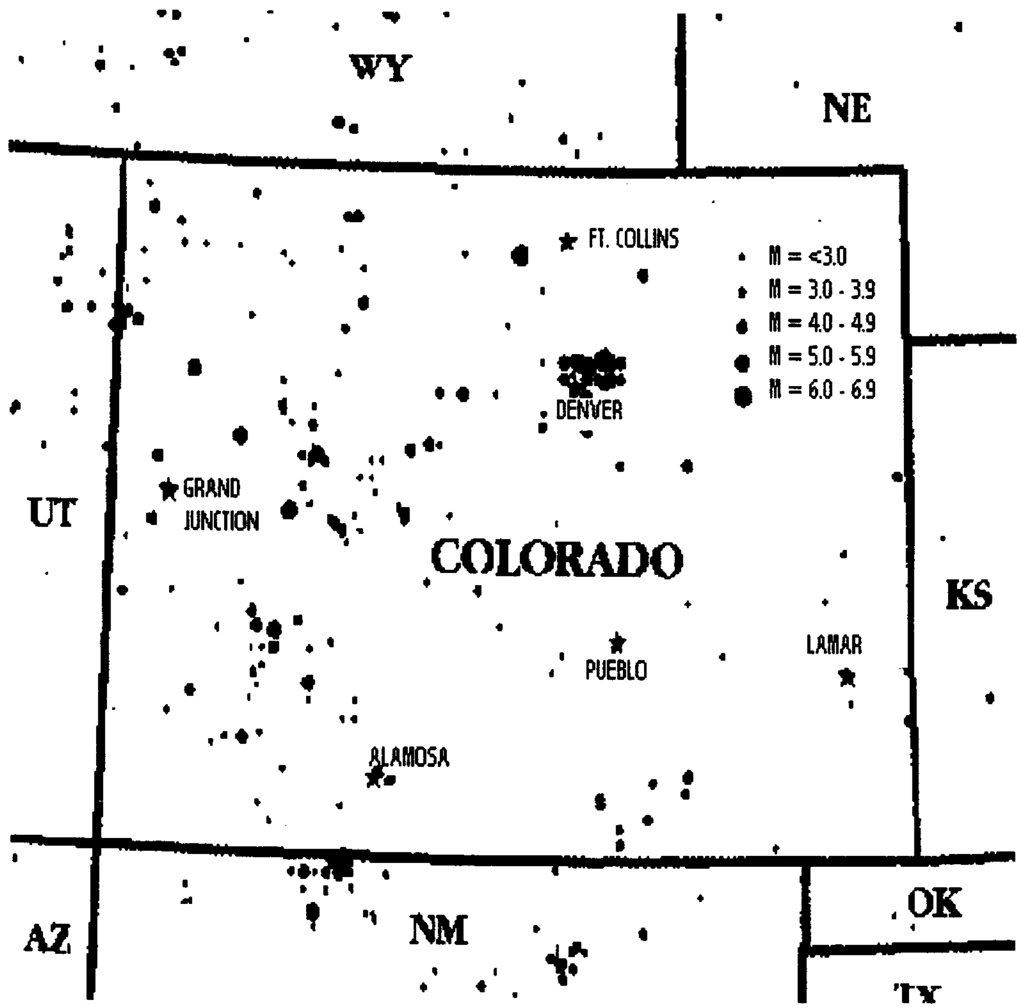
State and federal governments play a key role in educating local officials and citizens to insure they are aware of the dangers associated with seismic events and that they develop comprehensive plans to mitigate disaster losses. Citizens need to know where to go and what to do when the ground starts shaking. They need to be aware of and avoid constructing homes and businesses in hazardous areas. They need to understand the urgency to retrofit unsafe buildings and why improved building codes are necessary. In summary, citizens need to know they can take action to make their homes, schools, and work places safer in the event of an earthquake.

To better educate residents to earthquake hazards and to reduce the State's risk from earthquake, Colorado joined the Federal earthquake program and developed a five-year earthquake mitigation plan. This paper updates the original earthquake plan and the follow-on plans formulated by members of the Colorado Earthquake Project and the Colorado Office of Emergency Management.

II. THE EARTHQUAKE THREAT IN COLORADO

Colorado has a significant earthquake history. Hundreds of earthquakes have occurred since 1800. From 1980 to 1994, Colorado experienced 109 earthquake events with the largest recording a magnitude of 4.6. Figure 2 depicts the location of the majority of the quakes that have taken place from 1900 to 1993, as well as earthquakes that have taken place in adjoining states. Please refer to Appendix E for a more detailed discussion of the history of earthquakes in Colorado; and to Appendix D for a glossary of some common terms in seismology.

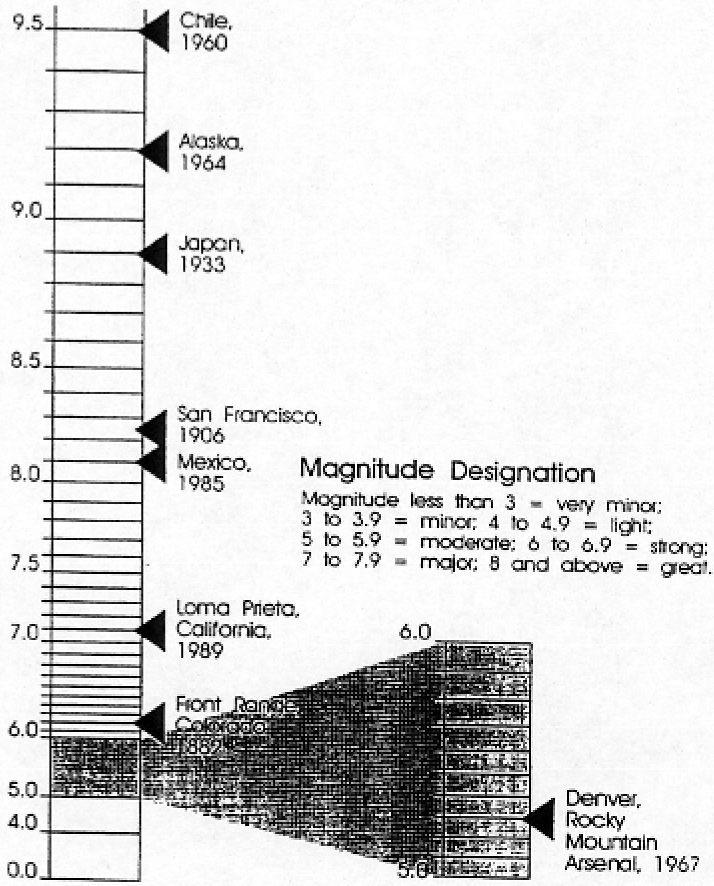
Figure 2: Seismicity of COLORADO and Surrounding Areas--1900-1993



(Prepared by the U.S. Geological Survey National Earthquake Information Center)

The strongest earthquakes centered in Colorado have been in the magnitude 5.5 to 6.5 range. Please refer to Appendix A for an explanation of earthquake magnitude and intensity. Other strong tremors have occurred in surrounding states and their effects have sometimes been felt within Colorado. The largest known earthquake in Colorado occurred on November 7, 1882. The magnitude for this event has been estimated at about 6.5. It caused damage on the eastern and western slopes and was felt throughout most of the state. Figure 3 compares the magnitude of Colorado's two largest earthquakes to some of the more notable earthquakes that have occurred worldwide.

Figure 3: Earthquake Comparison



(Prepared by the U.S. Geological Survey National Earthquake Information Center)

One of the more recent damaging earthquakes occurred along Colorado's Front Range in 1967. On August 9, I967, a 5.3 magnitude earthquake caused approximately one million dollars of damage in the north Denver suburbs. Three months later, on November 27, I967 a magnitude 5.2 Front Range earthquake caused minor damage. Minor damage also occurred in April, I982, when a tremor which registered 4.5 on the Richter Scale again impacted the Denver area. The earthquake was felt in Denver office buildings and slight damage occurred in Commerce City and Thornton. Figure 4 summarizes the date, place and magnitude of other significant earthquakes in Colorado.

Figure 4. Significant Colorado Earthquakes

DATE	LOCATION	MAGNITUDE	INTENSITY
1870, Dec. 04	Pueblo - Ft. Reynolds	(unknown)	VI
1880, Sep. 17	Aspen	(unknown)	VI
1882, Nov. 07	North-central Colorado	6.5*	VII
1891, Dec.	Maybell	(unknown)	VI
1901, Nov. 15	Buena Vista	(unknown)	VI
1944, Sep. 09	Montrose-Basalt	(unknown)	VI
1955, Feb. 10	Steamboat Springs	(unknown)	VI
1955, Aug. 03	Lake City	(unknown)	VI
1966, Jan. 04	Northeast of Denver	5.0	V
1966, Jan. 23	Southern Colorado Border (Dulce, NM)	5.5	VII
1967, Aug. 09	Northeast of Denver	5.3	VII
1967, Nov. 27	Northeast of Denver	5.2	VI

* = Magnitude estimated for older earthquakes; based on historical felt reports.

In the past few decades, scientists have learned more about the location and size of Colorado earthquakes. Geological and geophysical investigations have successfully identified potentially active faults that are considered capable of generating future damaging earthquakes. Many of these faults are visible on the land surface. Other faults however, are hidden under rock and soil. Networks of seismic instruments set up in different areas of the state have recorded earthquakes indicating additional seismic source zones. These investigations suggest parts of Colorado are low to moderately active earthquake areas with potential for significant earthquakes capable of causing deaths and extensive damage to buildings, roads and utilities.

A. The Geologic Record for the State

Geologic records of the past several million years suggest Colorado has recently experienced earthquakes of up to magnitude 6.5 to 7.5, yet only a few moderate sized earthquakes have occurred in the state in the last 130 years, despite this geologic record. Please refer to Appendix B for the zoning of maximum historical earthquake intensities in Colorado.

Recurrence intervals for major earthquakes on these faults may be hundreds, thousands, or even tens of thousands of years. It's difficult to determine just when the next big earthquake could occur, or how large it will be; however, some seismologists estimate the maximum credible earthquakes that could occur in different areas of the state range from 5.5 to 7.5 magnitude (Kirkham and Rodgers, 1981). These estimates were selected after studying both the earthquake and geologic history of active faults. Please refer to

Appendix C for the Seismotectonic Provinces in Colorado and the approximate maximum credible earthquakes that could take place.
More than 90 potentially active faults have been identified within Colorado's complex geologic structures. A number of potentially active faults in Colorado have moved during the Quaternary Period and several show evidence of Holocene activity, indicating they were active within the last 10,000 years. Of special concern are faults associated with the Rio Grande Rift, a major intra-continental rift that begins in the central mountains near Leadville and runs south into New Mexico and down through west Texas.

A specific area of concern is the Front Range Region. The Front Range, from Fort Collins to Pueblo, contains millions of people, major transportation systems, businesses, hospitals, and numerous major emergency response groups. The lives and property at risk are extremely great in this area. Although more research in needed, studies show that this area can sustain a maximum credible earthquake of up to 6.75 in magnitude (Kirkham and Rodgers, 1981). There is a great need for additional research and increased preparedness in this region as well as the Rio Grande Rift Zone.

Currently, several agencies devote a great deal of time to studying the seismic conditions in Colorado. Some of the agencies conducting these studies are the Colorado Geological Survey, (CGS) the United States Geological Survey, (USGS) the National Earthquake Information Center, (NEIC) the National Oceanic and Atmospheric Administration, (NOAA) the Colorado Office of Emergency Management, (OEM) the U. S. Bureau of Reclamation, and the Denver Water Department.

B. Colorado Earthquakes Induced by Human Activity

Colorado is one of a few places in the world where earthquakes may have been generated or triggered by human activity. One cause of this induced seismicity involves experimental nuclear explosions to stimulate natural gas recovery from low permeability sandstone reservoirs. Three such explosions were detonated in Colorado in the late 1960s and the early 1970s. For various reasons, the method proved too costly for widespread usage and the testing was terminated.

Another possible case of induced seismicity occurred in the l960s northeast of Denver. In l961, the U. S. Department of the Army used a deep injection well at the Rocky Mountain Arsenal, (RMA) to dispose of hazardous materials. Seismologists suspect this high pressure injection lubricated a fault, causing its slippage and rupture since a series of earthquakes initiated shortly thereafter. Figure 5 compares the earthquake frequency in the area to the monthly volume of material injected into the wells.

Figure 5: Earthquakes at the Rocky Mountain Arsènal

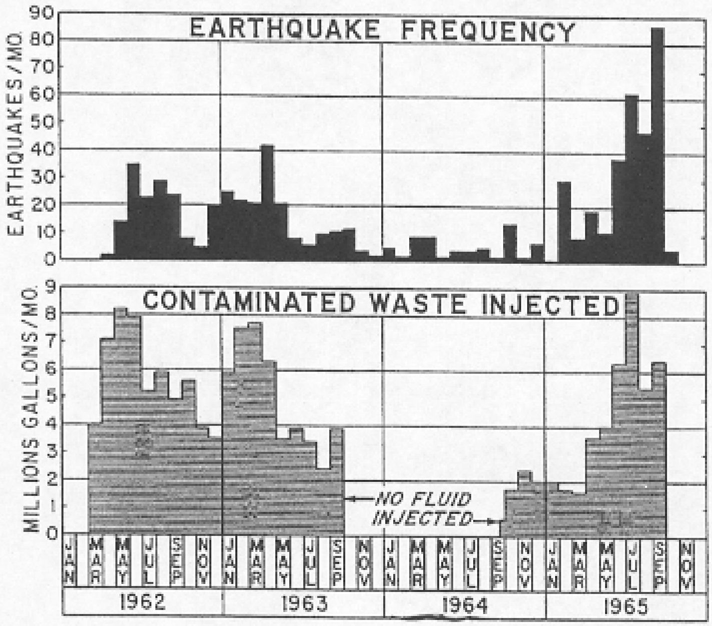


Chart showing the number of earthquakes per month recorded in the northeast Denver area (upper chart) and the monthly volume of injected liquid waste at the Rocky Mountain Arsenal well. (From Kirkham and Rogers, 1981)

The largest of the earthquakes, the August 9, l967, magnitude 5.3 and the November 27, l967, magnitude 5.2 earthquakes, occurred about l8 months after injection stopped. Smaller earthquakes continue to occur. The relationship between the fluid injection and the earthquakes was never conclusively verified; however, as stated previously, the two events in l967 caused more than one million dollars of damage in Denver and its northern suburbs.

C. Colorado Population and Facilities at Risk

Colorado's nearly four million residents, numerous businesses, and many private and public agencies are at risk to earthquakes and the secondary hazards often associated with the event. In addition to the permanent residents, approximately five million tourists annually visit the state. At present, the majority of Colorado's population lives along the Front Range. This dense population generates infrastructure needs and vulnerabilities.

The once rural or less populated areas are booming also, sometimes faster than local areas and state officials can plan and prepare for the new growth. For example, the population of Colorado is growing rapidly on the western slope and in southern Colorado. These municipalities are also becoming increasingly vulnerable to the earthquake hazards that threaten their quality of life. Prudent measures must be taken to lower the threat.

III. THE FEDERAL AND STATE PARTNERSHIP

The United States is becoming more complex and vulnerable to hazards with each passing year. Linkage of businesses worldwide, air travel, telecommunications, computers, environmental concerns, diminishing resources, and numerous other conditions and activities dramatically influence the citizen's quality of life. As such, the economic and societal costs associated with natural disasters are increasing. The nation as a whole must have a well coordinated, timely, and cost-effective means to help reduce the loss of life, minimize property damage, and reduce disaster costs. To better accomplish the above, the United States implemented, approximately twenty years ago, a hazardous mitigation program with national leadership.

In reviewing the accomplishments of the program, the federal government concluded that although the original program was successful in many respects, it lacked strategic planning capabilities as well as effective coordination between state and federal agencies.

A. The National Earthquake Program, (NEP)

In l996, the Federal Emergency Management Agency, (FEMA) was designated by the White House Chief Science Advisor as the lead agency responsible for directing and coordinating the newly established National Earthquake loss reduction Program, (NEP). The NEP is an interagency organization formed to ensure that federal earthquake mitigation research is focused on national priority goals; that duplication among the various local, state, and federal agencies is avoided; and that meaningful coordination with state and local governments, as well as the private sector is accomplished. These actions will ensure the use of effective mitigation strategies for all concerned. The goals of NEP are to:

provide leadership and coordination for federal earthquake research;

- improve technology transfer and outreach;
- improve engineering of the built environment;
- improve data for construction standards and goals;
- continue the development of seismic hazards and risk assessment tools;
- analyze seismic hazard mitigation techniques;
- develop understanding of the societal impacts and responses related to earthquake hazard mitigation;
- analyze the medical and public health consequences of earthquakes; and
- continue documentation of earthquakes and their effects.

B. The National Earthquake Hazards Reduction Program, (NEHRP)

The National Earthquake Hazards Reduction Program was established by Congress in 1977. The agencies responsible for managing the Program are the Federal Emergency Management Agency, the United States Geological Survey, the National Science Foundation, and the National Institute of Standards and Technology. NEHRP was formed to reduce the risks to life and property from earthquakes through the formation of an effective national earthquake risk reduction program. Over the years, the organization's activities have been directed toward research and development, preparedness and response, mitigation, and information dissemination and public education.

The organization has been extremely successful in conducting research into earthquake hazards and in reducing earthquake loss. However, in other areas of endeavor, for example, strategic planning and the adoption of earthquake resistant building codes by state and local governments, the NEHRP has not kept pace with federal expectations. Thus, the federal government decided to strengthen and expand NEHRP with the formation of NEP. The two organizations, mutually supporting each other, will continue to work with state and local governments and foreign countries in obtaining and exchanging information and developing effective mitigation, preparedness, and response programs.

C. The Colorado Earthquake Project, (CEP)

The Colorado Earthquake Project was established in 1991 when Colorado joined the National Earthquake Hazards Reduction Program as a low to moderate risk state. The purpose in forming the CEP was to formulate a plan to reduce loss of life and to decrease economic losses resulting from future earthquakes and the secondary hazards associated with the quakes. Authorization and funding for program development is a joint effort between the Federal Emergency Management Agency and the Colorado Office of Emergency Management. The program's leadership emanates from the Office of Emergency Management and the focus of this leadership over the past six years has been on education, mitigation and resource assistance to residents and visitors of the state of Colorado. More specifically, the CEP:

- educates and trains state and local government personnel as well as interested citizens on programs which fall into the emergency management system's four phases of a disaster; these phases being mitigation, preparedness, response and recovery;
- encourages and supports structural and nonstructural mitigation projects; and
- assists with the coordination of public and private projects that help to enhance the seismic safety of the state.

IV. THE FIVE YEAR PLAN

The current Five-y ear Plan covers the period from Federal Fiscal year 1998 through Federal Fiscal Year 2002. This follow-on plan replaces the current plan, covers FFY 99 through FFY 03, and summarizes the accomplishments during FFY 98 and the first part of FFY 99. The focus of the updated plan remains unchanged; this being the establishment of a proactive program that will enable individuals, both tourists and citizens of Colorado, to live, work and recreate in an atmosphere of personal safety and social stability.

A. LAST YEAR'S ACCOMPLISHMENTS

The objectives of the Five-year Plan are to assess the earthquake risk that exists in Colorado, to communicate this threat to the general public, and to improve the seismic safety of our built environment through sound, cost affordable mitigation measures. The following addresses the progress made this past year in accomplishing these objectives.

1. Assess Earthquake Risk

The Colorado School of Mines (CSM), in conjunction with the Earthquake Subcommittee of the Colorado Natural Hazards Mitigation Council (ES-CNHMC), and the Colorado Office of Emergency Management (COEM), continue to participate in the Princeton Earth Physics Project (PEPP). The first goal of PEPP is to establish a nationwide network of low-cost, high technology seismometer stations in high schools throughout the country. A second goal is to establish communications pathways for these high schools for sharing data for access to earthquake databases and for sharing of curriculum developments. A third goal is to provide for teachers and students an authentic research environment in which hands-on learning is encouraged. And the final goal is to stimulate interaction of teachers in earth science and physics with research scientists, (PEPP, 1996). Although sixteen Colorado high schools were originally selected to participate in the program, only five have received seismometers. These high schools are Durango, Frisco, Springfield, Westminster, and Fort Collins. Seismometer production challenges as well as operation and maintenance challenges have hampered the delivery of the remaining instruments. The five Colorado high schools presently in receipt and operating the instruments feel they are privileged to be part of a superb educational program. Seismograms for regional and teleseismic events can be accessed at the PEPP web site: http://lasker.princeton.edu/pepp.shtml. Seismograms for local earthquakes recorded by the instruments installed during this project can be viewed at Doctor Tom Boyd's web site: http://www.mines.edu/fs_home/tboyd/CoPEPP.

ES-CNHMC and the Colorado Geological Survey (CGS), with help from COEM established an Earthquake Reference Collection that contains governmental and professional society publications documenting Colorado seismicity. In addition, many hard-to-find unpublished seismotectonic reports and maps have been added to the library that are relevant to Colorado. These documents were researched by consultants or by students for their theses or dissertation. Each month, new documents are being received, cataloged, and added to the library. The Reference Collection is housed at the CGS offices at 1313 Sherman Street, Room 715, Denver, Colorado, and is available for use by the general public during normal working hours.

A publication on historical Colorado earthquakes has been compiled by CGS, and is titled, "Colorado Earthquake Data Interpretations." This publication documents over 500 earthquakes that have been felt in Colorado since 1867. The report contains a table that lists pertinent data on these earthquakes, isoseismal and intensity maps for the larger earthquakes, a description of each earthquake, and references for the earthquakes. The information in the publication is in the process of being published as a CD-ROM and will be available to the general public in the near future.

A database on Quaternary Faults in Colorado has been compiled by CGS. The project was, in part, funded by NEHRP through the U.S. Geological Survey and will be incorporated into the nationwide database on Quaternary Faults currently being developed by USGS. The database on Quaternary Faults will eventually be merged with another database on late Cenozoic Faults in Colorado and should be available to the general public sometime in late 1999.

COEM continues to support the state of Colorado's goal to develop, through public processes, a modern fixed guideway transit system to service the mountain communities of Colorado along the I-70 Corridor from Denver International Airport to Glenwood Springs. COEM, through the cooperative agreement it has with CSM, sponsored three studies this past year. These studies addressed various construction alternatives for the project as well as assessing the geology and geologic hazards that exist in the mountain corridor.

CGS and ES-CNHMC members are working with the Western States Seismic Policy Council (WSSPC) on a Western States technical/scientific response team for post earthquake evaluations. The mission of WSSPC is to provide a forum to advance earthquake hazard reduction programs throughout the Western Region of the United States and to develop, recommend and present seismic policies and programs through information exchange, research and education.

COEM, with help from CGS, is updating the "Earthquake and Related Hazards in Colorado" map that was originally published in 1993. The new map is being developed with the computer mapping capabilities of the Geographic Information Systems at COEM. The new map shows locations of earthquakes recorded on seismic instruments and earthquakes felt in Colorado from 1867 to 1996. The map also presents seismic related hazards such as faults and folds that are suspected to have moved within the Quaternary Period, or the past 1.6 million years. Colorado's rugged landscape, displayed with computer terrain modeling as a shaded relief image, is shown to illustrate the relationship between earthquakes, faulting, and topography. Potentially vulnerable infrastructure and population is represented on the map by the high and moderate hazard-class dam locations, transportation corridors, and urbanized areas shown by municipal boundaries. The map should be available to the general public in the last quarter of Calendar Year 1999.

2. Increase Earthquake Awareness

At the September 28-30, 1998 Colorado Governor's Conference on Emergency Management held in Breckenridge, Colorado, several members of ES-CNHMC hosted two, one-hour breakout sessions for the attendees of the conference. The sessions were titled "Colorado Earthquake Projects --- Recent and Future". The sessions were well attended and the audience learned about the PEPP project, the numerous studies being conducted by CGS, the establishment of the Earthquake Reference Collection, the cooperative agreement between COEM and CSM, the projects being reviewed by ES-CNHMC, and other earthquake related issues pertinent to Colorado.

ES-CNHMC prepared a three-page fact sheet that addresses earthquake information for Colorado. The document will be used when ES-CNHMC members discuss Colorado earthquake information with the public and the press. The paper identifies Colorado as a State comprised of areas with low to moderate potential for damaging earthquakes. It also notes that geological studies in Colorado indicate that there are about 90 faults that moved during the Quaternary Period (the past 1.6 million years), and that these faults should be considered potentially active. And finally, the paper summarizes past earthquakes recorded in Colorado as well as possible future earthquakes. A copy of this information sheet can be found at Appendix F.

COEM, with help from CGS, CSM, USGS, NEIC, and other agencies has spent several months planning and preparing for a Colorado "Earthquake Awareness Week" to be held in late August or early September 1999. One objective of this program is to insure that the citizens of Colorado are aware that the State has a low to moderate seismic risk, as opposed to a "zero hazard." A second objective is to insure that the public understands that the risk increases with increases in population, even if the level of hazard remains constant. A third objective is to educate citizens concerning County resources available after an earthquake. An earthquake brochure has being prepared, TV announcements will be aired, and newspaper articles will be published during the awareness week.

A student research team at CSM conducted an in-depth study for the town of Red Cliff, Colorado and the Colorado Department of Local Affairs. The project began as a site analysis for additional storage of water. It soon became evident that the real threat to the community was more of a water legal issue. The report researches the domestic water infrastructure; the geology and seismic conditions of the Red Cliff area; how Colorado water law could impact the town; discusses various courses of action that the town could take, and outlines a 30-year-plan of implementation that should preserve the town's water rights.

The city of Delta, Colorado and the Colorado Department of Local Affairs requested that a student research team from CSM conduct a study and render a technical report on how best to protect the cities' multi-million dollar wastewater treatment plant from flooding. The plant is built in a major flood plain and is inadequately protected from flood and geo-technical hazards, (liquefaction). The study concludes that new dikes must be constructed to adequate design specifications surrounding the plant. The report examines a wide range of options, none of which are totally adequate given the location of the plant. This problem needs further professional evaluation and perhaps State and Federal assistance.

The town of Palisade, Colorado and the Colorado Department of Local Affairs had a student research team from CSM do a study and prepare a technical report that analyzes the slope stability conditions, which caused the failure of a portion of the town's water supply collection system. The report describes options for relocating the water line outside of the failure area and recommends a solution.

The town of Frisco, Colorado and the Colorado Department of Local Affairs asked a student research team from CSM to analyze alternatives to alleviate the current transportation problems on Highway 9 between Frisco and Breckenridge. Because of Summit County's increasing popularity as a year round resort, the highway has become congested and dangerous. The students researched the geology and geologic hazards that currently exist along the corridor, the possibility of expanding the highway right-of-way, alternative transportation systems, and rendered a technical report that recommended the construction of a guideway system with terminals to alleviate the transportation problem.

A student team from CSM was asked by the Colorado Intermountain Fixed Guideway Authority to examine route hazards on two competing transportation routes along the I-70 Mountain Corridor from the Eagle County Airport in Gypsum, Colorado, to an area near Glenwood Springs, Colorado. This effort was part of an urgent analysis commissioned by the Colorado State Assembly. The overall study was of national significance, per language contained in Federal Transportation Bill, T-21. The research assisted both Eagle and Garfield counties and the report concludes that surface transportation should be restricted to Glenwood Canyon. The report also recommends that an elevated route, (elevated guideway) be built over Cottonwood Pass between the towns of Gypsum, Colorado and Carbondale, Colorado.

3. Enhance Seismic Safety

The Colorado Department of Local Affairs, acting on behalf of the Leroux Creek Water Users Association, requested that a student team from CSM conduct a comprehensive evaluation of the present condition of the Leroux Creek Reservoir System located south of Grand Junction, Colorado. The report addresses an existing dam failure, which drowned a herd of 40 sheep, and examines the condition of the 26 other dams in the Leroux Creek System. These structures exist in an earthquake and earth movement prone area. The report describes the nature of the dam failure, the susceptibility of the remaining structures, and recommends a 30-year plan for inspection and upgrade of the system, structure by structure.

COEM, in concert with the Colorado Engineer's Office, requested that a team of CSM students evaluate the Idaho Springs and Evergreen, Colorado reservoirs. The study finds that the Evergreen structure, although quite old and with high risk, has received considerable modifications and improvements over the years. The Idaho Springs structure needs some improvements. Recommendations for both sites include modifying and updating emergency action plans. Specific actions for the Evergreen dam include dredging along the upstream face of the dam to provide access and use of floodgates for emergency water releases. The Idaho Springs structure requires additional material and actions to reduce seepage and a renovation of the spillway.

A study conducted by the students at CSM assisted the State of Colorado in the design of the stanchions for the Colorado Intermountain Fixed Guideway Authority. The report finds that high winds, not earthquakes, are the dominant and controlling design criteria. The study also finds that rock-falls and avalanches are significant threats and the report provides preliminary design criteria to reduce impacts.

The El Paso County Department of Transportation and the El Paso Office of Emergency Management requested that a student team from CSM analyze the rock-fall hazards on U.S. Highway 24 from Colorado Springs, Colorado to Woodland Park, Colorado. This portion of the highway experiences numerous rock-falls and landslides. The report examines the physical and social aspects of the rock-fall problem. The report also includes an analysis and ranking of several hazardous sites along the highway with recommendations for site specific solutions. Finally, the study outlines a 15-year mitigation plan that addresses the majority of the problem areas that exist along the highway.

A CSM student team developed a site evaluation and a preliminary design for a new Continental Divide, (Loveland Pass) transportation tunnel in the general vicinity of the I-70 Corridor. The purpose of the project was to determine the best possible method to traverse the Divide should a fixed guideway transit system be built in the near future. The client for this project was the Corridor Alliance for a Rapid Transit Solution, (CARTS). CARTS is the grass roots group composed of and supported by all of the towns along the I-70 Corridor from Denver to Eagle, Colorado. The study provided a subsurface investigation and a preliminary tunnel design valued at approximately $250,000 by the CARTS Engineer.

A student team from CSM conducted a seismic safety analysis on two Colorado dams, Barker Reservoir and Aurora Rampart Reservoir for the dam owners and a Division Engineer for the Colorado Engineer's Office. Both dams were found to be in relatively good condition with regard to seismic hazards, providing reassurance to the State Engineer's Office.

ES-CNHMC requested that a CSM team review and evaluate the status of seismic building code adoption and operations within the state of Colorado's most earthquake prone counties. The process and interviews with County building officials reinforced awareness. It was found that even though some cities and counties have adopted seismic codes, enforcement is sporadic and in one case ignored.

B. FUTURE EARTHQUAKE GOALS

The following goals outline yearly targets for each of the three objective areas of the plan. In many instances, the goals are accomplished in one year. In other instances, the goals are targeted for accomplishment each year during the five year period. And finally, some goals have several sub-elements as part of the overall goal. As such, these goals may take two, three or four years to be completely accomplished.

1. Assess Earthquake Risk

Goals: Earthquake Risk	Implementation Year				
	99	00	01	02	03
Continue to work with PEPP to have all 16 Colorado high schools install, operate and maintain low-cost, high technology seismometer stations at their schools and to integrate these stations into the Project's nation-wide network. Explore the possibility of having appropriate Colorado officials review, over the Internet, the digital waveform data gathered by each school.	✓	✓	✓	✓	✓
Continue to work with ES-CNHMC and CGS to compile geological data pertaining to Quaternary Faults. Digitize and record the fault locations in a format compatible with USGS fault compilations. Publish the data, along with the updated information being compiled by CGS, on late Cenozoic Faults in Colorado.	✓	✓			
Continue to work with ES-CNHMC and CGS on the compiling of Colorado earthquake data and interpretations from 1867 to 1996. Publish the updated information. The bulletin containing this data will be a composite listing for larger events. Some interpretations and isoseismal maps will be included in the updated bulletin that will eventually be available in CD ROM format.	✓	✓			
Using the virtual office study completed by a CSM student team, establish a virtual office and a world wide web site for ES-CNHMC and the Colorado Earthquake Project.		✓	✓	✓	✓
Continue to support the State of Colorado's goal to develop, through public processes, a modern fixed guideway system to service the mountain communities of Colorado along the I-70 Corridor from Denver International Airport to Glenwood Springs.	✓	✓	✓	✓	✓
Continue to work with COEM and ES-CNHMC to update the Earthquake and Related Hazards in Colorado map, to include a listing of potentially active faults. Investigate the feasibility of adding the State highway systems bridges. Publish the revised information.	✓	✓			
Continue to work with ES-CNHMC and CGS to improve the earthquake and related hazards Reference Collection housed at CGS. Help in the collection of published and unpublished reports and maps that are relevant to Colorado seismicity. Compile a list of all documents on hand and make the list available to the general public, either through hard copy or the CGS web site.	✓	✓	✓	✓	✓
Work with ES-CNHMC to develop a handbook entitled "Hazards in Colorado," which will contain a county by county listing of geologic hazards and possible mitigation measures to reduce these risks.		✓	✓		

2. Increase Earthquake Awareness

Goals: Earthquake Awareness	Implementation Year				
	99	00	01	02	03
Build upon the "Hazards in the United States" study conducted by CSM students. Develop a way for representatives of State, regional and local government to learn how to use and understand the computer program. Update the program as revised editions become available. Assist emergency managers in revising their emergency preparedness, loss mitigation, and response and recovery plans based on the data generated by the HAZUS program for their geographical area of responsibility. For example, Saquache County, in the San Luis Valley, is extremely interested in having a CSM student team use HAZUS to estimate the loss and damage the county could expect in the event of a major earthquake.	✓	✓	✓	✓	✓
Continue to build and maintain relations with the media, the State Public Information Office, and other appropriate officials to ensure the public receives timely and factual information concerning natural disasters.	✓	✓	✓	✓	✓
Participate in earthquake training and conferences conducted by local, regional, and national agencies. Incorporate good ideas from these conferences into the Colorado earthquake program.	✓	✓	✓	✓	✓
When appropriate, implement the annual middle school poster award program Developed by a CSM student team, since this program is an excellent means for enhancing student and public awareness of geologic hazards in Colorado.		✓	✓	✓	✓
When funds become available, schedule appropriate personnel to attend the Applied Technology Council, ATC-21 course, designed for pre-disaster risk assessment of buildings. When implemented, the training should be directed toward professional engineers as well as senior and graduate engineering students. Eventually, expand this training to workshops.			✓	✓	✓
When funds become available, schedule appropriate personnel to attend the Applied Technology Council, ATC-20 course, designed for post-disaster safety evaluation of buildings. Eventually, expand this training to workshops.			✓	✓	✓
When funds become available, schedule personnel to train on the seismic and geological education curriculums sponsored by FEMA, titled "Tremor Troops" and "Seismic Sleuths."			✓	✓	✓
Work with ES-CNHMC to develop an information sheet regarding Colorado seismic hazards to use in communication with the general public and the media. Follow-on documents will be developed to provide individuals with accurate earthquake and safety information to follow prior to an event, as well as timely information to follow immediately after a natural disaster.			✓	✓	✓
Work with ES-CNHMC to develop and publish a newsletter designed to give the general public and local governments information relating to earthquakes and other geological hazards. Eventually, translate and publish the newsletter in Spanish as well as other appropriate languages.				✓	✓
Establish relations with local governments and professional groups to discuss earthquake information and related geologic hazards, as well as mitigation strategies for these hazards.	✓	✓	✓	✓	✓
Now that a CSM Student research team has developed a geologic hazards "Awareness Week" program for Colorado, implement a State-wide awareness week in conjunction with the U.S. Army Corps of Engineer's National Week and the State of California's Earthquake Preparedness	✓	✓	✓	✓	✓

Goals: Earthquake Awareness	Implementation Year				
	99	00	01	02	03
Month.					
Implement the earthquake public information program developed for COEM by a CSM student team. The program includes earthquake Safety pamphlets, earthquake fact sheets, media kits, and several other Items. The student team recommends that the program be fully adopted Over a five-year period.		✓	✓	✓	✓
Now that a CSM student team has developed a speaker's bureau Presentation on earthquakes and associated geologic hazards in Colorado, update and distribute the document for use by COEM and Other speakers when communicating these risks to the general public.		✓	✓	✓	✓
Per their request, develop a geologic hazards information module for the Thompson School District, Colorado, which will educate teachers, students, and the general public about hazards and safety measures required to minimize the impact of these hazards.		✓			

3. Enhance Seismic Safety

Goals: Seismic Safety	Implementation Year				
	99	00	01	02	03
Build upon the research studies conducted by CSM students concerning landslides in Colorado. Conduct future studies that address the landslide risks that exist along the I-70 Corridor and other hazardous areas in the mountains of Colorado. Study requests have been received from Garfield, Clear Creek, and Summit counties, as well as the town of Red Cliff.	✓	✓	✓	✓	✓
Continue to work with ES-CNHMC and other agencies to better assess the State's vulnerability to earthquakes based on present standards of construction. Promote the adoption and enforcement of seismic building codes for the State. Support the Director of FEMA in his efforts to create "disaster resistant communities."		✓	✓	✓	✓
Continue to study and recommend ways to mitigate the seismic hazards and other risks that threaten earthen dams in Colorado. Numerous dams have been recommended for review by the Division of Water Resources, Colorado Engineer's Office. A few of the dams recommended for study are the Georgetown Reservoir in Clear Creek County, Horse Creek Dam in the Hudson area, and Marshall Lake Dam in Boulder County.	✓	✓	✓	✓	✓
Design a shaker table that would demonstrate the seismic waves that propagate through the earth's crust that are responsible for the ground vibrations felt during an earthquake event. Display and demonstrate the table at appropriate conferences and meetings. model table at appropriate conferences and meetings.		✓	✓	✓	✓
Conduct a study for the town of Hot Sulfur Springs that addresses the geologic hazards contributing to the erosion of a quarter mile of road and river bank and the disruption of underground utilities. Recommend engineering solutions to eliminate the problem.		✓			
Develop a residential master plan for 97 acres owned by the town of Hugo, to include an environmental assessment and a geologic hazards			✓		

Goals: Seismic Safety	Implementation Year				
	99	00	01	02	03
analysis of the property.					
Design a paved bike path in the Swan Mountain area to complete the final section of an 18-mile bike path system around Dillon Reservoir. The bike path would cross several ravines, be adjacent to several miles of steep mountain slopes, and cross or follow Swan Mountain Road, which is narrow, winding, with no shoulders, and steep grades. The bike path would connect the Forest Service campground on Swan Mountain Road into the overall system and would require both environmental and geologic hazard studies for Summit County.	✓	✓			
Conduct a study for Hinsdale County of the infiltration of the Slumgullion Earth-flow into Lake San Cristobal to determine if there are economical ways to prevent, or at least slow this process. Included in the study would be the long-term forecast of impact on the Lake and also the potential economic impact on the area if fishing and boating are affected.		✓			
Conduct a study for the town of Palisade that will help them assess the geologic hazards that exist on the property of the Mount Garfield East School as well as the retrofitting required to insure the school building is in compliance with seismic building codes.		✓			
For the town of Silverton, conduct a study to determine what is causing the ground beneath the town's water treatment facility to shift, and to design a new, more modern treatment facility.		✓			
For Moffat County, evaluate the status of several county bridges, to include their stability, load capacity, and susceptibility to damage from geologic hazards that exist in the area.		✓			
For the town of Montezuma, determine the feasibility of constructing a water reservoir that will receive its water input from Saint Johns and Deer Creeks. Consider geologic hazards, water rights, availability of real estate, and cost factors.	✓	✓			
Conduct a study for the town of Delta to help them determine the safety of six Bureau of Reclamation dams and several private dams that are located above the town. Of immediate concern is knowledge of the risks associated with the dams and the development of appropriate emergency preparedness plans.		✓			
For the town of Palmer Lake, conduct a study to determine remedial actions required to protect the foundations of residential properties built on mountain slopes and actions required by future home builders to preclude structural damage.		✓			
Conduct a seismic analysis and bridge design study for the Fall River Road in Clear Creek County. The Clear Creek County Office of Emergency Management is overseeing the county's "Project Impact" Program. This program is funded by FEMA and allows counties to develop mitigation plans for various county projects with the overall goal being the design of disaster resistant communities.	✓	✓			
Conduct retrofit design studies of public buildings in mountainous towns to help mitigate damage to these buildings in the event of an earthquake. The towns of Idaho Springs and Georgetown are interested in a study of this nature.		✓	✓	✓	✓

V. CONCLUSION

Colorado is classified as a low to moderate risk State for earthquakes. However, the damage caused by an earthquake depends on the magnitude of the quake, where it occurs, and if the event is combined with secondary hazards. Examples of secondary hazards are landslides, dam failures, and disruption of utility services. Even though no highly destructive earthquakes have occurred in Colorado in the past 100 years, the risk is real and precautions need to be taken to protect the quality of life of the citizens and visitors of the State.

The population of Colorado is slightly under four million, and is growing rather rapidly. Earthquake risk increases with increases in population, even if the level of hazard remains constant. Many new families are choosing to build on less desirable land; for example, on steep, vulnerable slopes. Elected officials are being pressured to allow development in these potentially hazardous or high-risk areas. The general public and elected officials need to be better informed of the consequences of these actions and they need to be better educated on how to build safe and smart communities. Or, as the FEMA Director, James Lee Witt prefers to call them, "communities that are intrinsically resilient."

In recent years, the Federal Government's Natural Earthquake Hazard Reduction Program, in concert with numerous state and private agencies, have made tremendous progress in combating natural hazards. Extensive research has been conducted, resulting in a better understanding of earthquake dynamics. The effort put forth in this area has allowed engineers and scientists to formulate and implement new designs, to develop new and more effective analytical tools, to study and improve building codes, and to focus on the methods required to make existing buildings safer.

Colorado's elected officials are interested in "smart growth" and a goal of the Colorado Earthquake Project is to consider adopting new procedures and techniques that can reduce the citizens' risk to earthquakes and the secondary hazards associated with these events. No one can prevent an earthquake from happening; therefore, the hazard cannot be entirely eliminated. However, the State wants to mitigate and reduce the potential for loss through risk assessment, education and training of citizens and local officials, and the implementation of cost-effective actions that will better prepare Colorado for future earthquake events. This plan outlines procedures that will accomplish these objectives.

VI. BIBLIOGRAPHY

California Seismic Safety Commission, California at Risk, Report Number SSC 91-08, December, I99I.

Corridor Alliance for a Rapid Transit Solution, Draft Report to the Colorado Intermountain Fixed Guideway Authority, June 3, 1998.

Demography, Division of Local Government; press release December 28, 1994.

Federal Emergency Management Agency, National Mitigation Strategy, FEMA, December, I995.

Johnson, J.D. & Himmelreich, J.W., Geological Hazards Avoidance or Mitigation, Colorado Geological Survey, July, 1998.

Kirkham, R. M. and Rogers, W. P. ed.,1986, Contributions to Colorado Seismicity and Tectonics--A 1986 Update, Special Publication 28, Colorado Geological Survey.

Kirkham, R. M. and Rogers, W. P., 1985, Colorado Earthquake Data and Interpretations 1867 to 1985, Bulletin 46, Colorado Geological Survey.

Kirkham, R. M. and Rogers, W. P., 1981, Earthquake Potential in Colorado: A Preliminary Evaluation, Bulletin 43, Colorado Geological Survey.

National Earthquake Information Center public education documents.

National Hazards Research and Applications Information Center, Disasters by Design, Joseph Henry Press, Washington, D.C., 1999.

National Hazards Research and Applications Information Center, Natural Hazards Observer, Volume XX, Number 6, July, I996.

National Hazards Research and Applications Information Center, Natural Hazards Observer, Volume XXI, Number 2, November, I996, and Volume XXIII, Number 5, May, 1999.

National Science and Technology Council, Strategy for National Earthquake Loss Reduction, National Earthquake Strategy Working Group, April, I996.

Report of the Colorado PEPP Workshop, July 14-16, 1996, Colorado School of Mines.

S.D. Oaks, J.P. Brislawn, M. Mejia-Navarro and M.J. Koleis, Earthquakes and Related Hazards in Colorado, Map, COEHRP, 1993.

Shedlock, K.M. & Pakises, L.C., Earthquakes, USGS, 1994.

United States Geological Survey, Putting Down Roots in Earthquake Country, Southern California Earthquake Center, l995.

Utah Division of Emergency Management, Earthquakes: What You Should Know When Living in Utah, State of Utah, Earthquake Preparedness Information Center.

Utah Division of Emergency Management, Utah Five-Year Earthquake Plan, FY l993-l997, State of Utah, Epicenter, l996.

Utah Seismic Safety Commission, A Strategic Plan for Earthquake Safety in Utah, January, l995.

Witt, James L., "Creating Disaster Resistant Communities," Earthquake, Fall, 1997.

APPENDIX A: Magnitude (Richter Scale) and Intensity (Modified Mercalli Scale)

The magnitude or Richter Scale, (R) of an earthquake is a measure of the amplitude of the seismic waves and is related to the amount of energy released; this energy can be estimated from seismograph recordings. The magnitude scale is logarithmic, meaning a magnitude 7.2 earthquake produces 10 times more ground motion than a magnitude 6.2 earthquake. In terms of energy however, it releases about 32 times more energy. The energy release best indicates the destructive power of an earthquake.

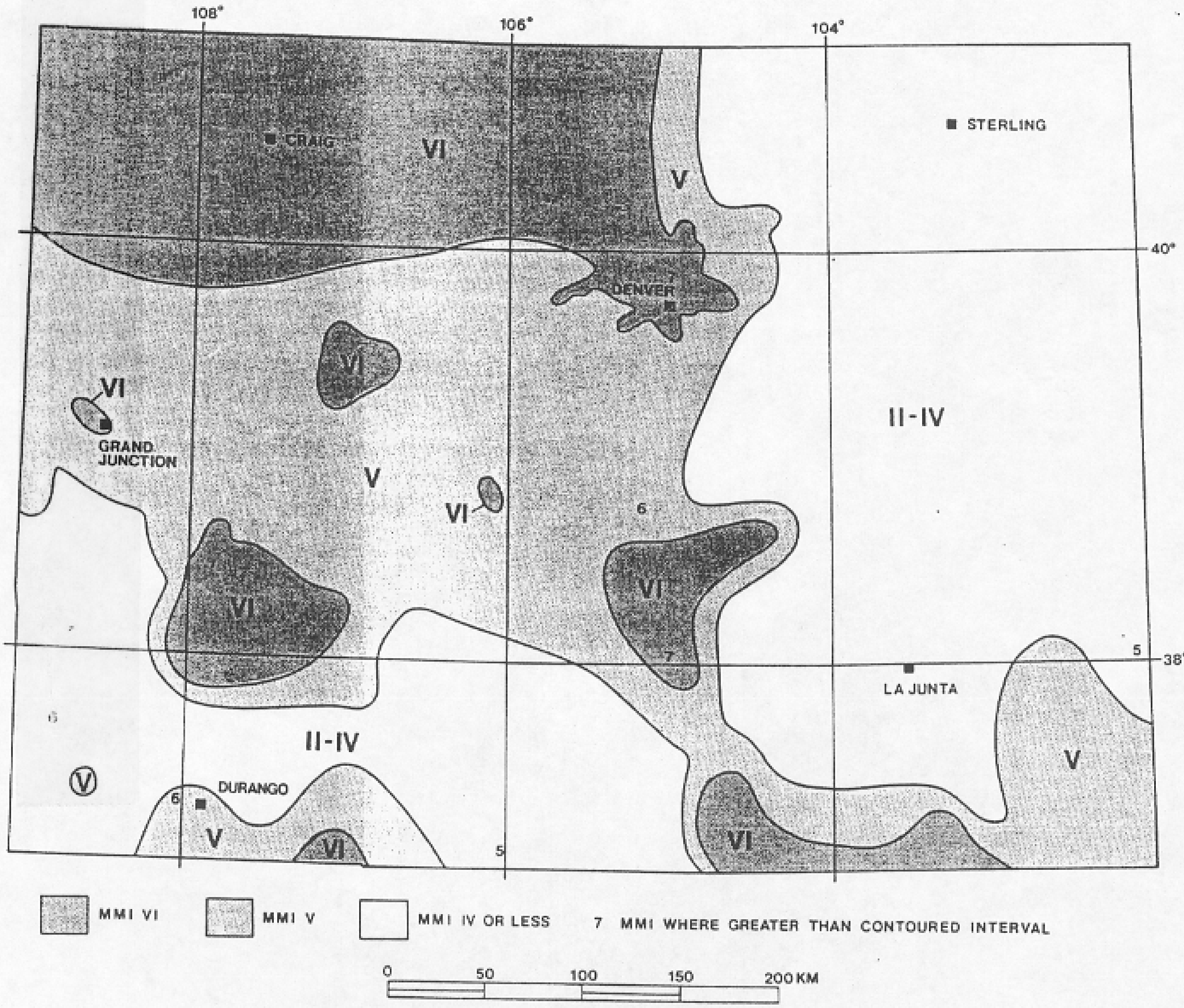
The Modified Mercalli Scale, (M) measures intensity rather than magnitude. It measures the effects of an earthquake at a particular place on humans as well as structures. The intensity at a point depends not only upon the strength of the earthquake, (magnitude) but also upon the distance from the earthquake to the epicenter and the local geology at that point. The following table depicts a rough comparison of the two scales.

Scales		Description of Earthquake
R	M	
2 -	I	The majority of people do not feel the earthquake; Must have extremely favorable conditions for motion to be detected.
3 -	II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
	III	Felt by persons on upper floors of buildings. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
4 -	IV	Felt outdoors by a few; at night, some awakened. Dishes and windows and doors disturbed. Sensation like a heavy truck striking building. Cars rocked noticeably.
	V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
5 -	VI	Felt by all, many frightened. Some heavy furniture moved. A few instances of fallen plaster. Damage slight.
6 -	VII	Negligible damage in well constructed buildings; slight to moderate in ordinary structures. Considerable damage in poorly built structures.
	VIII	Damage slight in specially designed structures; damage great in poorly built structures. Heavy furniture overturned; chimneys and walls may fall.
7 -	IX	Damage considerable in specially designed structures. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
	X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed. Rails bent.
8 -	XI	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
	XII	Damage total. Line of sight distorted. Objects thrown into the air.

(From "Earthquakes: What You Should Know When Living in Utah≅)

APPENDIX B: Maximum Historical Earthquake Intensities in Colorado

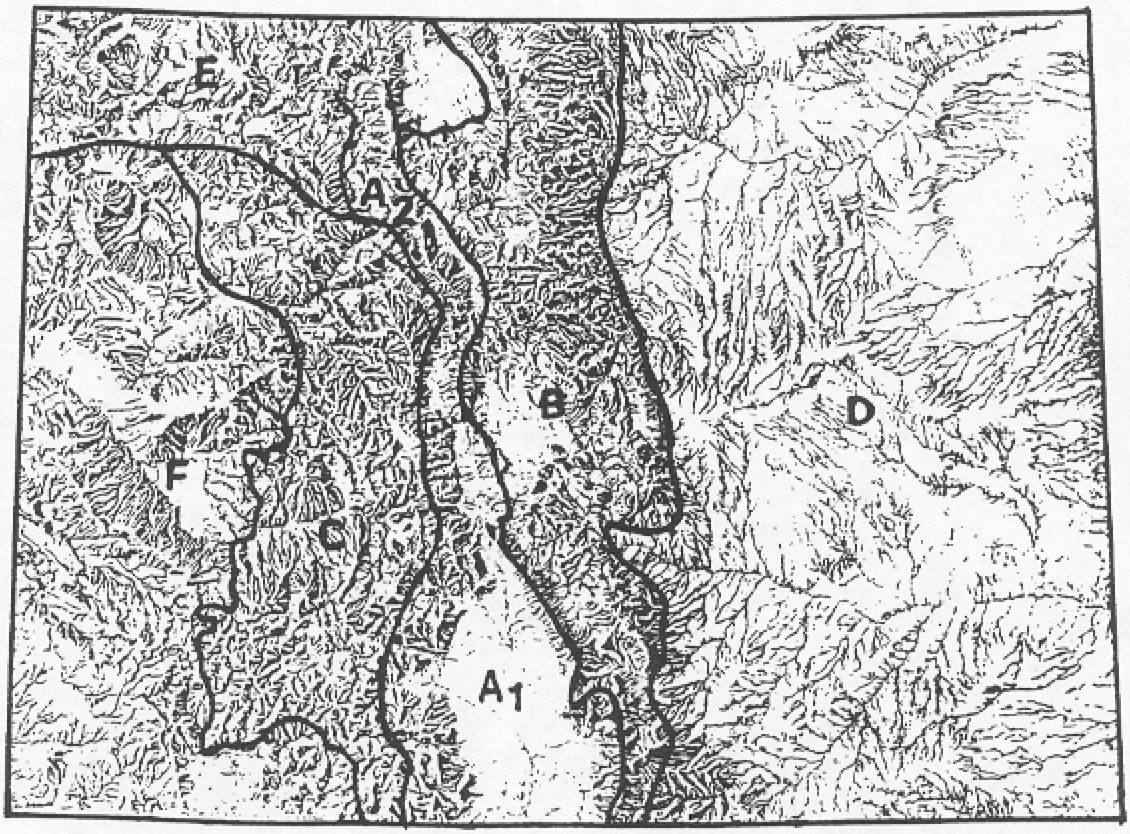
The following illustration graphically depicts historical earthquake intensity zones for the state of Colorado. Roman letters represent the Modified Mercalli Scale intensities. This scale is a qualitative measure of the degree of shaking to be expected during an earthquake and its effects on man-made structures. Please refer to Appendix A for a more complete explanation of the scale.



(From Kirkham and Rogers, 1981)

APPENDIX C: Seismotectonic Provinces in Colorado

The following map depicts the seismotectonic provinces that exist in Colorado. These providences, or geographical areas, may experience maximum credible earthquakes in the future as shown in the below table.



AREA	SEISMOTECTONIC PROVINCE	APPROXIMATE MAXIMUM CREDIBLE EARTHQUAKES
Al	Southern Rio Grande Rift Subprovince	M = 6.5 to 7.5
A2	Northern Rio Grande Rift Subprovince	M = 6.0 to 7.0
B	Eastern Mountain Province	M = 6.0 to 6.75
C	Western Mountain Province	M = 6.0 to 6.5
D	Plains Province	M = 5.5 to 6.0
E	Unita-Elkhead Province	M = 5.5 to 6.5
F	Colorado Plateau Province	M = 5.5 to 6.5

(From Kirkham and Rogers, 1981)

APPENDIX D: Seismology Glossary of Common Terms

The following glossary will help readers to better understand the terms often used in discussing earthquakes. The information presented in this appendix was taken from a fact sheet prepared by the National Earthquake Information Center, US Geological Survey, Golden, Colorado.

Aftershock - An earthquake, which follows a larger earthquake or main shock and originates at or near the focus of the larger earthquake. Generally, major earthquakes are followed by a larger number of aftershocks, decreasing in frequency with time.

Amplitude - The maximum height of a wave crest or depth of a trough.

Array - An ordered arrangement of seismometers or geophones, the data from which feeds into a central receiver.

Arrival - The appearance of seismic energy on a seismic record.

Arrival Time - The time at which a particular wave phase arrives at a detector.

Aseismic - Not associated with an earthquake.

Body Wave - A seismic wave that travels through the interior of the Earth and is not related to a boundary surface.

Crust - The outer layer of the Earth's surface.

Earthquake - Shaking of the earth caused by a sudden movement of rock beneath its surface.

Earthquake Swarm - A series of minor earthquakes, none of which may be identified as the main shock, occurring in a limited area and time.

Elastic Wave - A wave that is propagated by some kind of elastic deformation, that is, a deformation that disappears when the forces are removed. A seismic wave is a type of elastic wave.

Epicenter - That point on the Earth's surface directly above the hypocenter of an earthquake.

Fault - A weak point in the Earth's crust where the rock layers have ruptured and slipped.

First Arrival - The first recorded signal attributed to seismic wave travel from a known source.

Focus - That point within the Earth from which originates the first motion of an earthquake and its elastic waves.

Focal Zone - The rupture zone of an earthquake. In the case of a great earthquake, the focal zone may extend several hundred kilometers in length.

Foreshock - A small tremor that commonly precedes a larger earthquake or main shock by seconds to weeks and that originates at or near the focus of the larger earthquake.

Hypocenter - The calculated location of the focus of an earthquake.

Intensity - A measure of the effects of an earthquake at a particular place on humans and/or structures. The intensity at a point depends not only upon the strength of the earthquake (magnitude), but also upon the distance from the earthquake to the epicenter and the local geology at that point.

Love Wave - A major type of surface wave having a horizontal motion that is shear or transverse to the direction of propagation. It is named after A.E.H. Love, the English mathematician who discovered it.

Isoseismal Line - A line connecting points on the Earth's surface at which earthquake intensity is the same. It is usually a closed curve around the epicenter.

Leaking Mode - A surface seismic wave that is imperfectly trapped so that its energy leaks or escapes across a layer boundary causing some attenuation.

Low-velocity Zone - Any layer in the Earth in which seismic wave velocities are lower than in the layers above and below.

Magnitude - A measure of the strength of an earthquake or strain energy released by it, as determined by seismographic observations. The local body-wave and surface-wave magnitudes will have approximately the same numerical value.

Major Earthquake - An earthquake that has a magnitude of 7 or greater on the Richter scale.

Mantle - The layer of rock that lies between the outer crust and the core of the earth.

Microearthquake - An earthquake having a magnitude of 2 or less on the Richter scale.

Microseism - A more or less continuous motion in the Earth that is unrelated to an earthquake and that has a period of 1.0 to 9.0 seconds. It is caused by a variety of natural and artificial agents.

MM Scale - Mercalli scale modified for North America conditions.

Mohorvicic Discontinuity - The boundary surface or sharp seismic-velocity discontinuity that separates the Earth's crust from the underlying mantle.

P Wave - Longitudinal, irrotational, push, pressure, dilatational, primary, compressional, push-pull wave.

Phase - The onset of a displacement or oscillation on a seismogram indicating the arrival of a different type of seismic wave.

Plate - One of the huge sections that make up the Earth's crust. The plates are continuously moving.

Plate Boundary - The place where two or more plates in the Earth's crust meet.

Rayleigh Wave - A type of surface wave having a retrograde, elliptical motion at the free surface. It is named after Lord Rayleigh, the English physicist who predicted its existence.

Reflect - To bounce back from a surface.

Refract - To change direction.

Richter Scale - The system used to measure the strength of an earthquake.

S Wave - Shear, secondary, rotational, tangential, equivoluminal, distortional, transverse, shake wave.

Seiche - A free or standing wave oscillation of the surface of water in an enclosed basin that is initiated by local atmospheric changes, tidal currents, or earthquakes.

Seismic Belt - An elongated earthquake zone, for example, circum-Pacific, Mediterranean, Rocky Mountain.

Seismic Constant - In building codes dealing with earthquake hazards, an arbitrarily set quantity of steady acceleration (in units of gravity), that a building must withstand.

Seismogram - A written record of an earthquake.

Seismograph - An instrument that records the motions of the Earth's surface.

Seismologist - A scientist who studies earthquakes.

Signal-to-Noise Ratio - The comparison between the amplitude of the seismic signal and the amplitude of noise caused by seismic unrest and/or the seismic instruments.

Spread - The layout of seismometer or geophone groups from which data from a single shot (the explosive charge) are recorded simultaneously.

Subduction Zone - An elongated region along which a block of crusts descends relative to another crustal block, for example, the descent of the Pacific plate beneath the Andean plate along the Andean trench.

Teleseism - An earthquake that is distant from the recording station.

Travel Time - The time required for a wave train to travel from its source to a point of observation.

Tsunamis - A huge sea wave caused by earthquakes, (referred to by many as a tidal wave).

APPENDIX E: Earthquake History of Colorado

The following information was taken from a fact sheet compiled by the National Earthquake Information Center, US Geological Survey, Golden, Colorado. Although the State of Colorado has been able to document the occurrence of numerous earthquakes since the mid-1800s, this abbreviated earthquake history of Colorado discusses only a few of the less than 3.0 magnitude earthquakes. The information in this appendix focuses on the higher magnitude earthquakes (earthquakes greater than magnitude 3.0), that have occurred from the late 1800s to 1993.

Colorado is considered a region of minor to moderate earthquake activity, although there are many uncertainties because of the very short time period for which historical data is available. The northwestern and southwestern corners, and the Sangre de Cristo Mountains in the south-central section of the State, have had no earthquake activity in historic times. Eastern Colorado is nearly aseismic, with just a few epicenters in the Arkansas and Platte River Valleys. Most shocks in the history of this State have centered west of the Rocky Mountain Front Range.

F.A. Hadsell, writing in the Colorado School of Mines Quarterly (col. 63, No. 1, Jan. 1968), reports the first known reference to an earthquake in Colorado occurred on December 7, 1870. The Colorado Transcript states, "A careful observer at Fort Reynolds, 20 miles east of Pueblo, noted that bottles standing 1 inch apart were knocked together violently." Hadsell also notes that, although the first seismograph in Colorado was installed by Father Armand W. Forstall at Regis College in 1909, seismographs of sufficient quality and quality were not available to monitor Colorado earthquakes until about 1962. As such, between 1870 and 1962, newspaper accounts are the prime source of published data on Colorado shocks.

The most damaging shock in Colorado's history occurred on August 9, 1967. The magnitude 5.3 earthquake, rated intensity VII on the Modified Mercalli Intensity Scale, caused moderate damage in Northglenn, Commerce City, Denver, and several nearby towns. This is the only intensity VII earthquake listed for Colorado in the NEIC files. Hadsell has assigned an intensity VII to the November 7, 1882 tremor northwest of Denver. The NEIC, however, lists this shock as intensity VI.

The 1882 earthquake, the first ever to cause damage at Denver, probably centered in the Front Range near Rocky Mountain National Park and is probably the largest known earthquake in the state. The magnitude is estimated to be about 6.2 on the Richter scale. In Boulder County the walls of the depot cracked, and plaster fell from walls at the University at Boulder. The quake was felt as far away as Salina, Kansas and Salt Lake City, Utah.

An earthquake on November 15, 1901 cracked windows and rolled boulders onto the highway in Buena Vista; the water of Cottonwood Lake was reportedly agitated. Another shock of similar intensity (VI) did not occur until September 8, 1944. During this tremor, bricks fell from chimneys and walls and chimneys cracked at Basalt, about 100 miles west of Denver. Eleven years later, in August 1955, a strong earthquake left cracks in chimneys and ground at Lake City, about 170 miles southwest of Denver. On October 11, 1960, a shock cracked a foundation and loosened cupboards from walls at Montrose. Windows, plaster, and chimneys were damaged in several towns in southwestern Colorado.

In 1961, a 12,000-foot well was drilled at the Rocky Mountain Arsenal, northeast of Denver, for disposing of waste fluids from Arsenal operations. Injection was commenced March, 1962, and an unusual series of earthquakes erupted in the area shortly after.

Over 1,300 earthquakes were recorded at the Cecil H. Green geophysical Observatory at Bergen Park, Colorado between January 1963 and August 9, 1967. Three shocks in 1965 - February 16, September 29, and November 20 - caused intensity VI damage in Commence City and environs.

The Denver series was forgotten, however temporarily, in October 1966, when a southeast Colorado tremor rocked a 15,000 square-mile area of the State and bordering New Mexico. Minor damage, in the form of broken windows and dishes and cracked walls and plaster, occurred at Aguilar, Segundo, Trinchera, and Trinidad.

On April 10, 1962 a large earthquake in the Denver area occurred, and this quake was believed to be associated with the activities at the Rocky Mountain Arsenal. 118 window panes were broken in buildings at the Rocky Mountain Arsenal, a crack in an asphalt parking lot was noted in the Derby area, and schools were dismissed in Boulder, where walls sustained cracks. Legislators quickly moved from beneath chandeliers in the Denver Capitol Building, fearing they might fall. The Colorado School of Mines rated this shock magnitude 5.0.

Boulder sustained minor damage to walls and acoustical tile ceilings on April 27, 1967 as a result of a magnitude 4.4 earthquake. Then a year and a half after the Rocky Mountain Arsenal waste dumping practice stopped, the strongest and most widely felt shock in Denver's history struck that area on August 9, 1967. The magnitude 5.3 tremor caused the most serious damage at Northglenn where concrete pillar supports to a church roof were weakened, and 20 windows were broken. An acoustical ceiling and many light fixtures fell at one school. Many homeowners reported wall, ceiling, floor, patio, sidewalk, and foundation cracks. Several reported basement floors separated from walls. Extremely loud, explosive like earth noises were heard. Damage on a lesser scale occurred throughout the area.

During November 1967, the Denver region was shaken by five moderate earthquakes. Two early morning shocks occurred November 14. They awakened many residents, but were not widely felt. A similar shock, magnitude 4.1, occurred in the Denver area on November 15. Residents were generally shaken, but no damage was sustained.

The second largest earthquake in the Denver series occurred on November 26, 1967. The magnitude 5.2 event caused widespread minor damage in the suburban areas of northeast Denver. Many residents reported it was the strongest earthquake they had ever experienced. It was felt at Laramie, Wyoming, to the northwest, east to Goodland, Kansas, and south to Pueblo, Colorado.

On January 7, 1971, a minor 3.8 earthquake shook the Glenwood Springs area. Most residents were frightened by the tremor but damage was light. A minor 3.0 earthquake rumbled through the East Denver - Commerce City area on March 11, 1971. The early morning tremor caused no damage.

A sharp earthquake struck western Colorado January 30, 1975. The magnitude 3.7 earthquake occurred at 7:49 a.m. MST. The quake was felt strongest at Colorado National Monument and in the Fruita area.

On April 2, 1981, a sharp earthquake, magnitude 4.1, occurred that was centered approximately 20 km north of downtown Denver in the Thornton area. Some slight damage (MM VI) was observed at Commerce City and Thornton. This was the last magnitude 4.0 or greater earthquake locate in the Denver area to date (May, 1993).

A minor but alarming earthquake occurred in the north-central part of Colorado on November 1, 1981. The magnitude 3.1 tremor was centered in the Evergreen area about 22 miles southwest of Denver. The effects registered MM V, and were experienced in the Conifer, Evergreen, and Pine Junction areas.

A minor earthquake occurred in western Colorado on August 14, 1983. This shock was located about 28 miles southeast of Montrose in a sparsely populated area. The northwestern corner of Colorado was shaken by a light earthquake on September 24, 1983. It was a magnitude 4.0 and was located about 25 miles north of Dinosaur National Monument. MM III effects were experienced at Maybell and Rangely; it was also felt at Point Rocks, Wyoming.

The western part of the State experienced a series of earthquakes beginning with a magnitude 2.4 on April 12, 1984. These quakes were located about 5 miles south of Carbondale. The largest quake located in the area occurred on April 22 and had a magnitude of 3.1 which was felt in the Carbondale and Glenwood Springs area. Of the hundreds of earthquakes that occurred in the Carbondale area, 12 were reported as felt.

A minor earthquake occurred in the south-central part of the State on March 16, 1985. The magnitude 3.3 earthquake was located about 15 km northeast of Salida and was felt in the Salida-Nathrop area.

Several minor earthquakes occurred in 1986. Many were in the Crested Butte and Aspen area. During August, 14 earthquakes were located in this area. A magnitude 3.5 occurred on September 3 about 13 km northwest of Crested Butte. Intensity MM V effects were noted at Aspen and Crested Butte. Other quakes in the series included a magnitude 3.2 on September 17 and a magnitude 3.4 on September 18.

A minor earthquake occurred in the southern part of the State on January 15, 1988. The magnitude 3.1 earthquake was located about 60 km west of Alamosa. On February 14 a minor earthquake took place in the northwest corner of the State. The quake had a magnitude 3.3 and was located about 80 km west of Craig. It produced MM IV effects at Maybell.

The western part of Colorado experienced four earthquakes during September and October of 1990. The first, on September 12, had a magnitude 3.0 and was located about 40 km southwest of Fraser near Frisco and Vail. Intensity MM V effects were produced at Vail. On October 18, two earthquakes occurred. Both earthquakes were located about 35 km west of Glenwood Springs in the vicinity of New Castle. On December 12, another very minor earthquake occurred in the western part of Colorado. This magnitude 2.7 tremor was located about 35 km west of Glenwood Springs. On May 10, 1991, residents of the southwestern part of Colorado felt four small earthquakes. The first had a magnitude of 3.4 and was located about 40 km northeast of Pagosa Springs. This earthquake was felt strongly in the Summerville area. Intensity MM III effects were experienced at Chromo and Pagosa Springs. The first quake was followed by three aftershocks: a magnitude 2.4, a magnitude 2.0 and a magnitude 2.4.

The last earthquake NEIC located in the State was on April 1993, located about 20 miles northwest of Steamboat Springs, having a magnitude 2.5. The state of Colorado continues to have a number of small earthquakes every year, but according to the NEIC, few cause major damage.

APPENDIX F: Colorado Earthquake Information

The following information was taken from a fact sheet prepared by the Earthquake Subcommittee, Colorado Natural Hazards Mitigation Council, (ES-CNHMC). The purpose of the information published in this document is to insure that Colorado geologists, geophysicists, seismologists, and engineers are in agreement when briefing the general public or the press on earthquake related issues.

Introduction

Colorado is comprised of areas with low to moderate potential for damaging earthquakes, based on research by geologists and geophysicists who specialize in seismology. There are about 90 potentially active faults that have been identified in Colorado, with documented movement within the last 1.6 million years. However, there are several thousand other faults that have been mapped in Colorado that are believed to have little or no potential for producing future earthquakes. Because the occurrence of earthquakes is relatively infrequent in Colorado and the historical earthquake record is short (only about 130 years), it is not possible to accurately estimate the timing or location of future dangerous earthquakes in Colorado. Nevertheless, the available seismic hazard information can provide a basis for a reasoned and prudent approach to seismic safety.

Faulting

Sudden movement on faults is responsible for large earthquakes. By studying the geologic characteristics of faults, geo-scientists can often determine when the fault last moved and estimate the magnitude of the earthquake that produced the last movement. In some cases it is possible to evaluate how frequently large earthquakes occurred on a specific fault during the recent geological past.

Geological studies in Colorado indicate that there are about 90 faults that moved during the Quaternary Period (the last 1.6 million years), and that these faults should be considered potentially active. The Sangre de Cristo Fault, which lies at the base of the Sangre de Cristo Mountains along the eastern edge of the San Luis Valley, and the Sawatch Fault, which runs along the eastern margin of the Sawatch Range, are two of the most prominent potentially active faults in Colorado. Not all of Colorado's potentially active faults are in the mountains and some can not be seen at the earth's surface. For example, the Cheraw Fault, which is in the Great Plains in southeast Colorado, appears to have had movement during the recent geologic past. The Derby Fault near Commerce City lies thousands of feet below the earth's surface but has not been recognized at ground level.

Several potentially active faults in Colorado are thought to be capable of causing earthquakes as large as magnitude 6 ½ to 7 ¼. In comparison, California has hundreds of hazardous faults, some of which can cause earthquakes of magnitude 8 or larger. Furthermore, the time interval between large earthquakes on faults in

Colorado is generally much longer than on faults in California.

Past and Possible Future Earthquakes

More than 400 earthquake tremors of magnitude 2 ½ or higher have been recorded in Colorado since 1867. More earthquakes of magnitude 2 ½ to 3 probably occurred during that time, but were not recorded because of the sparse distribution of population and limited instrumental coverage in much of the State. For comparison, more than 20,500 similar-sized events have been recorded in California during the same time period. The largest known earthquake in Colorado occurred on November 7, 1882 and had an estimated magnitude of 6 ½. The location of this earthquake, which has been the subject of much debate and controversy over the years, appears to be in the northern Front Range west of Fort Collins.

Note: Please refer to Figure 4 on page 5 of this report for a listing of Colorado's largest historic earthquakes.

Although many of Colorado's earthquakes occurred in mountainous regions of the State, some have been located in the western valley and plateau region or east of the mountains. The most economically damaging earthquake in Colorado's history occurred on August 9, 1967 in the northeast Denver metropolitan area. This magnitude 5.3 earthquake, which was centered near Commerce City, caused more than a million dollars damage in Denver and the northern suburbs. This earthquake is believed to have been induced by the deep injection of liquid waste into a bore-hole at Rocky Mountain Arsenal. It was followed by a second earthquake of magnitude 5.2 three months later. Although these events cannot be classified as major earthquakes, they should not be discounted as insignificant. They occurred within Colorado's Front Range Urban Corridor, an area where nearly 75% of Colorado residents and many critical facilities are located. Since March of 1971, well after the initial flurry of seismic activity, 15 earthquakes of approximate magnitude 2 ½ or larger occurred in the vicinity of the northern Denver suburbs.

Relative to other western states, Colorado's earthquake hazard is higher than Kansas or Oklahoma, but lower than Utah, and certainly much lower than Nevada and California. Even though the seismic hazard in Colorado is low to moderate, it is likely that damaging earthquakes will again occur. It is prudent to expect future earthquakes as large as magnitude 6.5, the largest event of record.

Summary and Conclusions

Based on the historical earthquake record and geologic studies, an event of magnitude 6 ½ to 7 ¼ could occur somewhere in the State. Scientists are unable to accurately predict when the next major earthquake will occur, 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 provisions in critical and vulnerable structures and to insure that statewide emergency planning continues. Concurrently, we should expand earthquake monitoring, geological and geophysical research, and mitigation planning.

Further Published Information

The Colorado Geological Survey has several publications on Colorado earthquakes and potentially active faults, and maintains a Reference Collection on Colorado seismicity that includes reports by consultants and various agencies. A listing of these reports and documents can be viewed at the CGS web site: www.dnr.state.co.us/geosurvey.

Contacts

Vicki Cowart
State Geologist and Director
Colorado Geological Survey
1313 Sherman Street, Room 715
Denver, CO 80203
(303) 866-2611

Bob Kirkham
Colorado Geological Survey
P.O. Box 172
Monte Vista, CO 81144
(719) 587-0139

Waverly Person
National Earthquake Information Center
U.S. Geological Survey
Golden, CO 80401
(303) 273-8500
(800) 525-7848

John Nicholl
URS Greiner Woodward Clyde
4582S. Ulster Street, Suite 1000
Denver, CO 80237
(303) 740-2668
John-Nicholl@urscorp.com