BULLETIN 43

Earthquake Potential in Colorado

A Preliminary Evaluation

by Robert M. Kirkham
and William P. Rogers

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado / 1981

Cover photograph: Low-sun-angle vertical aerial photograph of the Sangre de Cristo fault zone southeast of Villa Grove. Dark rectilinear shadow extending northward from center of photo is a fault scarp in late Quaternary alluvial fan deposits.

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This report is an updated version of Colorado Geological Survey open-file report 78-3.

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ABSTRACT

Colorado has long been considered an area of low seismicity with only a minor potential for future earthquakes. Recent geological and geophysical investigations, however, have discovered several active faults that are capable of generating future damaging earthquakes and numerous other faults that are suspected of being potentially active. These investigations suggest Colorado is a moderately active earthquake area and in time larger earthquakes than yet have been experienced can occur.

A major period of extensional faulting initiated in Colorado about 28 m.y. ago and has continued at least to a limited extent to the present. Faults that have moved during this period of Neogene tectonism are herein classified as "potentially active faults" and are suspected of being capable of future movement. These faults need to be thoroughly evaluated to ascertain their importance for the design of engineered structures. Some of these designated potentially active faults have been shown to be capable of generating future damaging earthquakes. Others, however, may have been inactive for millions of years and pose no serious earthquake hazard.

Colorado can be divided into six distinct seismotectonic provinces based on the distribution and characteristics of Neogene faults, historic earthquakes, major structural and physiographic regions, and our interpretation of earthquake potential. Designated provinces include the Rio Grande rift, eastern mountain, plains, western mountain, Uinta-Elkhead, and Colorado Plateau provinces. Many of the potentially active faults in these seismotectonic zones have moved during the Quaternary and several show evidence of late Quaternary and Holocene activity. The dominant seismotectonic feature in Colorado is the Rio Grande rift, a major intracontinental rift that is closely affiliated with the Neogene extensional tectonics prevalent throughout much of the western United States. Most of the Neogene faulting and associated igneous activity in Colorado appears to be related to the Rio Grande rift.

Colorado's historic earthquake record is somewhat misleading. A few moderate-sized events have caused local damage over the past 110 years, and hundreds of smaller earthquakes have been felt and/or instrumentally located within the state. No large earthquakes nor any very damaging earthquakes have occurred during this period of written history. The geologic record, nonetheless, suggests that parts of Colorado have repeatedly experienced earthquakes of up to magnitude 6.5 to 7.5 during the past several million years. Some faults that exhibit abundant evidence of multiple large-displacement movements during the late Quaternary, such as the Sangre de Cristo fault, have had virtually no seismicity associated with them during the historical period. This does not indicate a lack of potential for future earthquakes because these faults may have recurrence intervals on the order of thousands or tens of thousands of years.

Seismic hazards can be effectively mitigated in Colorado. Construction should be avoided on proven active faults or be specially designed to resist damage due to surface rupture. Critical, high-risk structures should be carefully sited, designed, and constructed to withstand ground shaking caused by nearby moderate to large earthquakes.

Secondary earthquake hazards such as landslides, rockfalls, liquefaction, ground deformation, and abnormal water-wave action can be minimized by undertaking appropriate geotechnical investigations and incorporating indicated construction practices.

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1. INTRODUCTION

This report is a slightly revised update of Colorado Geological Survey open-file report 78-3: "Earthquake Potential in Colorado--A Preliminary Evaluation". Some new information has been added to the original open-file report and it has been reorganized and edited for grammar and technical aspects.

1.1. PURPOSE

Thousands of lives are lost and billions of dollars worth of property are destroyed by large earthquakes throughout the world almost every year. In California alone, earthquakes are predicted to cause over $21 billion in damage by the year 2000 (Alfors and others, 1973). Wiggins and others (1978) indicate that Colorado ranks third in the country for expected annual losses due to earthquakes. Such damage results from severe ground shaking, surface rupture, and other land-level changes. Secondary effects, such as landsliding, liquefaction, differential settlement, dam failure, ground lurching, and abnormal water-wave action, including tsunamis and seiches, are also responsible for much damage.

Colorado has had a relatively quiet, recorded earthquake history (Hadsell, 1968; Simon, 1969, 1972a, 1972b; Rogers and others, 1974). The first reported Colorado earthquake occurred in 1870 and during the following 110 years only a few earthquakes have exceeded Richter magnitude 5.0 or Modified Mercalli Intensity VI. This relatively short, recorded history, however, may be misleading. Prediction of future earthquakes cannot be based entirely on the historic earthquake record (Allen, 1975). Even in China, Japan, and the countries of the Middle East, where historic annals cover up to 3,000 years, the data are not adequate to satisfactorily predict where earthquakes may occur or how large they might be. Our very limited records for North America should, to quote Allen (1975), "be used with extreme caution in estimating future seismic activity."

A sometimes more realistic source for information about the location and frequency of future large earthquakes is recent geologic history, especially the history of recent fault movements. Seismotectonic relationships in California, Nevada, and many other parts of the world indicate a direct correlation between large earthquakes and active faults. Small earthquakes may result from other causes, but the vibrational energy released during these events is generally not large enough to cause significant damage.

This investigation was undertaken to better understand the earthquake potential of Colorado and to attempt to predict in a general way where and how large future seismic events might be. To accomplish this goal, both the earthquake history and geologic history of recent fault activity were studied. A great deal of background information was available in the literature. Existing information was evaluated and additional unpublished data were obtained from geoscientists familiar with Colorado seismicity or the recent geologic history of specific areas. All faults were studied on high-altitude, remotely sensed imagery, and many were briefly examined in the field. Several fault systems, in particular the Golden, Sangre de Cristo, and Sawatch faults, were further analyzed through regional and local geologic mapping. Two trenches were excavated through a graben near Golden. A twenty-day microearthquake survey in the Elkhead Mountains-Steamboat Springs area added to the understanding of certain problems with seismicity in that area.

It should be emphasized that the findings presented herein are of a preliminary nature. Determination of future seismicity is an extremely complex undertaking that must incorporate a thorough knowledge of both historic earthquakes and geologic evidence of recent fault activity. Assessment of the recent history of most faults is a difficult task. It can be accomplished only through detailed geological and geophysical investigations that may require trench and drill-hole studies. Such information is available for far too few faults in Colorado to permit complete confidence in our knowledge of state-wide fault activity. The earthquake history of Colorado is not by itself adequate for predictive purposes. Our historic earthquake record is far too short to confidently predict future seismic activity on faults with recurrence intervals of thousands or tens of thousands of years. The instrumental earthquake record is even shorter. Another significant limitation involves the problems resulting from incomplete seismic monitoring of the entire state. Existing stations function adequately, but there are too few seismographs to satisfactorily locate small earthquakes. This problem will continue to plague any efforts to define future seismicity until several additional strategically located seismographs are in full-time operation throughout the state.

1.2. FAULTS AND EARTHQUAKES

Most destructive earthquakes result from a sudden differential movement of large blocks of the earth's crust along faults. A fault is defined by the American Geological Institute (1957) as "a fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture. The [total] displacement may be a few inches or many miles." There are hundreds of thousands of faults in Colorado that meet this definition, but only a relatively few have been active during the Neogene, and only part of those are believed to be capable of generating earthquakes in the future.

An earthquake occurs when stresses acting on a rock mass exceed the rock shear strength. This causes brittle failure along a fault plane and releases stored strain energy. The exact manner in which this occurs is the subject of much current debate and extensive research. Pore pressure may play a critical role (Hubbert and Rubey, 1959), as indicated by the earthquakes at Rangely oil field and the Rocky Mountain Arsenal. Movement on the fault begins in a small area and rapidly propagates outward along the fault surface. The location where movement or energy release initiates is the earthquake focus or hypocenter, and the point on the earth's surface vertically above the hypocenter is the epicenter. As the fault ruptures, strain energy is released as seismic waves that travel outward in all directions from the hypocenter. These waves cause the familiar ground shaking experienced during an earthquake.

Not all fault movement is rapid nor does it all occur during large earthquakes. A very slow, almost imperceptible movement called fault creep is common on some faults, especially strike-slip faults. Fault creep is often accompanied by microearthquakes (not of sufficient size to be felt by man), but it usually does not produce large earthquakes. This does not imply that faults which creep are not capable of large earthquakes. Strain release through creep may be less than strain accumulation, or creep may be a very shallow phenomenon. In such situations large quakes may eventually occur when the excess accumulated strain is greater than rock strength. Fault creep is in itself damaging to man-made structures because of the displacements resulting from the slow movement and should, therefore, be considered in engineering designs.

In the United States two scales are commonly used to describe earthquakes and are both employed in this study. The Modified Mercalli Intensity Scale (Appendix 1) is a qualitative measure of the degree of shaking and its effects on man-made structures. It is particularly useful in assessment of felt earthquakes prior to establishment of seismograph networks. The Richter Magnitude Scale rates earthquakes based on a logarithmic scale of the maximum amplitude of seismic waves recorded on a Wood-Anderson seismograph, normalized to a distance of 100 km. Maximum wave amplitude is related to the total energy released, is instrumentally measured, and is therefore a better measure of an earthquake than intensity. Other earthquake characteristics, such as ground displacement, velocity, and acceleration, are helpful for design studies of man-made structures.

Faults can be recognized in many ways. If a fault is exposed in a roadcut, cliff, mine working, or other similar exposure, it may be readily observed because of discontinuity of structures, repetition, omission, offset, or juxtaposition of strata, or the presence of fault drag, slickensides, gouge, breccia, silicification, or mineralization. Such direct evidence may not be observable, therefore one must rely upon physiographic criteria observed both in the field and on remotely sensed imagery to locate faults, or on geophysical studies. Primary features often associated with recently active faults include 1) fault scarps, 2) triangular facets on mountain fronts, 3) diverted or dammed streams, 4) closed depressions, 5) fault valleys, 6) sidehill ridges, 7) fault gaps, 8) fault saddles, and 9) knick points. Many other features are also suggestive of active faults, but are too numerous to list.

Faults can be classified by type of movement (Figure 1). A dip-slip fault has predominantly vertical movement, whereas a strike-slip fault moves in a horizontal sense. A fault that moves with both horizontal and vertical components is an oblique-slip fault. Dip-slip faults may be either normal, reverse, or thrust faults. A thrust fault is a special type of reverse fault in which the dip of the fault plane is at a low-angle, usually less than 45°.

Recency of fault movement can be established by crosscutting relationships between the fault and the deposits that it comes into contact with. If a fault displaces a deposit, movement has occurred since

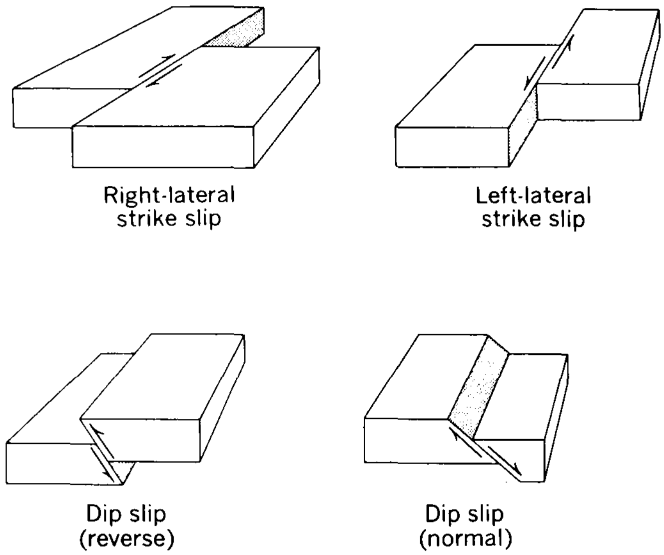

Figure 1. Fault classification based on type of movement. (from Wesson and others, 1975)

deposition of the unit. If a fault is covered by the deposit, the most recent movement pre-dates deposition of the unit. Age of the most recent movement on a fault is bracketed by the ages of the youngest deposit offset by the fault and the oldest deposit that covers the fault.

The recurrence interval for major movement on a fault is very critical in the assessment of fault capability or activity. Faults with short recurrence intervals generate significant earthquakes more often than faults with long recurrence intervals. Accurate establishment of the recurrence rate for a particular fault can be very difficult. Oftentimes, very detailed geological and geophysical studies are needed to develop an understanding of the recurrence interval.

The maximum magnitude of future earthquakes on a fault can be roughly estimated from the length of expected surface rupture and the maximum displacement per event. Various relationships between these fault characteristics and earthquake magnitudes have been derived by several workers through study of historical earthquakes (Tocher, 1958; Iida, 1965; Albee and Smith, 1967; Bonilla, 1970; Bonilla and Buchanan, 1970; Bolt, 1973; Slemmons, 1977). Problems with this approach include the difficulty of determining fault length, uncertain relationships between surface fault rupture and faulting at depth, inability to determine how much of a fault may rupture during a given earthquake, and theoretical considerations (Thatcher and Hanks, 1973).

Slemmons (1977) recently added new data, revised older data, and developed relationships that appear to be the most satisfactory to date. Equations and charts can be used to define the maximum expected earthquake magnitude. Because of considerable scatter in the data, one should determine magnitudes using several different techniques and select the best value based on the specific fault characteristics and seismological data. Plots of magnitude versus log of maximum surface displacement or log of length of surface rupture usually provide the best magnitude estimates. Other values that should be considered are provided by plots of magnitude versus log of the displacement times length and magnitude versus log of the length times displacement squared. For each chart Slemmons (1977) plots curves using worldwide data, North American data, and data for specific fault types. Results from each of these curves should be examined to determine the expected maximum magnitude for surface rupture on a particular fault.

1.3. DEFINITION OF POTENTIALLY ACTIVE FAULTS

Faults capable of future movement are often termed active faults. Many definitions have been proposed for active faults, but none is universally accepted (Slemmons and McKinney, 1977). They range from seemingly simple definitions such as that of Willis (1923) who distinguishes between active and dead faults as follows: "An active fault is one on which a slip is likely to occur. A dead fault is one on which no movement may be expected...", to highly specific definitions such as that used by the U. S. Atomic Energy Commission (1973). They define a capable fault as having one or more of the following characteristics:

1. Movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years.

2. Macro-seismicity instrumentally determined with records of sufficient precision to to demonstrate a direct relationship with the fault.

3. A structural relationship to a capable fault according to characteristics 1 or 2 of this paragraph such that movement on one could be reasonably expected to be accompanied by movement on the other.

In the southern Rocky Mountains a period of widespread block faulting and accompanying volcanism initiated about 25 to 28 million years ago and has continued, at least to a limited extent, into the present (Tweto 1979a; Taylor, 1975a; Scott, 1975a). Many of the faults active during this tectonic period displace rocks of Miocene and Pliocene age or they offset the late Eocene erosion surface. Quaternary activity on these faults often cannot be easily documented because of a general absence of Quaternary deposits with which cross cutting relationships could be established. Faults that have moved during this period of Neogene block faulting (Miocene and younger age) should, in our opinion, be considered "potentially active faults" that are suspected of being capable of generating future earthquakes. These potentially active faults should be thoroughly evaluated during detailed earthquake hazard investigations to determine their activity during the Quaternary. The decision as to whether or not a specific fault is "active" and needs to be accounted for in the design of a structure depends upon the particular definition selected or applied for each project. Critical, high-risk structures should utilize definitions that assure minimization of seismic hazards. Low-risk facilities such as single-family homes may choose more restrictive definitions of active faults to avoid unfavorable cost/benefit ratios.

1.4. ACKNOWLEDGMENTS

This study was a two-year cooperative effort between the Colorado Geological Survey and the U.S. Geological Survey and was supported by U.S.G.S. Grant 14-08-001-G-239. We thank the U.S. Geological Survey, in particular Wallace R. Hansen, for financial assistance and cooperation in making both file and other information available to us.

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Trench excavation of the graben near Golden would not have been possible without the permission of William Parfet, landowner of the site. Michael W. West contributed significantly to the geologic evaluation of the trench exposures and was especially helpful in the study of the surface soil and paleosol at the site. Mr. West also led the authors on a field excursion to view evidence of recent fault movement on the Frontal fault along the east side of the Gore Range. We thank Glen A. Izett and Charles W. Naeser of the U.S. Geological Survey and John Boellstorff of the Nebraska Geological Survey for their analysis of the volcanic ash

exposed in the excavation. Their age dates provided absolute age control on the timing of recent movements on the graben.

The authors are indebted to Richard Burroughs and Herbert Dick of Adams State College for their advice about the geology and archaeology of San Luis Valley. Arrangements for the low-sun-angle flight reconnaissance of the Sangre de Cristo fault were made by Dr. Burroughs and Art Benson. Blast records kept by Seneca Coals, Ltd., Pittsburgh and Midway Coal Mining Company, and Energy Fuels Corporation aided our microearthquake study of the Elkhead Mountains-Steamboat Springs region. The microearthquake study would have been impossible without the help of David Butler of Microgeophysics Corporation.

2. REGIONAL SEISMOTECTONIC SETTING

Colorado lies well within the interior of the North American Plate far from any known active plate boundary. It is on the eastern edge of an area within the western United States that has experienced tremendous extensional crustal spreading and associated volcanism during the late Cenozoic. A major intracontinental rift, the Rio Grande rift, forms the easternmost prominent expression of this regional extension. The Rio Grande rift dominates the late Cenozoic tectonic history of Colorado and strongly influences the Neogene activity of many faults in Colorado that are adjacent to the rift (Tweto, 1979a).

2.1. TECTONIC HISTORY

Tectonic activity in Colorado dates back well into the Precambrian. Tweto (1980a,b) describes recurrent movement on major faults and shear zones during the Precambrian that accompanied an early period of intense folding, three periods of batholithic intrusion, and three periods of localized sedimentation which probably occurred in deep tectonic troughs or rifts. Many of the faults and shear zones underwent strike-slip movement, but direction of movement repeatedly reversed on some faults and dip-slip movement occurred on others in later times. Four major Precambrian fault trends are recognized in Colorado by Tweto (1980a,b): an extensive zone of north to northwest-trending faults, a northeast trend coincident with the Colorado Mineral Belt, a west-northwest trend that extends across much of southern Colorado, and an east trend in the northern Front Range. Figure 2 illustrates the location of the major Precambrian fault and shear zones.

The north-northwest trend dominates the Precambrian structural zones. The Ilse-Gore system is the most extensive group of faults with this trend. It includes the Ilse, Currant Creek, South Park, Gore and Frontal (Blue River) faults and extends from the Wet Mountains through South Park at least to the north end of the Gore Range. Tweto (1980b) suggests the faults on the west side of the Park Range are en echelon continuations of the Ilse-Gore system, and that the Ilse fault runs south-southeastward in the subsurface and forms the western edge of the Apishapa uplift. Also included in the north-northwest trend are numerous faults within the Front Range, some of which are described as breccia reefs and dikes that are often highly mineralized.

A system of faults with northeast trend are coincident with the Colorado Mineral Belt. Two of the prominent shear zones within this system are the Homestake shear zone in the northern Sawatch Range, and the Idaho Springs-Ralston shear zone in the eastern Front Range. This zone of faulting probably continues in the Precambrian rocks that underlie the plains of eastern Colorado. Laramide activity on the eastern part of the fault system is indicated by appreciable thinning and erosion of the Niobrara Formation (Weimer, 1978, 1980) and structural uplift of Late Cretaceous and early Tertiary formations along the Greeley arch (Kirkham and Ladwig, 1979). Warner (1978, 1980) suggests this northeast-trending zone of faulting is part of a mega-shear zone that he calls the Colorado

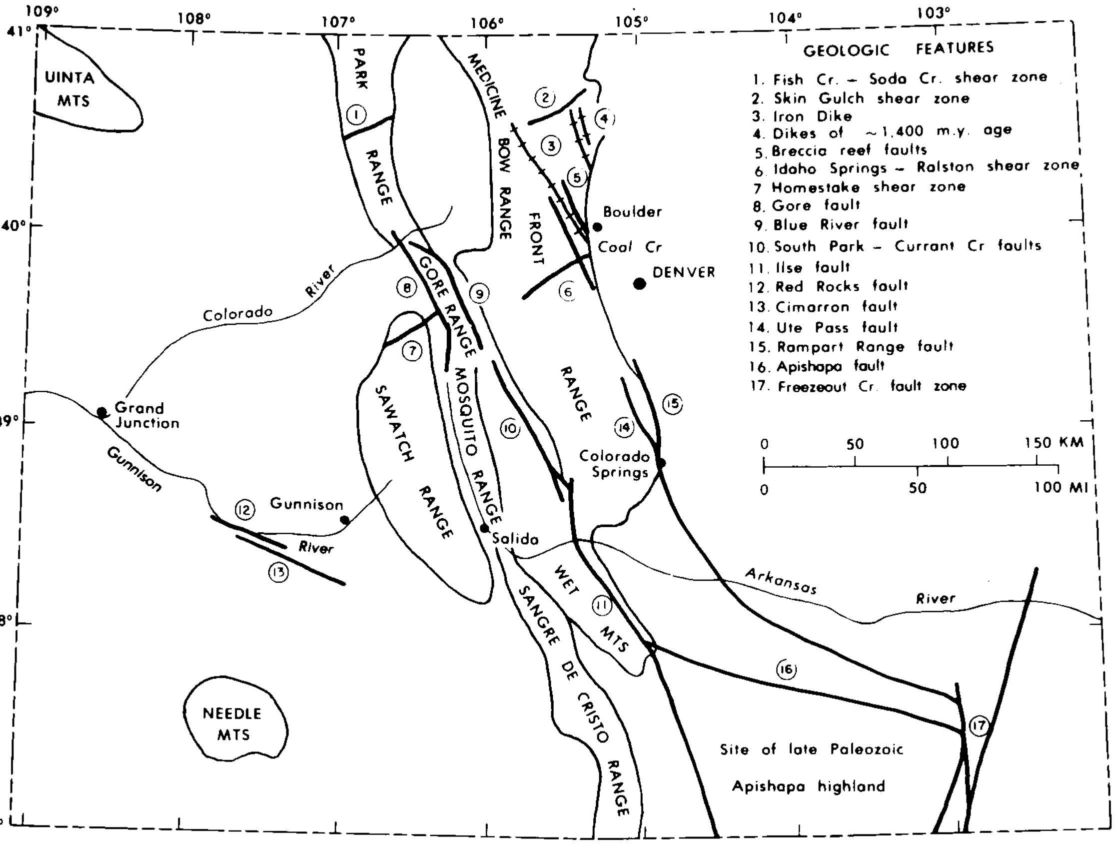


Figure 2. Principal Precambrian faults and shear zones. (from Tweto, 1980b)

lineament. Warner believes the zone of faulting continues southwestward to northern Arizona and may possibly run as far northeastward as Lake Superior.

Precambrian faults of west-northwest trend extend across much of southern Colorado. Tweto (1980b) indicates this system of faults bounds the north edge of the Apishapa uplift and continues across the Wet Mountains and northern Sangre de Cristo Mountains. To the west the principal faults with west-northwest trend are the Cimarron and Red Rocks faults, but indications of this fault system are also apparent in Utah.

Faults of the east trend are found in the northern Front Range, but not to the west in the Medicine Bow Range. These faults are mappable only for short distances, but are represented by wide crushed or sheared zones that show evidence of repeated movements, primarily in a dip-slip manner (Abbott, 1976; Tweto, 1980b).

The early and middle Paleozoic were times of repeated regional uplift (epiorogeny) with only minor fault activity and very localized, mainly Cambrian, igneous intrusion. Renewed tectonism initiated during the late Paleozoic when three large uplifted areas rose in Colorado. These areas, the Uncompahgre-San Luis, Front Range, and Apishapa highlands, comprise the Ancestral Rocky Mountains. Locations of these highlands, as illustrated in Figure 3, were in part controlled by Precambrian fault zones. Tweto (1980a) suggests all three uplifts were fault bounded on one flank, but only upwarped at a moderate angle on the other flank. Abrupt formation thickening occurs along the fault-bounded flanks of the Uncompahgre-San Luis and Front Range highlands. For instance, the central part of the west flank of the Front Range highland was bounded by the Gore fault. On the east side of the Gore fault the Jurassic Morrison Formation rests on Precambrian rocks, but on the west side about 3,000 m of Paleozoic and lower Mesozoic rocks are between the Morrison and the Precambrian.

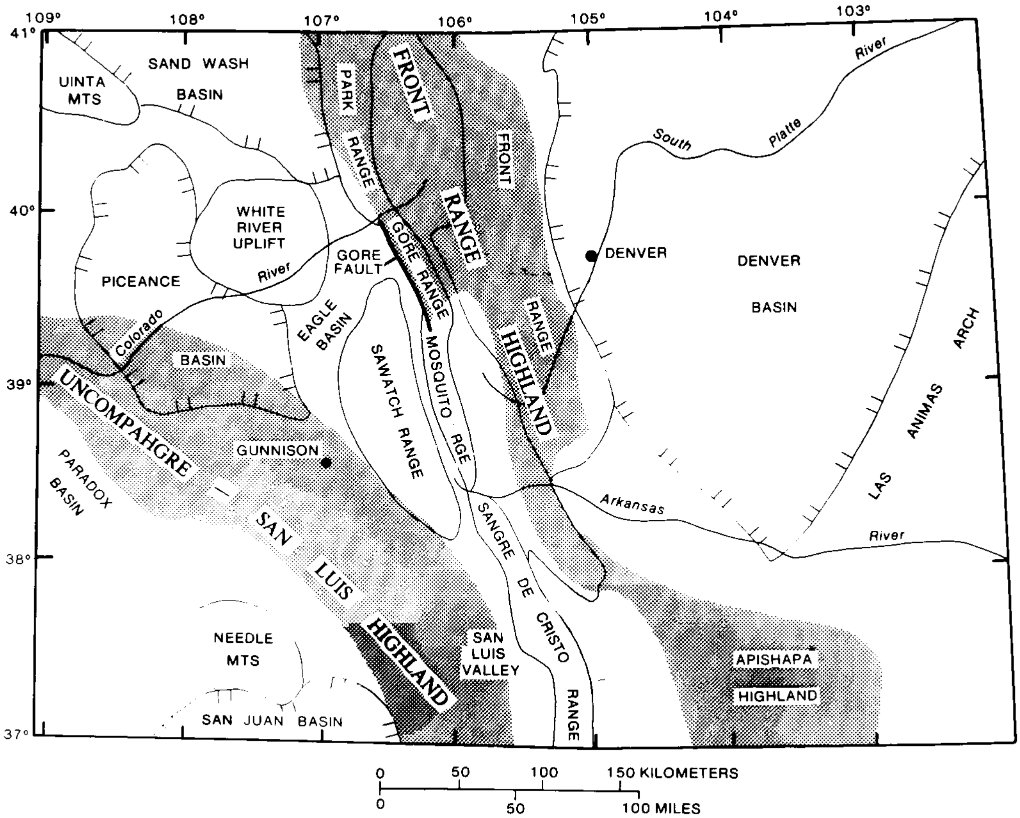


Figure 3. Late Paleozoic uplifts of the Ancestral Rocky Mountains in Colorado. Uplifted areas are indicated by the shaded pattern. (from Tweto, 1980a)

Late Paleozoic deformation was not restricted to uplifts, but also occurred within sedimentary basins. This deformation was not of a tectonic nature, but was instead related to plastic flowage of thick sequences of evaporite deposits. Flowage of salt within the Paradox member of the Pennsylvanian Hermosa Formation created northwest-trending salt anticlines in the Paradox basin that were located along pre-Paradox faults (Cater, 1970). These salt anticlines were later exposed by erosion and their crests collapsed during the late Tertiary. Folding and flowage of evaporite deposited in the Eagle basin between the Front Range and Uncompahgre highlands began in the Permian, continued through the Triassic, and later resumed during the Laramide and late Tertiary. Flowage and associated deformation in both areas has continued into the Holocene (Kirkham and Rogers, 1978).

During much of the Mesozoic, Colorado was tectonically quiet. This period of quiescence ended with initiation of the Laramide orogeny at the close of the Cretaceous. Orogenic activity began at different times in different places within the state. The principal Laramide uplifts and basins are shown in Figure 4. Uplift of the Sawatch anticline and the rejuvenated southeast end of the Uncompahgre-San Luis highland about 72 m.y. ago marked initial stages of the Laramide orogeny (Tweto, 1975b, 1980c). Between 65 to 70 m.y. ago, renewed uplift of the late Paleozoic Front Range highland resulted in the Front, Medicine Bow, Park, and Gore Ranges, while simultaneous structural sags formed North, Middle, and South Parks (Tweto, 1975b, 1980c). Other uplifts, including the Uinta Mountains, Needle Mountains, and northwestern end of the late Palezoic Uncompahgre-San Luis highland, also rose at this time. Concurrently, basins adjacent to the uplifts, such as the San Juan, Denver, Piceance, Sand Wash, and Raton basins were created. Orogenic activity continued through the Paleocene, when the northeastern part of the Front Range and Laramie Ranges were uplifted, and into the Eocene as the White River Plateau began to rise (Tweto, 1975b, 1980).

The Laramide orogeny terminated in a manner similar to its beginning in that activity ended at different times at different places. Throughout the Laramide orogeny, particularly during its later stages, erosion removed large amounts of rock from uplifted areas and redeposited it in adjacent sedimentary basins. Erosion continued after the close of the orogenic period and by the end of the late Eocene a widespread erosional surface had developed over much of Colorado (Epis and Chapin, 1975; Epis and others, 1976b, 1980). Most of the surface was a broad undulating plain with local relief of only a few hundred meters between channels and ridges.

Extensive, intermediate volcanism characterized the Oligocene. Widespread volcanic flows and volcaniclastic sedimentary rocks were deposited throughout much of the state on the late Eocene erosion surface. Volcanic centers were located in the Thirtynine Mile area, San Juan Mountains, Wet Mountain Valley, Cripple Creek area, and several other areas. Eaton (1979) suggests these centers were part of the intermediate volcanic arc related to the underlying subducted Farallon Plate.

A major episode of extensional faulting associated with development of the Rio Grande rift began about 28 m.y. ago in Colorado (Tweto, 1979a) and

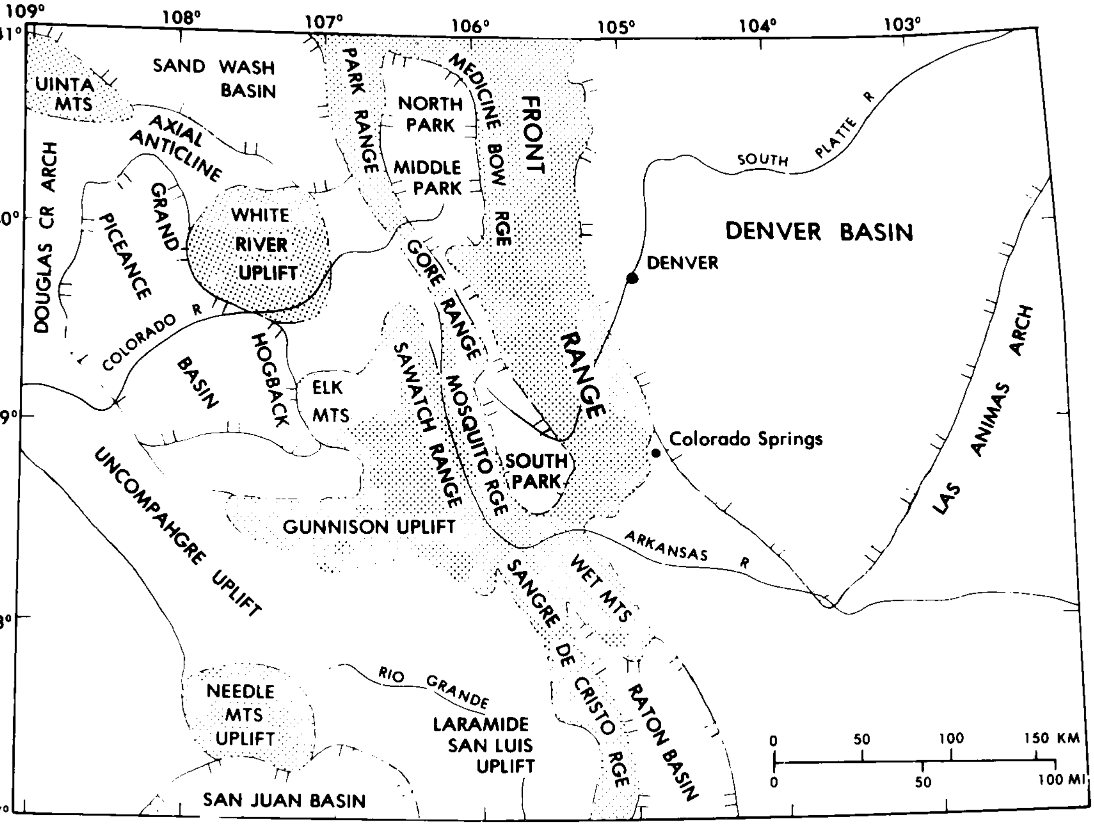


Figure 4. Laramide uplifts and basins in Colorado. Topographically prominent uplifts are shaded. (from Tweto, 1980a)

continued through the Neogene. This deformation is intimately associated with the regional extension experienced by much of the western United States that initiated at about the same time or shortly thereafter (Eaton, 1979). New faults formed during this period, but many faults of Precambrian, late Paleozoic, or Laramide age were reactivated. The Neogene faults offset the late Eocene surface and overlying deposits thousands of meters in some areas. Bimodal basalt-rhyolite volcanism, local intrusions, and sedimentation in grabens and down-faulted areas accompanied extensional faulting.

The Rio Grande rift dominates Neogene faulting in Colorado. Prominent physiographic expression of the rift extends through the San Luis and upper Arkansas Valleys to near Leadville. A belt of faults probably associated with the rift continue northward to near the Wyoming border. At this point the rift-related faults die out in a zone of west to northwest-trending faults associated with an older, recurrently active tectonic zone (Tweto, 1979a, 1980a). A number of additional faults were activated by extensional tectonism and are probably related in some manner to the Rio Grande rift. They include faults on the east side of the Sangre de Cristo Range, on both sides of the Wet Mountains, in North, South, and Middle Parks, and within and east of the Front Range. Faults that bound the Uncompahgre uplift were also reactivated during this period of extension, but their relationship with the Rio Grande rift is not known.

Faults that have moved during this period of Neogene tectonism are considered very relevant to this investigation. Many of them show evidence of Quaternary movement, several offset late Quaternary deposits, and a few are documented to have moved during the Holocene. Future damaging earthquakes in Colorado may result from recurring movement on these faults.

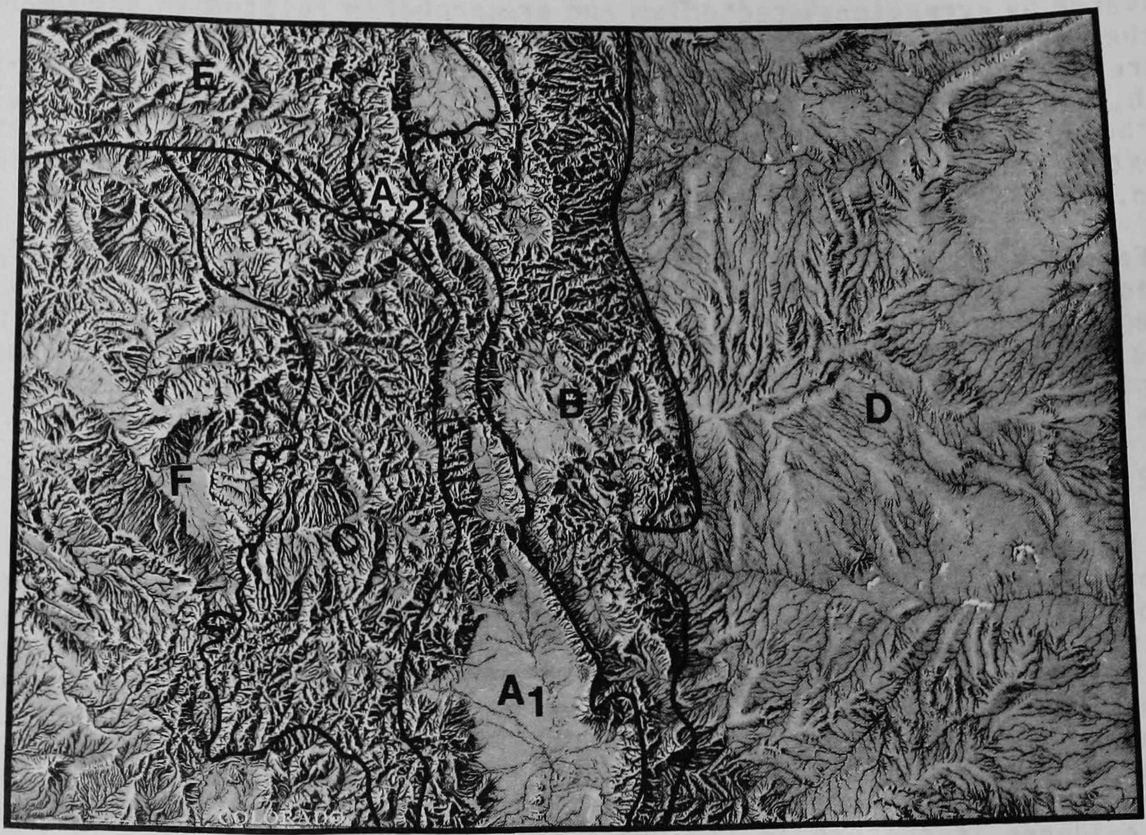
2.2. SEISMOTECTONIC PROVINCES

Seismotectonic provinces in Colorado, as shown in Figure 5, can be delineated by the distribution and characteristics of Neogene faults, historical earthquakes, major structural and physiographic regions, and our interpretation of earthquake potential. Designated provinces include the Rio Grande rift, eastern mountain, western mountain, plains, Uinta-Elkhead, and Colorado Plateau provinces. The Rio Grande rift may be futher subdivided into northern and southern subprovinces on the basis of young faulting. Well-defined evidence of repeated, late Quaternary movements is abundant on several faults in the southern province, whereas such evidence is obscure in the northern province.

The Rio Grande rift province extends through Colorado from New Mexico to near the Wyoming border, almost bisecting the state. A high percentage of all potentially active faults in the state are within this province. Included in the southern Rio Grande rift subprovince are the west flank of the Sangre de Cristo Range, San Luis Valley, easternmost part of the San Juan Mountains, and Poncha Pass area. The east flank of the Sawatch Range, upper Arkansas Valley, and west flank of the Mosquito Range up to the Mount Oxford-Buffalo Peaks area are also included in the southern Rio Grande rift province. The northern parts of the Sawatch Range, upper Arkansas Valley, and Mosquito Range, and the Gore Range, Blue River Valley, upper Yampa River Valley and part of the west flank of the Park Range are within the northern Rio Grande rift subprovince.

The southern Rio Grande rift subprovince is characterized by two long and deep graben complexes (San Luis and upper Arkansas Valleys) separated by a horst block (Poncha Pass area). As is shown later, San Luis Valley actually is a complex half-graben that encompasses a buried horst. The Sangre de Cristo fault, a Holocene fault, bounds the east side of San Luis Valley. The Sawatch fault, also active during the Holocene, forms the west side of the southern graben in the upper Arkansas Valley. A series of step faults border the east side of this valley.

A number of major faults, many of which have ancestry dating back as far as the Precambrian, are within the northern Rio Grande rift



EXPLANATION

A_1	Southern Rio Grande Rift subprovince
A_2	Northern Rio Grande Rift subprovince
B	Eastern Mountain province
C	Western Mountain province
D	Plains province
E	Uinta - Elkhead province
F	Colorado Plateau province

Figure 5. Seismotectonic provinces in Colorado.

subprovince. They include the north end of the Mosquito fault, and the Gore, Frontal (Blue River), and Steamboat Springs faults. North of the Colorado River, the rift begins to die out. Near the Wyoming state line the rift merges with a zone of west to northwest-trending faults in the Uinta-Elkhead province. The nature of this union is not clear, but it appears that movement within the fading rift province is translated to movement on faults in the Uinta-Elkhead province.

The eastern mountain province lies between the Rio Grande rift and plains provinces. It includes the Front and Medicine Bow Ranges, Middle and South Parks, Wet Mountains, Wet Mountain Valley, and the east flanks of the Mosquito and Sangre de Cristo Ranges. Delineation of the western boundary of this province was difficult and at places arbitrarily selected. Most of the faults in this province have Laramide, late Paleozoic, or even Precambrian ancestry (Tweto, 1979a). Several of the faults, particularly those in the southern and central parts of this province show considerable Neogene movement. A few of these faults have moved during the Quaternary, and the one fault that has been studied in detail offsets late Quaternary deposits (Shaffer, 1980). The distribution, orientation, and character of Neogene movement on these faults suggest rejuvenation is related to the extensional stresses responsible for rifting.

Mountainous areas to the west of the Rio Grande rift province form the western mountain province. Included in this province are the San Juan Mountains, Elk and West Elk Mountains, west flank of the Sawatch Range, White River uplift, and Gunnison uplift. Neogene faults are relatively scarce in this province. Many of the ones that are present are not truly tectonic features, but rather are the result of evaporite flowage or caldera collapse. Despite an apparent absence of major Neogene tectonic faults, numerous earthquakes have been felt and/or instrumentally located in the western mountain province (Plate 3).

Over one-third of Colorado is within the plains province that lies east of the Rocky Mountain front. Neogene faults are rare in this province; only four have been recognized to date (Plate 1). Historic movement on one of these four, the Rocky Mountain Arsenal fault, was triggered by deep fluid injection. The other three faults show evidence of Quaternary movement (Scott, 1970; Kirkham and Rogers, 1978). Though most of this province appears "stable", a number of eathquakes have occurred in it historically (Plate 3). The majority of these earthquakes were associated with fluid injection at the Arsenal, but several have occurred in the southern part of this province along the Arkansas River Valley. In contrast, the northeastern part of the plains province is relatively free of historic earthquakes. This apparently anomalous earthquake distribution may relate to the intense faulting in Precambrian rocks in the southern part of the province and/or to proximity to other active zones, particularly the Rio Grande rift zone.

The Uinta-Elkhead province, a zone of west to northwest-trending faults, effectively terminates the north to northwest-trending Rio Grande rift province near the Wyoming border. Included in the Uinta-Elkhead province are the collapsed Uinta arch, faults that bound Cross Mountain, a series of en echelon faults near Craig, a number of faults that cut through the Elkhead Mountains, and the Spring Creek and associated faults in North Park. Tweto (1979a) suggests the Spring Creek fault may extend eastward and join a long fault of Precambrian origin in the Front Range. Geophysical data indicate these west to northwest-trending faults are surface expressions of deep crustal structure (Tweto, 1979a). Long, west-trending magnetic and gravity highs coincide with the Uinta-Elkhead province (Zietz and Kirby, 1972; Behrendt and Bajwa, 1974). Seismic crustal studies show crustal thinning in this area from about 50 km thick on the south to about 35 to 45 km on the north (Jackson and Pakiser, 1965). The boundary between 1.8 billion year (b.y.) old Precambrian rocks in Colorado and rocks older than 2.5 b.y. in Wyoming generally coincides with the Uinta-Elkhead province (Tweto, 1979a).

The Colorado Plateau seismotectonic province generally corresponds to the physiographic and structural province known as the Colorado Plateau. In Colorado the boundaries of this province are usually well defined, but in a few places they are not. The Grand Hogback and western and southern edges of the San Juan Mountains clearly outline part of the east edge of the Colorado Plateau province, but between these areas and north of the Grand Hogback, the boundary is arbitrarily located. For this report the Elk and West Elk Mountains are included in the western mountain province, although the province boundary could have extended eastward in this area to the west base of the Sawatch Range. At about Meeker prominent expression of the Grand Hogback wanes. We extend the border of the Colorado Plateau northwest from this area along the west edge of the Axial basin arch to the Uinta-Elkhead province.

Except for the Uncompahgre uplift, the Colorado Plateau province appears to be fairly stable tectonically. A series of faults associated with collapsed salt anticlines and evaporite flowage in Paradox and Big Gypsum Valleys show considerable Neogene movement and some late Quaternary and Holocene activity, but their non-tectonic origin and movement due to plastic deformation indicate a low potential for even moderate-sized earthquakes. The Uncompahgre uplift, however, is a major tectonic feature that has been recurrently active at least since the late Paleozoic. Some faults that flank the uplift show evidence of Quaternary activity and Cater (1966) infers considerable Quaternary uplift of the entire structure based on abandonment of Unaweep Canyon. One fault on the southeast end of the uplift, the Ridgeway fault, has microseismicity associated with it (Sullivan and others, 1980). Quaternary movement may also have occurred on one or more of the northwest-trending faults in the Piceance basin.

2.3. ESTIMATED MAXIMUM CREDIBLE EARTHQUAKES

Since this investigation was first published as an open-file report, we have received numerous requests from both regulatory and industry groups for some suggestive guidelines for seismic safety evaluations on many different kinds of projects. In a later section of this report we express the opinion that all of Colorado, except perhaps the extreme northeast corner, probably should be considered as Zone 2 in the U.B.C. scheme of seismic zonation. For provisional evaluation of projects, we have prepared a table which is intended to be suggestive of maximum credible seismic events in each seismotectonic province of the state. Use of this table should be limited to areas not directly affected by known potentially active faults or fault zones. Projects located in known fault zones will almost certainly require detailed site investigations.

Furthermore, even in parts of a seismotectonic province that are relatively remote from known faults, a minimum of 0.1 g horizontal acceleration should probably be used in design and safety analyses.

For any given project, the degree of conservatism required as well as the intensity of investigative effort will depend in part on the severity and extent of possible off-site impacts and the period of time for which integrity of project construction is needed.

The following table presents our estimates of the magnitude of maximum credible earthquakes for each seismotectonic province. Our estimates are based on fault lengths and displacements, recency of movement, historical earthquakes, stress/strain information, and comparisons with other areas that have similar seismotectonic characteristics. These approximations can be used as very general guides to future seismicity in Colorado, but they are not meant to be substituted for detailed, site specific evaluations for critical facilities.

Southern Rio Grande Rift Subprovince:	M = 6.5 to 7.5
Northern Rio Grande Rift Subprovince:	M = 6 to 7
Eastern Mountain Province:	M = 6 to 6.75
Western Mountain Province:	M = 6 to 6.5
Plains Province:	M = 5.5 to 6
Uinta-Elkhead Province:	M = 5.5 to 6.5
Colorado Plateau Province:	M = 5.5 to 6.5

3. DESCRIPTION OF POTENTIALLY ACTIVE FAULTS

This section summarizes available information on Neogene or potentially active faults in Colorado. The descriptions are grouped by seismotectonic provinces beginning with the Rio Grand rift province. All known potentially active faults are plotted and labeled on Plate 1. The number on each fault group indicates the fault number assigned herein that is used in the text and keyed to Appendix 2, a chart summarization of the important characteristics of all potentially active faults. The group of letter symbols associated with each fault on Plate 1 and Appendix 2 indicates the age of most recent movement. The first letter symbol represents the youngest deposit known to be offset by the fault. The second letter symbol indicates the oldest deposit that covers the fault.

3.1. RIO GRANDE RIFT PROVINCE

The Rio Grande rift province extends from Mexico, through west Texas and New Mexico, and into Colorado to near the Wyoming line (Figure 6). Distinctive physiographic expression of this structural province, which Tweto (1979a) has referred to as the Rio Grande rift proper, is found as far north as Leadville. This generally corresponds to the southern Rio Grande rift subprovince. A belt of high-angle Neogene faults continues north to northwest from the Leadville area (Plate 1). Faults within this belt are similar both in character and in timing of deformation to faults within the Rio Grande rift proper (Kirkham and Rogers, 1978; Tweto, 1979a). For this reason these faults are included in the Rio Grande rift province in this report. Development of the Rio Grande rift initiated in the early Neogene and has actively continued through the Quaternary. The rift is characterized by Neogene basin-fill sedimentary rocks, a bimodal suite of mafic and silicic igneous rocks, and abundant features suggestive of recently active faults, such as fault scarps in young alluvium, abrupt mountain fronts that exhibit faceted spurs, and deep, narrow, linear valleys.

San Luis Valley is a complexly faulted basin that appears as a half-graben on the surface. A major fault along the steep western front of the Sangre de Cristo Range, the Sangre de Cristo fault (fault groups 113 through 116), bounds the east side of the valley. The west flank of the valley consists of east-dipping Oligocene volcanic rocks from the San Juan Mountains that locally are broken by small-displacement faults.

Most of the San Luis Valley, except for its northernmost end, is situated on the late Paleozoic Uncompahgre-San Luis highland and the Laramide age San Luis uplift. The Sangre de Cristo Range and upper Arkansas Valley extend across a late Paleozoic sedimentary basin that separated the Uncompahgre-San Luis and Front Range highlands. The upper Arkansas Valley also cuts through the east flank of the Laramide Sawatch anticline. From near Breckenridge northward, the rift is on or near the west flank of the late Paleozoic Front Range highland (Tweto, 1979a).

The upper Arkansas Valley consists of a northern and southern graben separated by a Precambrian high. The Sawatch fault borders the west flank of the southern graben, whereas a series of faults flank the west side of the northern graben. A group of step faults form the east side of both grabens. East-trending cross valley faults terminate the south end of the northern graben near Twin Lakes.

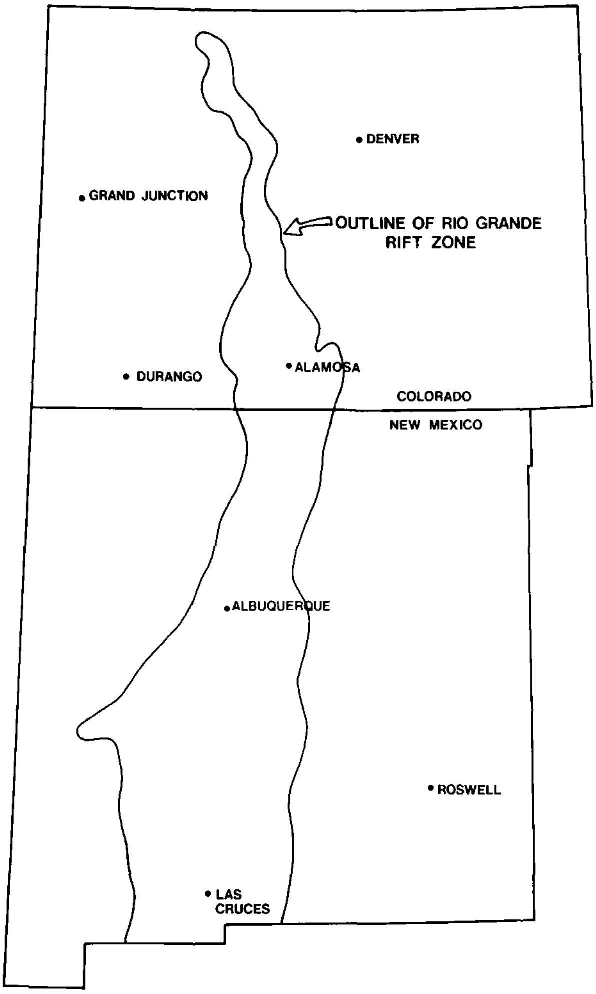


Figure 6. General outline of the Rio Grande rift province in Colorado and New Mexico.

3.1.1. SAN LUIS VALLEY

The Rio Grande rift enters Colorado through the large, north-trending San Luis Valley. The valley is about 160 km long and up to 75 km wide. In Colorado it is bounded on the east and north by the towering, upfaulted Sangre de Cristo Range and on the west by dip slopes from the San Juan Mountains. The valley floor is nearly flat, interrupted only by the uplifted San Luis Hills and local low relief features such as sand dunes in other areas. Elevation of the valley floor averages about 2,450 m.

Subsurface valley structure is interpreted by use of surface geology, gravity and resistivity data, and a few deep drill hole logs. Thick alluvial and eolian deposits cover most of the valley floor and bury the underlying structure. Two horst blocks disrupt the basin. One horst lies in the south end of the valley and includes the San Luis Hills. This block has been elevated along the Manassa fault, a high-angle normal fault that extends from near the base of Blanca Peak southwestward to Antonito. A second horst block extends to the north from this area and forms a mid-valley structural high (Plate 1).

A gravity study by Gaca and Karig (1965) contributed significantly to understanding the subsurface valley structure. Their work not only confirmed the presence and magnitude of the Sangre de Cristo fault, but also revealed the mid-valley, north-trending horst bounded on the east by a deep graben and on the west by a half-graben. Figure 7 is a Bouguer gravity map of the San Luis Valley area. The broad, mid-valley gravity high is the horst described by Gaca and Karig (1965) and the elongated gravity lows on the east and west flanks of the gravity high are the grabens. A prominent 60 milligal low in T.41N.,R.11E. is believed to mark the location of maximum thickness of Cenozoic valley fill, estimated to be 9,754 m thick by Gaca and Karig (1965) using a density of 2.37 gm/cc for the valley fill. This thickness is probably excessive, as is indicated by reinterpretation of the gravity data by Huntley (1976). Huntley, using density values obtained from a deep drill hole near the 60 milligal anomaly, computed the maximum thickness of valley fill at 5,029 m. Interpretation of seismic reflection data by Stoughton (1977) suggests about 6,000 m of fill at this location. This thickness estimate also agrees with recent gravity work by Davis and Keller (1978).

Deep drill holes in the valley provide absolute control on subsurface structure. A 3,011 m deep oil test, AMOCO 1-32 State Well, was drilled into the eastern graben in sec. 32, T.40N., R.12E. about 15 km south of the gravity low (Figure 7). The well bottomed in volcanic and volcaniclastic rock thought to be of Oligocene age, suggesting basement rock is at least 4 km deep at this location (Tweto, 1979a). The TENNECO 1-B State Well was drilled in the western graben in sec. 14, T.41N., R.7E. It penetrated 3,024 m of Cenozoic valley fill (sedimentary and volcanic rocks) before encountering granitic gneiss. Pre-Cenozoic basement rock was reached at a depth of 1,430 m by AMERADA 1-F State Well, drilled over the mid-valley horst in sec. 16, T.39N., R.10E.

Figure 8 is an interpretive east-west cross section through the central part of the San Luis Valley prepared by Tweto (1979a) from surface geology, drill hole information, and gravity interpretations. The east side of the valley is bounded by the Sangre de Cristo fault, the dominant fault of the entire valley. Basement rock has been offset about 5.5 km since the Eocene along the Sangre de Cristo fault. As described in the following section, the Sangre de Cristo fault has probably been the most active fault in the entire state during the Neogene.

The Sangre de Cristo fault bounds the east side of the deep graben while the west side of this graben is step-faulted along at least two faults (fault numbers 183 and 184). Fault number 184 appears to correlate with a fault exposed at the surface that trends through Mineral Hot

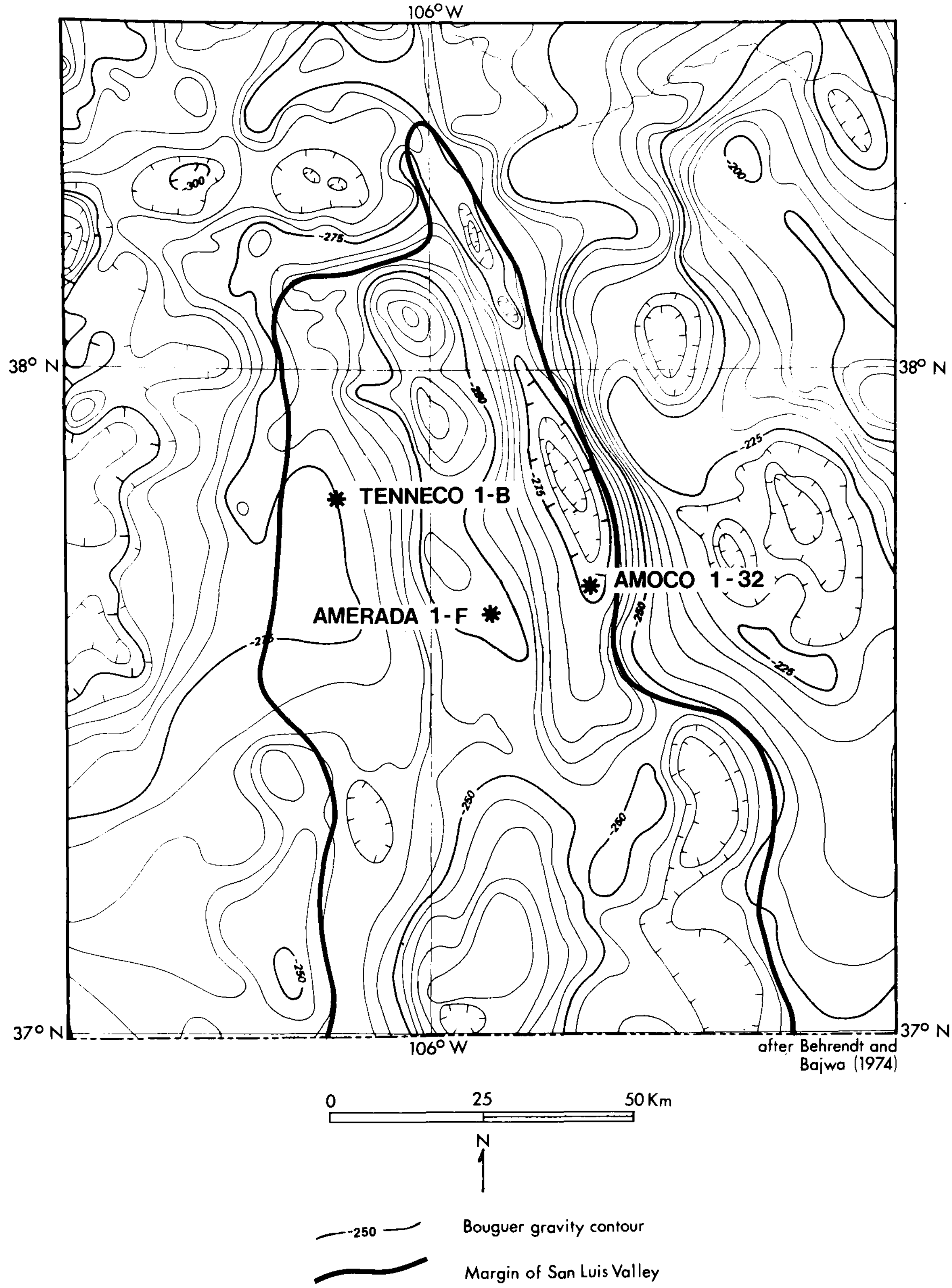


Figure 7. Bouguer gravity map of San Luis Valley. (from Behrendt and Bajwa, 1974)

Springs and offsets late Quaternary deposits. If this correlation is correct, it is the only fault that bounds the mid-valley horst that is known to have moved during the late Quaternary. The west side of the mid-valley horst is formed by fault number 182, but there is no evidence of late Quaternary movement on it. Surface geology and drill hole information indicate the westernmost part of the San Luis Valley is an east-tilted half-graben that gently dips eastward from the San Juan Mountains towards fault 182. Anomalous thickening and thinning of Eocene and Oligocene rocks in the graben and over the horsts has been interpreted by Tweto (1979a) to be due to early rifting that probably initiated in the middle Oligocene.

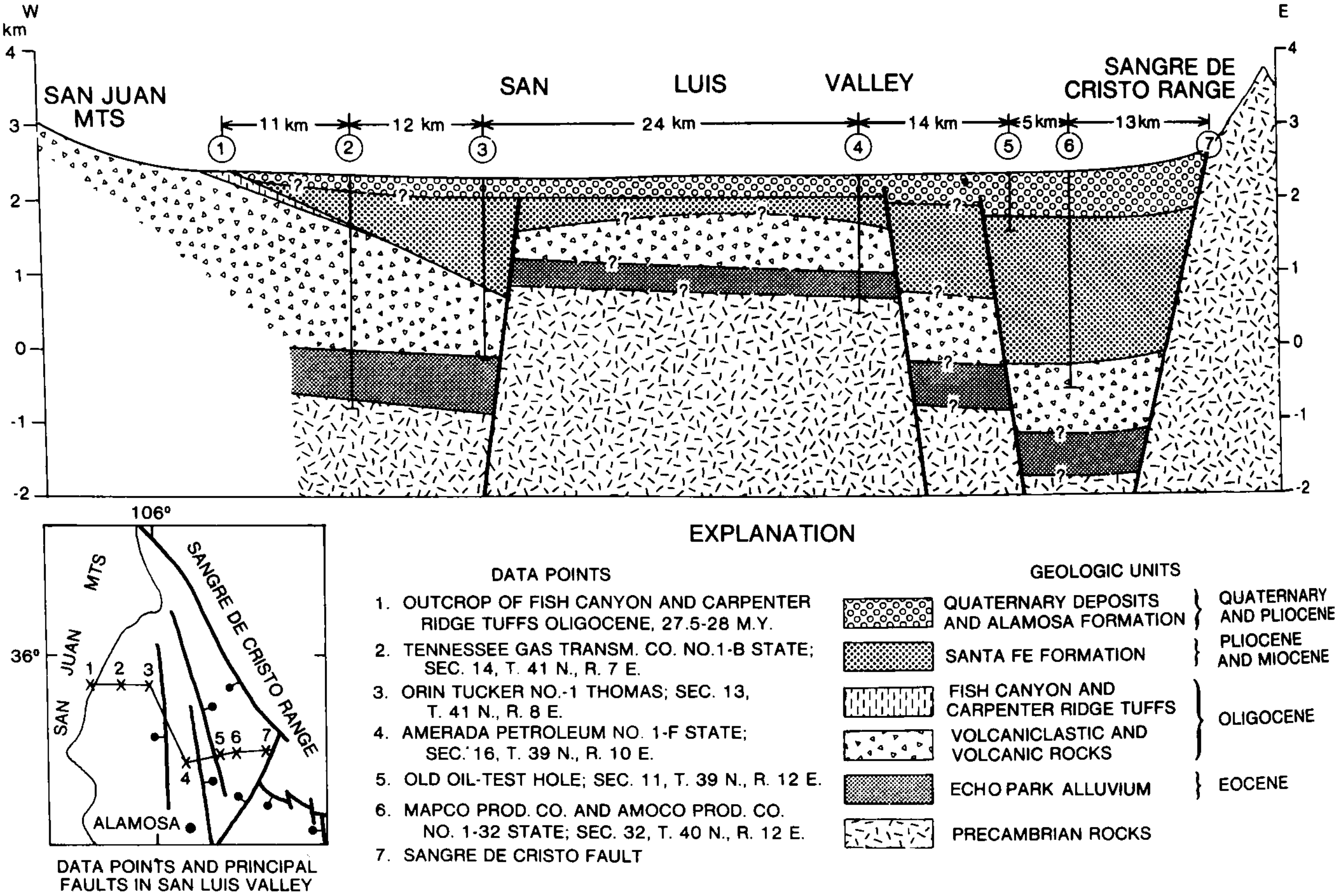


Figure 8. Interpretive east-west cross section through the central part of San Luis Valley. (from Tweto, 1979a; copyrighted by the Amer. Geophysical Union)

A second horst that consists of a series of upthrown blocks of Oligocene Conejos Formation and Pliocene Servilleta Formation extends across the south end of San Luis Valley. The Manassa fault (fault number 107) bounds the northwest flank of this upfaulted block and separates the San Luis Hills from the Alamosa basin (Burroughs, 1978). Existence of the Manassa fault is based on gravity and geomorphic interpretations. A noticeable gravity high coinçides with the San Luis Hills on the south-southeast side of the fault and the fault is marked by a steep gravity gradient (Figure 7). Geomorphic evidence suggests the San Luis Hills have been uplifted and exhumed. Volcanic flows and cinder cones on the horst block were at one time largely covered by unconsolidated sands and gravels that are now being stripped by erosion. The Rio Grande River flows near the general level of the valley floor in the Alamosa basin, but has carved a canyon over 100 m deep in the volcanic rocks on the upthrown side of the Manassa fault.

Structure of the northern part of San Luis Valley north of Mineral Hot Springs has recently been studied by Stoughton (1977) and Davis and Stoughton (1979) using seismic reflection data. The structure is very complex and several major faults other than the Sangre de Cristo fault are evident in the subsurface. This portion of the valley coincides with a zone of deformation that formed the east flank of the late Paleozoic Uncompahgre-San Luis highland and possibly the Laramide San Luis uplift (Davis and Stoughton, 1979; Tweto, 1980a, 1980c). Many of these older flank faults have been reactivated during Neogene rifting. The Villa Grove fault zone (fault number 118) may coincide with one of these older faults.

The Sangre de Cristo fault has long been recognized as a recently active fault (Upson, 1938; Bryan, 1938) and has since been studied by many workers, including Baltz (1965), Johnson (1969), Scott (1970), Knepper and Marrs (1971), Wychgram (1972), Knepper (1974,1976), Taylor and others (1975b), Colton (1976), Huntley (1976), Scott and others (1976), Stoughton (1977), Kirkham and Rogers (1978), Tweto (1979a), and Davis and Stoughton (1979).

The Sangre de Cristo fault from about Blanca Peak northward is a narrow fault zone that is expressed at the surface by fault scarps and scarplets ranging in height from a few centimeters to many tens of meters. Typically, the scarps are discontinuous, colinear surface breaks from a few meters to over a few hundred meters in length. South of the Great Sand Dunes National Monument, however, there is a spectacular, continous scarp over 6 km long (Figure 9). Exceptions to this relatively simple surface expression exist at several places along the length of the fault. At the north end of the valley a zone of numerous short faults, the Villa Grove fault zone, branches from the main trace. Geophysical data suggests a number of cross-valley faults are present in the subsurface of this area (Davis and Stoughton, 1979). At Uracca Creek the fault consists of two main traces about 1.7 km apart (Figure 14) with the most recent movement occurring on the western fault. Some previous investigators believe the western fault may be related to the Manassa fault.

In areas south of the Blanca Peak massif the fault distribution is complex. We believe displacement on the Sangre de Cristo fault in this area is distributed across a wide zone of step faults that have predominant down-to-the-west movement. Included in this zone are fault groups 112, 113, and 117, and fault numbers 109, 110, 114, and 115. The Alvarado fault (fault number 122) may play an important role influencing this change in character of the Sangre de Cristo fault.

Figure 9. Vertical aerial photograph of the Sangre de Cristo fault between Great Sand Dunes National Monument and Zapata Creek. Arrows indicate prominent continuous scarp. (photograph by Army Map Service; held by U.S. Geol. Survey)

Fault group 117 constitutes the easternmost set of faults within the Sangre de Cristo fault zone south of the Blanca Peak area. These faults form the west flank of the Culebra Range and bring the Miocene-Pliocene Santa Fe Formation into fault contact with Precambrian rocks. We know of no evidence of Quaternary movement on any of the faults of this group. Hills to the west of this area are underlain by the Santa Fe Formation. Fault group 113 and fault 115 form a prominent zone of dominantly west-facing scarps that generally separate the hills underlain by the Santa Fe Formation from Quaternary fan deposits to the west (Figures 10 and 13). One of the large scarps shown in Figure 10 is especially obvious because of its height (up to 100 m) and striking influence on stream drainages. Most of these faults offset late Quaternary deposits, and along Rito Seco (Figure 13) late Holocene movement can be demonstrated.

The westernmost fault within the Sangre de Cristo fault zone in this southern area bounds the west flank of San Pedro Mesa (fault number 109). Burroughs (1978) indicates the Servilleta Formation that caps San Pedro Mesa is down-faulted to the west along fault number 109 about 600 m. Any evidence of recent movement on fault number 109 is largely obscured by massive earthflows. The Mesita fault (fault number 108) may also be included in the Sangre de Cristo fault zone.

Several faults within the Sangre de Cristo fault zone exhibit down-to-the-east movement and create small grabens within the overall fault zone. We believe the east flank of San Pedro Mesa may be bounded by such a fault (fault number 110), but it has not yet been proved by drilling. A number of faults disrupt the volcanic cap rock of the Basaltic Hills north of San Pedro Mesa (fault group 112) and appear to form the southwest side of a small graben. Fault number 114 is down-faulted to the east and borders a small graben that is bounded on the northeast by the north end of fault group 117.

On the north end of San Pedro Mesa a suite of small-displacement, N.20°W.-trending faults (fault group 111) cuts the Servilleta Formation that caps the mesa. These faults may be the result of tectonic stresses, but a more reasonable cause is tensional release due to mass movement along the margins of the mesa. San Pedro Mesa consists of unconsolidated, low-strength, sedimentary deposits overlain by the dense volcanic flows of the Servilleta Formation, a situation that readily yields large earthflows around the flanks of the mesa. It is likely that the fractures which disrupt the mesa cap rock (fault group 111) are a result of the lateral removal of material by this mass wasting process.

The Mesita fault, first recognized by Colton (1976), lies west of San Pedro Mesa. It is a high angle normal fault that displaces the Quaternary basaltic Mesita cinder cone a maximum of 13 m in a down-to-the-west manner. The cinder cone is overlain by small outcrops of gravel that have a thick carbonate soil horizon developed on them. This soil profile suggests a pre-Wisconsin age for the gravel. The basalt cinder cone must also be of pre-Wisconsin age, although previous investigations have suggested a Holocene age (Johnson, 1969). Drilling in this area indicates the underlying Servilleta Formation is offset about 15 to 30 m along the Mesita fault (Burroughs, 1978).

Figure 10. Vertical aerial photograph of the Sangre de Cristo fault east of San Luis. Fault indicated by arrows and C-14 sample location indicated by diamond. Area shown in Figure 13 is outlined by the box. (photograph by Army Map Service; held by U.S. Geol. Survey)

The character of the Sangre de Cristo fault is much simpler from La Veta Pass northward and in most places the fault lies at the base of the mountain front. A single prominent scarp marks the fault along much of the south side of Blanca Peak and wraps northward around the west side of the mountain front. Near Uracca Creek two prominent faults about 1.7 km apart represent the fault zone. The most recent fault movements in this area apparently occurred on the westernmost of the two faults, away from the mountain front.

From Zapata Creek northward to Great Sand Dunes National Monument the fault is marked by a single scarp for 6 km (Figure 9). Directly west of one of the lowest parts of the range, the Medano Pass-Mosca Pass area, the fault birfurcates and begins to lose its identity at the surface. For several kilometers, no evidence of recent surface rupturing can be detected on high-altitude aerial photographs. A similar absence of recent surface faulting occurs west of Hayden Pass, another area where there is a low sag in the range crest. North of the National Monument the fault scarps reappear and continue along the range front as discontinuous colinear scarps that extend almost to the Poncha Pass area.

The Villa Grove fault zone (fault group 118) splits off from the range front fault between Garner Creek and Hot Springs Canyon, just south of Valley View Hot Springs (Plate 1). This N.55°W.-trending zone of over 50 discrete scarps and scarplets was first studied by Wychgram (1972) and later by Knepper (1974), Taylor and others (1975b), and Huntley (1976). In general the scarps have their greatest height at the range front and decrease in height to the northwest. Near U. S. Highway 285 the scarps are so small that they can be only detected by low-sun-angle observation from the air, but not on the ground. Figure 11 is a low-sun-angle photograph of part of the Village Grove fault zone. The decrease in scarp height to the northwest is obvious on the photograph.

Several interesting phenomena are associated with the Villa Grove fault zone. In secs. 16, 17, 20, and 21, T.46N., R.10E., ground water is ponded on the upthrown side of small fault scarplets, resulting in an increase in surface moisture and vegetation. Huntley (1976) proposes several explanations for this phenomenon:

> (1) upwelling of confined water along the fault zone,
> (2) juxtaposition of the impermeable beds against permeable beds upgradient from the fault,
> (3) ground water cascading from an area of shallow basement rock to an area of deep basement rock, and
> (4) development of gouge along the fault zone, ponding ground water upgradient of fault.

The authors believe juxtapositioning of beds of differing permeability to be the most acceptable explanation.

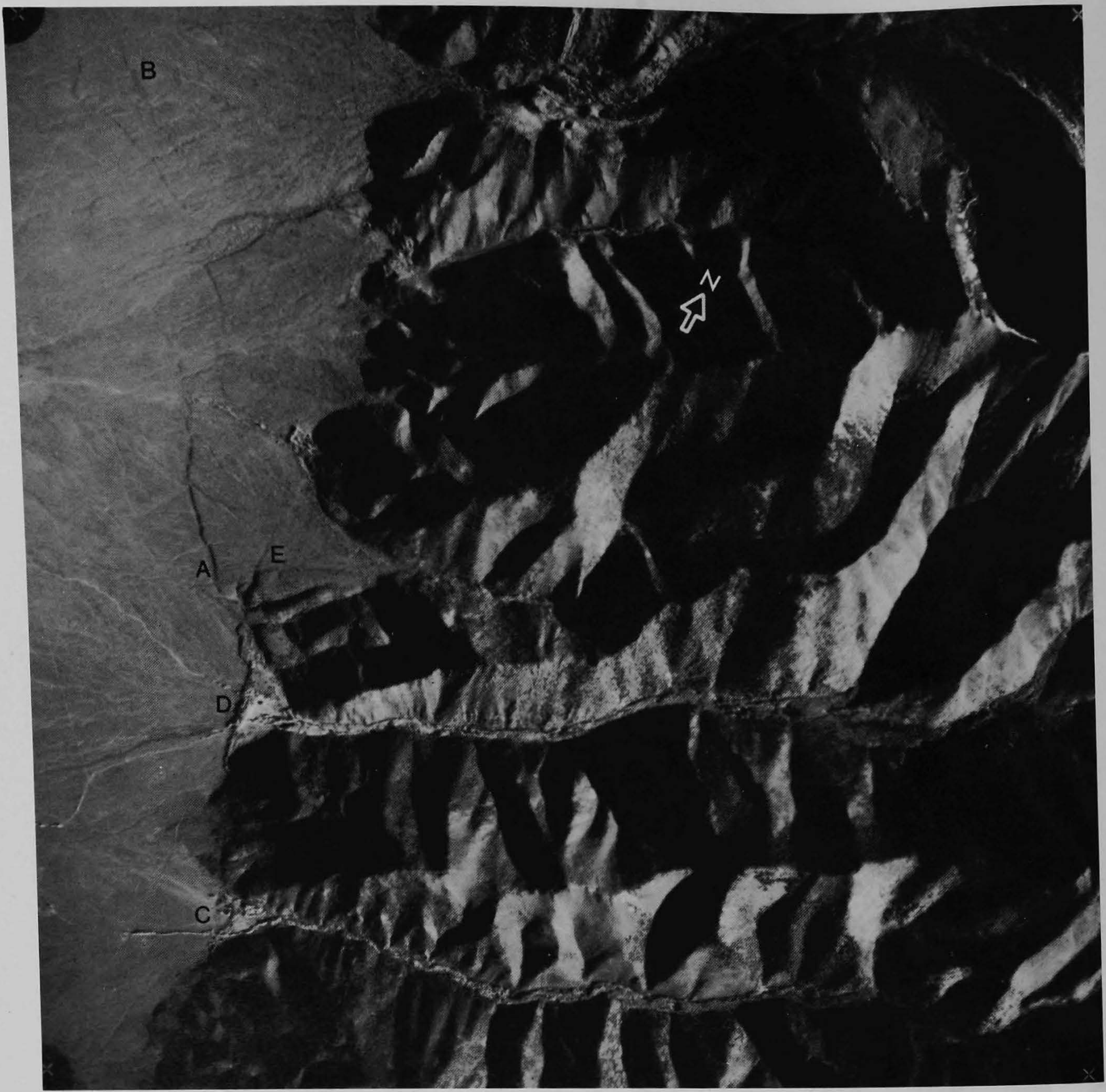


Figure 11. Vertical low-sun-angle aerial photograph of parts of the Villa Grove and Sangre de Cristo fault zones. Note decrease in scarp height from "A" to "B" along the Villa Grove fault zone. Prominent scarps are present along the Sangre de Cristo fault at the mouths of Major Creek (C), Garner Creek (D), and Hot Springs Canyon (E). (NASA photograph, courtesy of Keenan Lee, Colorado School of Mines)

Another interesting phenomenon found along a few of the scarps on the Steel Canyon alluvial fan are small closed depressions. The depressions are 0.3 to 1 m wide, up to 0.4 m deep, and are found on both sides of the faults. They are thought to be piping features related to ground fissuring that were later modified by surface-water movement and sheet flow. Similar, but more youthful-looking features are developed along fault scarps near Lone Pine, California that were created during the large 1872 Owens Valley earthquake.

Other faults associated with the San Luis Valley part of the Rio Grande rift province include the two faults west of Bonanza, faults to the west of the valley, and several prominent, generally east-trending lineaments northeast of Saguache. The faults west of Bonanza (fault numbers 119 and 120) are in a geologically complex area near the Bonanza Caldera and are not well understood. The faults west of Monte Vista and Saguache (fault groups 97 through 106) are probably related to extension along the Rio Grande rift. They displace the Neogene volcanic rocks (Plate 1) up to a few 100 meters, but Quaternary movement on most cannot be documented because of the general absence of Quaternary deposits. A few of the faults, however, are covered by Wisconsinan and Holocene alluvial deposits (Plate 1, Appendix 2). T. A. Steven (1976, oral commun.) believes these faults are relatively minor extensional faults formed during the tilting of San Luis Valley.

Evidence of recurrent late Cenozoic movement on the Sangre de Cristo fault is found throughout its length. Development of facted spurs on ridge lines along the range front, a feature long recognized as characteristic of recently active block-faulted mountains (Davis, 1903), is one line of evidence. Beautifully preserved faceted spurs are found at several places along the western flank of the Sangre de Cristo Range. Figure 12 shows the range front from Hayden Pass north to near Bushnell Peak. Features characteristic of faulted range fronts dominate the geomorphology of this part of the range. Elongate drainage basins extend normal to the range crest and are separated by interdrainage triangular faceted spurs. At least four and possibly five distinct sets of spurs are developed on the interdrainage ridge lines. At the base of the lowest and youngest triangular faceted spur is a rectangular basal fault scarp, created by repeated movement on the Sangre de Cristo fault during the Quaternary.

Presence of multiple sets of facets indicates intermittent fault activity during the last several million years (Hamblin, 1976). Development of multiple sets probably occurs as follows: The range front is uplifted a few hundred meters during a period marked by recurring fault activity and a basal fault scarp is created. V-shaped valleys are carved by stream erosion into the basal fault scarp both during uplift and during a period of tectonic quiescence. This process results in triangular faceted spurs. The face of the faceted spurs are eroded by mass wasting and water action during the dormant period. Repetitions of this cycle result in development of multiple sets of faceted spurs.

Figure 12. Photograph showing faceted spurs on the western flank of the Sangre de Cristo Range from Hayden Pass north to near Bushnell Peak.

Relative lengths of the periods of uplift and dormancy can be estimated by the height of the faceted spurs and the horizontal distance between sets of spurs (Hamblin, 1976). Sets of high faceted spurs separated by short horizontal distances imply long periods of uplift and short periods of quiescence. The presence of several sets of short faceted spurs separated by long horizontal distances suggest relatively short periods of uplift and long periods of inactivity. Features on the Sangre de Cristo Range indicate approximately equal periods of uplift and tectonic quiescence.

Inset terraces or hanging valleys often develop along faults that experience repeated movement. In a typical alluvial fan-piedmont drainage system, ephemeral streams lie on or near the surface of the fan. Movement on a fault transverse to this drainage results in the formation of a new, local stream base level. The stream responds to the new base level by eroding into the upthrown side of the fault, creating a new stream level below the alluvial fan surface. Additional fault movement again changes the local base level and the stream responds by eroding an inset stream level into the higher terrace. Several streams in San Luis Valley exhibit this characteristic. The drainage that crosses the Villa Grove fault zone in the N1/2 NW 1/4 sec. 1, T.45N., R.10E, 0.9 km southwest of Valley View Hot Springs is a good example of an inset terrace or hanging valley, and indicates repeated movement on this fault zone.

To establish the age of the most recent movement on the Sangre de Cristo fault, crosscutting relationships between the fault and various alluvial and eolian deposits were studied. In general the fault displaces most deposits along the range front except for very young, in part contemporary, alluvium, small alluvial fan deposits, wind-blown sand, and sand dunes. At one location northeast of San Luis, it was possible to accurately date the most recent fault movement.

About 3 km northeast of San Luis, at approximately 37° 14'N. and 105° 23'W., datable organic material was obtained from a meander cut along Rito Seco which enabled establishment of the age of most recent movement of this part of the Sangre de Cristo fault. Figure 13 shows the surficial geology of the area, herein referred to as the Rito Seco site, and the location of the C-14 samples. Quaternary deposits of several ages unconformably overlie the Santa Fe Formation which crops out in the eastern part of the mapped area. As shown in Figure 13 the fault displaces both Qf1 and Qf2, and is covered by Qa2 and Qf3.

At the location designated by the asterisk, datable C-14 samples were collected from Qf2 and Qf3. A charcoal sample from a fire pit within the upper one meter of Qf3 was dated at 1,940 ± 120 years B.P. The fire pit may have been used by Indians during the Basket Maker II period (Wilson, 1971). A charcoal sample from a fire pit within the upper one meter of Qf2 was dated at 4,715 ± 170 years B.P. Thus, the last major movement on this segment of the Sangre de Cristo fault occurred during the Holocene between 1,940 and 4,715 years ago.

Additional analysis of the geology at the Rito Seco site suggests recurrence rates for large surface ruptures and accompanying large earthquakes. Fault A (Figure 13) displaces both Qf1 and Qf2. Scarp height in Qf2 is approximately 2.4 m and the scarp in Qf1 is about 6.7 m high. Assuming the 2.4 m scarp is the result of one surface rupture (much of the area has been disturbed by man, but remaining scarp morphology does suggest only one movement) and that this value is typical of surface ruptures for large earthquakes in this region, there has been one surface rupture since deposition of Qf2 and possibly three surface ruptures since deposition of Qf1. Soil development and weathering characteristics on Qf1 and its elevation above Rito Seco suggest it may be of late Pinedale age, and therefore is approximately 10,000 to 15,000 years old. C-14 dating of Qf2 indicates an age of 4,715 years B.P. This implies a recurrence interval of approximately 3,000 to 5,000 years for significant surface rupture and accompanying major earthquakes.

Admittedly, this is a very rough estimate of the recurrence rate, but it does provide a useful approximation. The primary objections to this

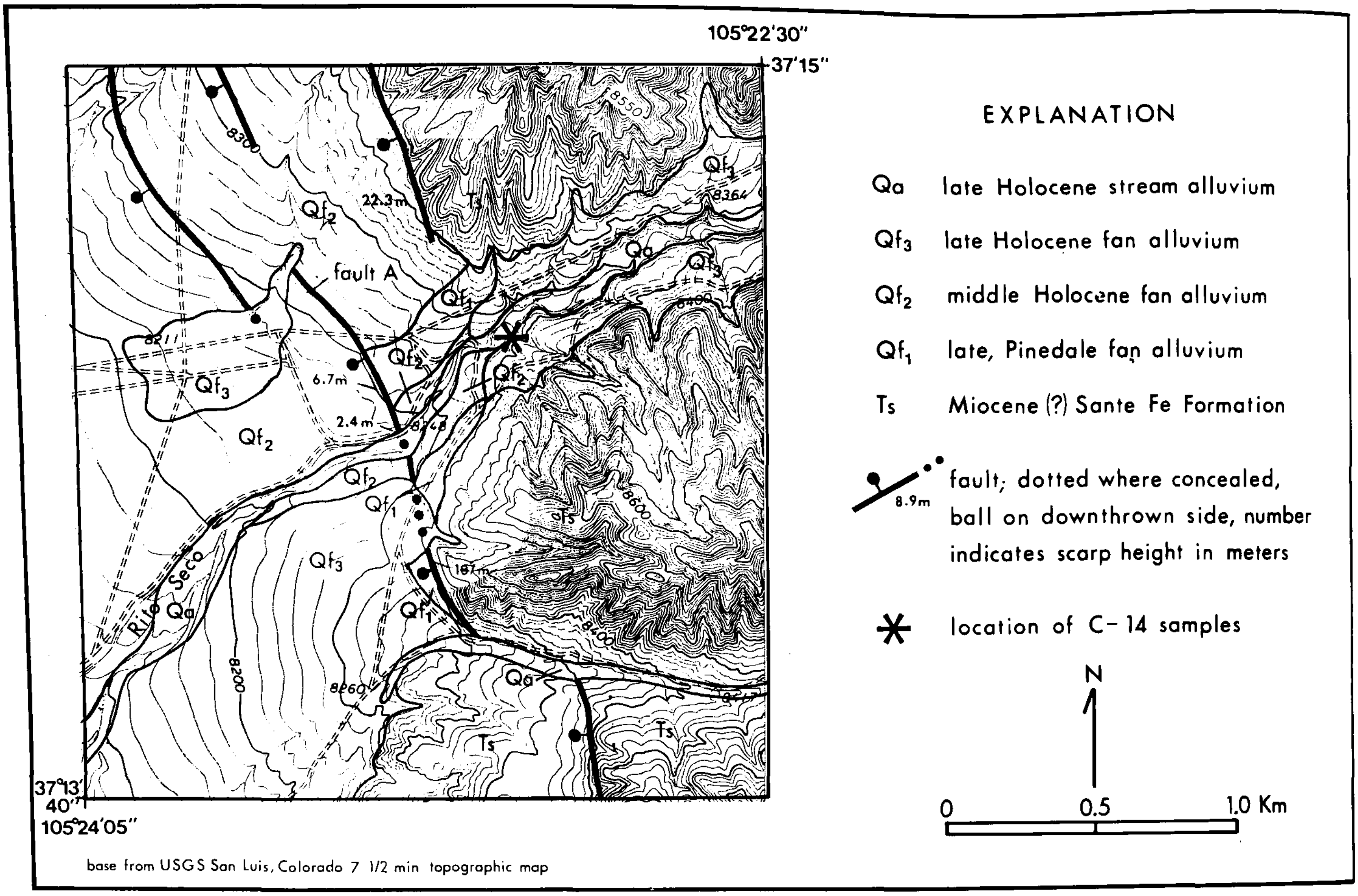


Figure 13. Reconnaissance surficial geologic map of the Rito Seco site.

approach are (1) the amount of surface rupture (i.e., scarp height) may not be equal for different earthquakes, and (2) our age estimation, based on soil and weathering characteristics, is at best an approximation. In view of these facts a more conservative method of recurrence rate estimation could be employed. Since the scarp height is significantly different in Qf1 and Qf2, there has been at least two surface ruptures since deposition of Qf1. Let us also assume that Qf1 may actually be early Pinedale in age, with an age of possibly 30,000 years B.P. The recalculated recurrence rate would then be about 15,000 years.

Further evidence of recurrent fault movement was studied at two additional sites. Figure 14 shows the geology of an area along Uracca

Creek in T.39N., R.13E., called the Uracca Creek site, between the range front and Colorado Highway 150. This area was previously mentioned because of the unusual structure exposed here. A large fault lies at the base of the range, but the most recent movement has occurred on a 2.7 km long, normal fault that is 1.7 km west of the range front.

As indicated on Figure 14, the geology of the Uracca Creek site between the two faults consists of tilted blocks of volcaniclastic conglomerate thought to be the Tertiary Santa Fe/Vallejo Formation (Huntley, 1976). This formation is unconformably overlain by pediment gravels, alluvial fan deposits, and landslide deposits. As at the Rito Seco site, the fault displaces deposits of different ages differing amounts. Qf4 is offset by a 2.7 m high scarp thought to be the result of one surface rupture. The scarp is not well preserved in Qf4 because the material in the scarp is fine-grained and easily eroded. No evidence remains to suggests multiple movement on the scarp in Qf4. Qf1 is offset an average of 21.0 m by the fault. Assuming the 2.7 m displacement is a representative amount of surface rupture per event, the 21.0 m scarp in Qf1 may be the result of seven or eight periods of surface rupture. Figures 15 and 16 illustrate the change in scarp height at the Uracca Creek site.

Ages of the deposits at the Uracca Creek site were roughly estimated using amount of soil development, weathering characteristics, and elevation above Uracca Creek. The following correlations are suggested: Qf4 - Holocene (5,000 years B.P.); Qf3 - late Pinedale (10,000 to 15,000 years B.P.); Qf2 - early Pinedale (30,000 years B.P.); Qf1 - Bull Lake (60,000 to 180,000 years B.P.); and Qp - pre-Bull Lake. Scarp heights and ages of the deposits suggest a recurrence rate for large-magnitude surface rupturing of 7,500 to 26,000 years; depending on which age for Qf1 is used.

East of Villa Grove, along Major Creek in sec. 7, T.45N. R.11E., is another site that exhibits recurrent fault movement. Figure 17 is a surficial geologic map of the Major Creek site. Scarp height in Qf3 is a 5.5 m, whereas it is 10.4 m high in Qf2. Qf3 is believed to be late Pinedale in age (10,000 to 15,000 years B.P.). Qf4, which covers the fault, is of late Holocene age, and Qf2 is interpreted as being early Pinedale (30,000 years B.P.).

The 5.5 m scarp in Qf3 is probably the result of two periods of fault rupture. Often a scarp which results from multiple movements will have bevels preserved on the upper part of the scarp. This scarp is not well preserved, perhaps because Qf3 is very fine-grained and easily eroded. It is reasonable to assume that the 5.5 m scarp resulted from two breaks averaging 2.7 m per rupture, a value similar to that seen at the Rito Seco and Uracca Creek sites, and that the 10.4 m scarp may be the result of four periods of surface faulting. A recurrence interval of 7,500 to 15,000 years is suggested by this data.

The preceding information indicates the Sangre de Cristo fault has probably been the most active fault in Colorado during the Quaternary.

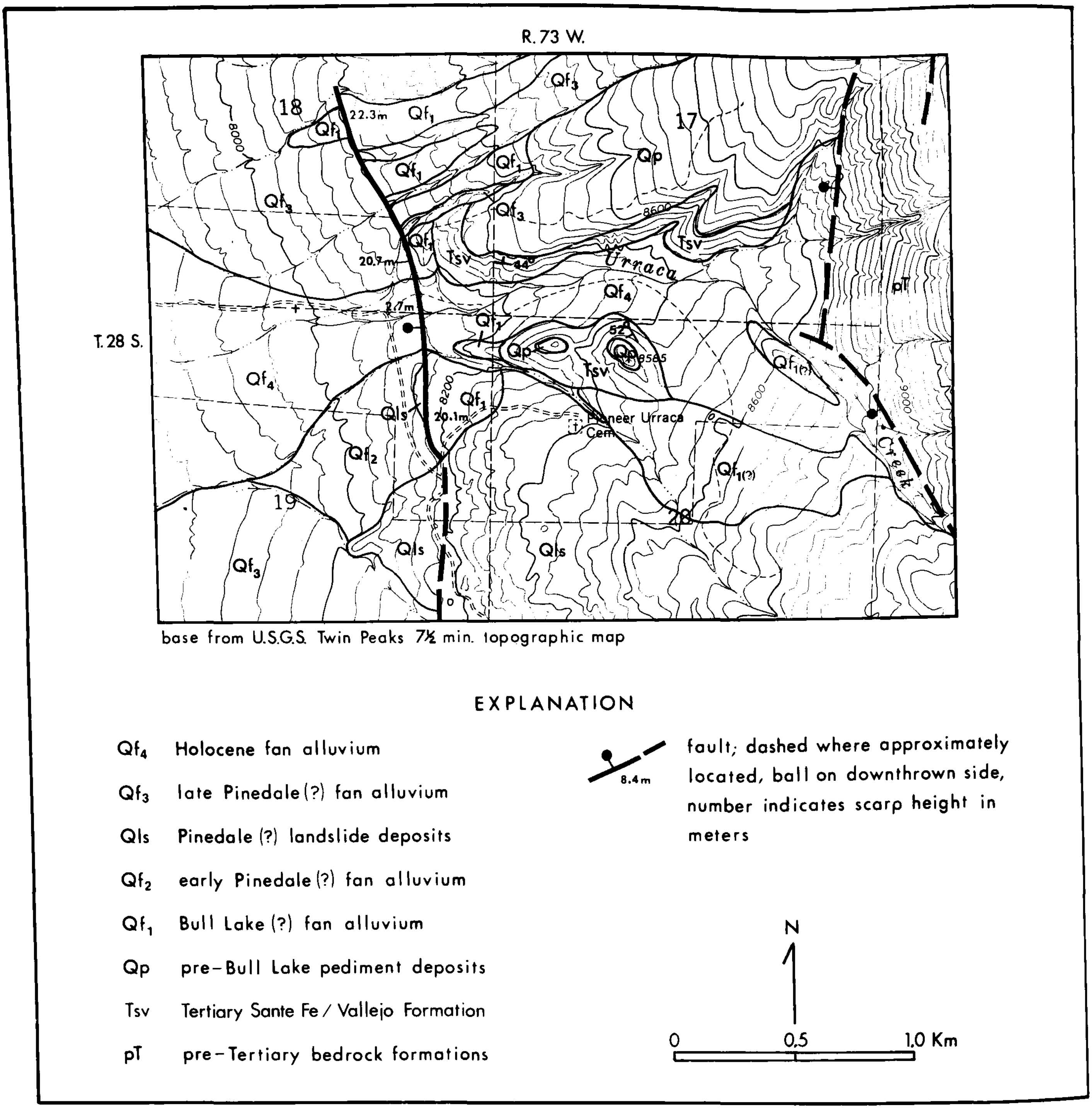


Figure 14. Reconnaissance surficial geologic map of the Uracca Creek site.

Figure 15. Oblique aerial photograph of the Sangre de Cristo fault at Uracca Creek. Note change in scarp height in alluvium of different ages. Arrows indicate scarp and diamond indicates location of truck shown in Figure 16.

Figure 16. Close-up photograph of the scarp at Uracca Creek shown on left side of Figure 15.

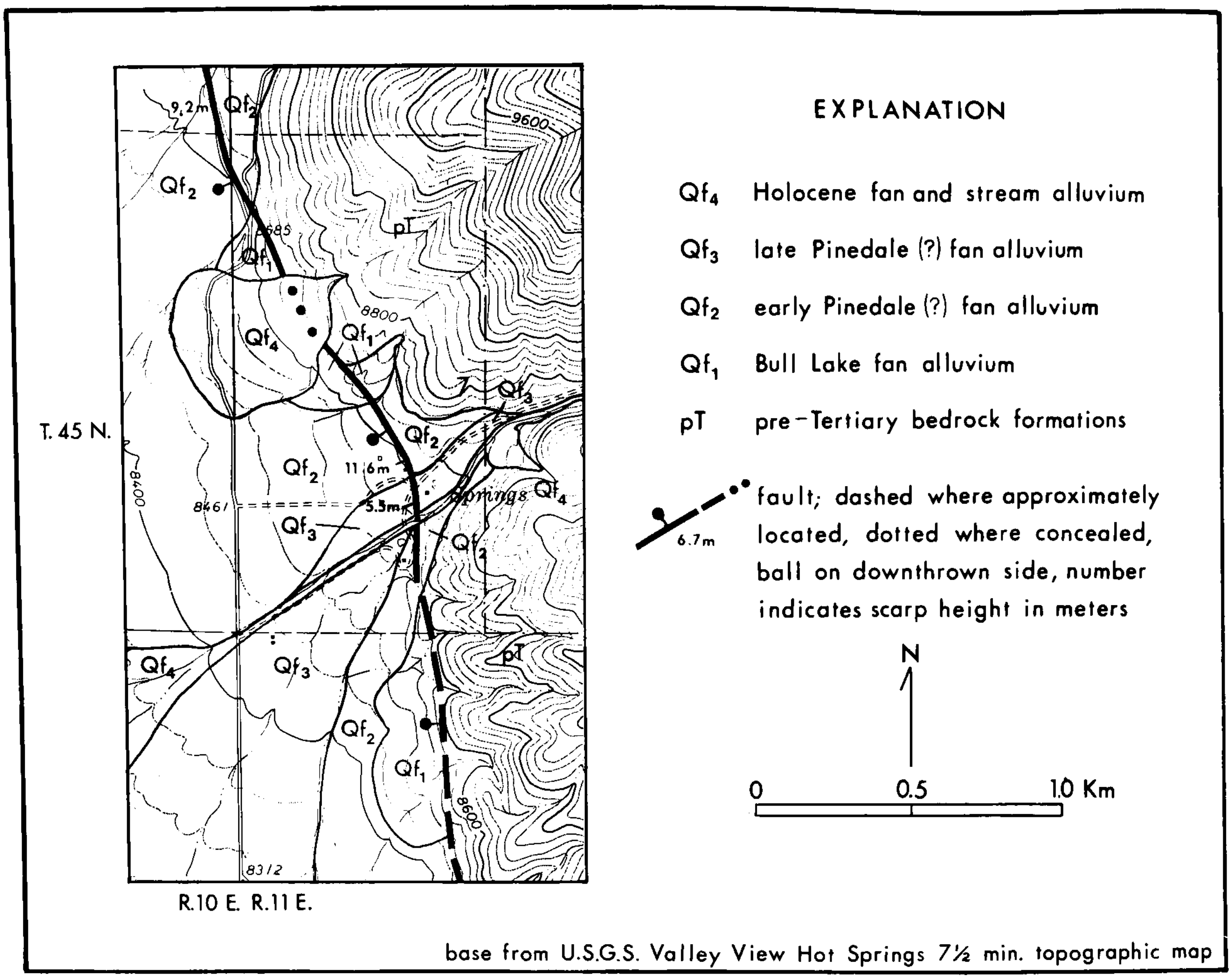


Figure 17. Reconnaissance surficial geologic map of the Major Creek site.

Major surface faulting near San Luis is known to have occurred between 1,940 and 4,715 years ago. Large earthquakes accompanied by surface displacements averaging about 2.6 m apparently have recurred on the fault once every several thousand years, as the range in calculated recurrence intervals suggests. Fault characteristics, both length and surface displacement, suggest the maximum magnitude of these large earthquakes could be as great 7.5 (Slemmons, 1977).

When considering the above calculations, it is important to remember that the normal frequency-magnitude relationships for earthquakes are such that smaller, but still damaging earthquakes occur more frequently than the very large ones calculated above. For instance, assume the Sangre de Cristo fault generates a magnitude 7.5 event every 5,000 years. Using the frequency-magnitude relationships suggested by Richter (1958) and a "b" value of 0.9, a magnitude 6.5 earthquake should occur on the Sangre de Cristo fault about once every 625 years. If a 15,000 year recurrence interval is used, magnitude 6.5 events should occur on the Sangre de Cristo fault about every 1,800 years.

Additional detailed studies of the Sangre de Cristo fault are currently being conducted by Jim McCalpin, a graduate student at the Colorado School of Mines. He is evaluating the Quaternary history of the area with special emphasis on the glacial and tectonic aspects. His work will further existing knowledge of the Sangre de Cristo fault.

3.1.2. PONCHA PASS AREA

The Sangre de Cristo Range and San Luis Valley are terminated on their north end by a complex of east- and north-trending Neogene faults (fault group 121). The present-day topographic barrier between San Luis Valley and the upper Arkansas River Valley, Poncha Pass, is bounded by these faults. Presence of Miocene-Pliocene Dry Union Formation on this block indicates the region was at the same general level of the upper Arkansas River Valley during the late Cenozoic and has since been faulted up many hundreds of meters (Van Alstine, 1970; Knepper, 1974). Knepper (1974) believes the region between Poncha Pass and Villa Grove was a positive topographic feature that separated the two valleys during the Miocene. This is based on the apparent absence of late Tertiary deposits and topographic configuration of this part of the valley. Only one fault (fault number 158) of this entire complex is known to have Quaternary movement. Scott and others (1975) show this fault to displace Quaternary alluvium of early Pinedale age.

3.1.3. UPPER ARKANSAS RIVER VALLEY

The upper Arkansas River Valley is the northernmost valley within what Tweto (1979a) calls the Rio Grande rift proper. Prominent topographic expression of the rift ends near Leadville. The distribution of Neogene faults in part of the valley is shown on Plate 2. Microearthquakes that have been recorded in the valley and the local surficial geology near faults that have moved during the Quaternary is also shown on Plate 2.

The valley consists of two grabens, a northern and southern graben separated by a Precambrian high south of Twin Lakes. A series of north-trending normal faults (fault groups 156, 157, and 161) that have progressive step-down displacement to the west bounds the east side of both grabens. This set of faults extends from near the crest of the Mosquito Range westward to the east edge of the valley. The west side of the southern graben is bounded by relatively narrow, high-angle, normal fault zone herein referred to as the Sawatch fault (fault group 159). A series of faults also forms the west side of the northern graben.

The upper Arkansas River Valley longitudinally cuts across the east flank of Laramide age Sawatch anticline. Precambrian rocks in the Sawatch Range west of the valley comprise the core of the older anticline and the east-dipping Paleozoic rocks that cap the Mosquito Range form the east flank of the Sawatch anticline. Abundant Neogene movement on the faults that bound the graben is established by offset of Oligocene volcanic rocks, Miocene-Pliocene Dry Union Formation, and Quaternary deposits. Tweto (1979a) believes the step faults on the east side of the graben are reactivated Laramide-age structures that were antithetic faults along the east flank of the Sawatch anticline.

Most of the valley fill within the graben is Dry Union Formation, but a widespread cover of Quaternary deposits blankets much of the valley, and Oligocene volcanic rocks underlie the Dry Union at least locally. Resistivity studies by Zohdy and others (1971) and unpublished gravity and magnetic data by Case (1974, written commun. in Limback, 1975) indicate about 1,500 m of basin fill near Salida and about 1,200 m near Buena Vista. Tweto and Case (1972) estimate up to 1,220 m of fill in the northern part of the valley, southwest of Leadville.

Zohdy and others (1971) believe a considerable portion of the movement on the east side of the valley may have occurred on a north-trending fault east of the Arkansas River that is now concealed beneath Quaternary alluvium. A northwest-trending horst, bounded by fault group 155, is developed along the east side of the valley near Browns Canyon. Neogene movement can be demonstrated on the faults on this side of the valley by cross-cutting relationships with the Dry Union Formation and offset of the late Eocene surface, but evidence of Quaternary activity has not yet been discovered.

Relief on the west side of the valley suggests about 3,000 m of Neogene displacement on the Sawatch fault (Limback, 1975). The fault zone is marked by linear topography, weakly developed faceted spurs on the mountain front, prominent scarps in alluvial deposits, and numerous hot and cold springs. Hortense Hot Spring, the hottest spring in the state (Pearl, 1972), and Mt. Princeton Hot Springs issue from the Sawatch fault near Chalk Creek (Plate 1).

Long, east-trending faults may cut across the valley along Chalk and Cottonwood Creeks. Limback (1975) believes the location of hot springs (Cottonwood and Mt. Princeton Hot Springs), hydrothermal alteration (Chalk Cliffs), apparent offset of the mountain front at Chalk Creek, and the linear nature of both valleys support this interpretation. A large, east-trending crustal discontinuity that may represent one of cross-valley faults was detected by Crompton (1976) during a seismic study of mine blasts. Crompton believes the irregularities in arrival times of seismic waves generated by blasting at Climax may be accounted for by refraction of the waves at a major cross-valley fault extending eastward from Chalk Creek. The presence of an east-trending resistivity anomaly along this same trend provides additional evidence of a large cross-valley fault (Arestad, 1977).

Surface scarps along the Sawatch fault provide evidence of Quaternary activity. The scarps occur in major scarp groups that are up to several kilometers long and are distributed in an en echelon manner. Individual scarps are usually discontinuous and are separated in a right-stepping fashion suggestive of dominant vertical slip with a minor left-lateral component. Unlike parts of the Sangre de Cristo fault, there is no singular fault scarp that follows the mountain front for long distances.

Just south of Chalk Creek a 2.9 km long, continuous scarp cuts Quaternary deposits of several ages. A 48.2 m scarp in a Bull Lake(?) lateral moraine (Plate 2) is a prominent feature on this fault. The fault also displaces late Bull Lake(?) outwash about 11.3 m and early Pinedale(?) outwash about 3.4 m. North of the 48.2 m scarp, the fault encounters progressively younger, nested lateral moraines on the south side of Chalk Creek. Early Pinedale(?) morainal deposits are cut by an 8.8 m scarp, but the fault becomes difficult to trace beyond this point. There is a suggestion of a 5 m scarp in the middle of the nested Pinedale moraines, but the innermost and youngest moraine (late Pinedale) does not appear to be faulted. Thus, the surface geology at this location suggests the most recent major displacement on the Sawatch fault occurred between the late and early Pinedale glaciations, approximately between 10,000 and 30,000 years ago.

Recent detailed studies of the Sawatch fault by the U.S. Water and Power Resources Service (Ostenaa and others, 1980) included excavation of trenches across several scarps on the south side of the Chalk Creek and near Cottonwood Creek. Relationships exposed in the trenches expands and clarifies knowledge of recent activity on the Sawatch fault. Ostenaa and others (1980) believe a minimum of five discrete periods of faulting have occurred during the past 150,000 to 200,000 years, based on their interpretation of truncated fault zones, colluvial wedges, and soil profiles exposed in the trenches and geomorphic characteristics of the fault scarps. The most recent major displacement happened during the late Pleistocene, but a small displacement event offsets a 4,000 year old colluvial unit about 0.1 m. Relationships observed by Ostenaa and others (1980) suggest a recurrence interval of 10,000 to 40,000 years for major displacements.

Historic ground surface deformation has been reported on the east side of Mt. Princeton (George Chisom and James Asher, 1977, oral commun.). This deformation may possibly be related to creep on the Sawatch fault, although other phenomena could also cause it. In the summer of 1975 a 5-year-old, 12.2 cm diameter cast-iron pipe was sheared about 4 cm in a left-lateral sense. The location of this deformation is indicated on Plate 2 by the symbol "A". During December of 1976 and January of 1977 additional deformation was observed at both locations A and B on Plate 2. A prominent N.20°W.-trending ground crack at least 40 m long opened about 0.5 cm in a dirt road about 70 m east of the 1975 water-line break. Further investigations revealed a north-trending zone of older cracks up to 60 m wide and 65 m long in several dirt roads.

During this same period several smaller diameter water lines were ruptured at B on Plate 2. Ground cracks were observed to extend northward from the sheared pipes to a sidewalk and cabin. Both the sidewalk and cabin foundation experienced cracking at this same time. Offsets primarily were oblique-slip with nearly equal amounts of vertical and horizontal movement. Severe cracking was noted at approximately this same time in the Young Life Ranch manager's cabin.

Several mechanisms, including landsliding, subsidence, hydrocompaction, frost action, and fault movement could cause the observed deformation. Reconnaissance study of the area did not determine the causative mechanism, but fault movement could not definitely be ruled out. Seismograph records from GOL, the Colorado School of Mines station at Bergen Park, were examined by R. B. Simon (1977, oral commun.) to determine if any earthquakes centered in this area during the period when the observed deformation occurred. Unfortunately, the records were very noisy at this time, and no events could be assigned to this area with any certainty. AMAX Exploration, Inc. set up a microearthquake seismograph for a few days after the damage had been reported, but no local earthquakes were recorded. These facts do not support fault movement as the cause of the deformation, but neither do they eliminate fault creep as a possible explanation.

The northern end of the upper Arkansas River Valley extends to near Leadville. This northern graben contains numerous potentially active faults (fault numbers 160, 164, and 165, and fault groups 161, 162, and 163). Some of these faults have over 1,000 m of Neogene movement (Tweto, 1961; Tweto and Case, 1972) and a few appear to have moved during the Quaternary. Tweto and Case (1972) and Tweto and others (1976b) map an abundance of faults in the Leadville area, however only the larger ones are shown on Plate 1.

Tweto (1961) and Tweto and Case (1972) believe many of these faults have experienced movement in the Quaternary. The best documented evidence of recent activity is found on fault 165 at Lake Fork, just below Turquoise Lake (Tweto and Case, 1972). Interpretation of data from several drill holes suggests the Malta Gravel (pre-Bull Lake age), till no. 1 of Tweto and Case (1972), and the Dry Union Formation are faulted against Precambrian rocks at this location. About 1.7 km south of Lake Fork, an exposure in a ditch bank shows the Malta Gravel in fault contact with Precambrian rocks (Tweto and Case, 1972).

3.1.4. MOSQUITO FAULT

The Mosquito fault (fault group 56) begins at the north end of the upper Arkansas Valley. It trends N.40°E. for about 13 km to where it joins a N.10°E.-trending fault and then continues northward for 49 km to the south end of the Gore Range. The south end of this west-dipping, high-angle normal fault bounds the west flank of the Mosquito Range and to the north it forms the western margin of Tenmile Range. Localization of Laramide intrusives along the fault suggests it may have been a conduit for these igneous bodies (Tweto and Case, 1972). Tweto and Sims (1963) present evidence that the fault may have Precambrian ancestry.

Near Leadville the Mosquito fault and its subsidiary faults have a total vertical displacement of about 3,660 m, whereas at Climax the displacement could be as great as 4,720 m (Tweto and Case, 1972). Wallace and others (1968) find about 2,745 m of vertical movement and possibly 458 m of left-lateral slip along the 70° west-dipping fault at Climax since the Oligocene, based on offset of the Ceresco ore body. South of Climax, thin slivers of Dry Union Formation lie within the Mosquito fault zone about 610 m above similar deposits in the Arkansas Valley (Tweto, 1974a). Thus, there has been considerable Neogene movement on the Mosquito fault and it subsidiary faults to the west.

Evidence for Quaternary displacement on the Mosquito fault is relatively scarce. Tweto (1976, oral commun.) suggested that the area just south of Climax on the south side of the East Fork of the Arkansas River many contain evidence of recent fault movement. In this region the main trace of the Mosquito fault crosses the river in the center of the E 1/2 of sec. 13, T.8S., R.79W. It continues southward and wraps around the west side of Mt. Arkansas at a break in slope at an elevation of about 3,720 m. The fault is marked by a prominent scarp in bedrock that resulted from differential erosion along the silicified, brecciated fault zone. There are also anomalous geomorphic features where the fault crosses the south lateral moraine. Unfortunately, this late Quaternary moraine has been modified by erosion and mass wasting since deposition, and the nature of the anomalous features that occur along the fault trace in the moraine can only be ascertained through detailed studies which probably would have to include trenching.

About 0.9 km west of the main trace of the Mosquito fault, in the center of the N 1/2 of sec. 14, T.8S., R.79W., there are several distinctive scarps up to 12 m high that parallel the main trace of the fault. The scarps are found within both morainal and landslide deposits and are usually east-facing. They may well be subsidiary antithetic faults related to the main trace of the Mosquito fault. However, they also occur upslope from an earthflow and could have been formed by movement of the earthflow. Three of the scarps appear to continue southward beyond the upper reaches of the earthflow. This is suggestive of a tectonic origin. Holocene stream alluvium along the East Fork of the Arkansas River is not displaced by the fault.

3.1.5. FRONTAL FAULT

The Frontal fault, also known as the Blue River fault (fault number 50), begins near Hoosier Pass on the east side of the the Tenmile Range and extends northward along the east flank of the Gore Range. It is a wide and complex fault zone that is not thoroughly understood, primarily because it is largely covered by glacial and landslide deposits. West (1977) reports a fault-line scarp 610 m high along the Frontal Fault on the east side of the Gore Range. As much as 1,220 m of relief exists between the Precambrian rocks beneath Blue River Valley and the crest of the Gore Range, providing a minimum value for displacement along this part of the Frontal Fault. How much of this movement is of Neogene age is not known, but it is believed to be considerable (Tweto and others, 1970; West, 1977).

The Frontal fault is part of the Precambrian Ilse-Gore fault system and has been reactivated during both the Laramide orogeny and the period of Neogene tectonism associated with rifting. Direct evidence of Neogene activity is found in several locations in the Blue River Valley and northwest of Breckenridge. In the upper Blue River Valley remnants of the Dry Union Formation are faulted against Precambrian rocks in several areas along the Frontal fault (Tweto, 1979a). To the north the Miocene Troublesome Formation is also faulted against Precambrian rocks.

Tweto and others (1970) cite evidence of recent fault movement on the Frontal fault. They describe faulted late Quaternary moraines and avalanche deposits, gouge "boils", and earthquake-triggered landslides, all indicative of recent fault activity. Recent detailed mapping by West (1977) suggests the features described by Tweto and others (1970) are due to mass movement, not recent faulting. The most recent large-magnitude surface rupture of the Frontal fault probably occurred before the Bull Lake glaciation, possibly during the early part of the Quaternary.

3.1.6. GORE FAULT

The west side of the Gore Range is bounded by the Gore fault (fault group 49), a 70 km long, steeply southwest-dipping or near vertical normal fault (Tweto and others, 1970). It is a complex fault zone up to 4.8 km wide that was part of the Precambrian Ilse-Gore fault system and was reactivated during the late Paleozoic, Laramide, and Neogene (Tweto, 1979a). Evidence of Neogene movement is found along the northern end of the fault in T.1S., R.81W. and T.2S., R.81W. (Tweto, 1973b; Tweto and others, 1976b), where Miocene sedimentary rocks are displaced by the fault in this area. Quaternary movement on the Gore fault has not been documented.

3.1.7. OTHER FAULTS

The Rio Grande rift begins to die out north of the Colorado River, but several faults displace the Miocene-Pliocene Browns Park Formation in the region from Toponas to Steamboat Springs. The faults form an irregular, complex graben and are of two general types: (1) high-angle, east-dipping faults on the west side of the graben (fault group 43), including the Steamboat Springs fault, and (2) high-angle, west-dipping faults (fault group 44) along the west flank of the Park Range and the east side of the graben. Kucera (1962) describes at least 120 m and possibly as much as 1,200 m of Neogene, post-Browns Park Formation movement on a large fault near Yampa that bounds the west side of the graben. In many places the Neogene faults coincide with Laramide faults, but the direction of movement during the Neogene is opposite that which occurred during the Laramide (Kucera, 1962; Izett, 1975). Numerous other examples of late Cenozoic faulting and folding in this area are suggested by the presence of coarse gravel within the Miocene rocks (Izett, 1975).

The northern end of fault group 43 is dominated by the Steamboat Springs fault. The fault is thought to have about 300 m of vertical movement since deposition of the Browns Park Formation (Buffler, 1967; G. L. Snyder, 1973, written commun., in Izett, 1975). The Steamboat Springs fault is approximately parallel to an older Laramide fault zone mapped by Segerstrom and Young (1973) and G. L. Snyder (1973, unpub. data, in Izett, 1975). No evidence of Quaternary movement has been discovered on any of the faults that bound this graben.

The Sand Mountain fault (fault number 30) is a large, high-angle normal fault about 15 km long, just south of Sand Mountain in the Elkhead Mountains. This fault and fault group 23 are the northernmost faults thought to be within the Rio Grande rift province in Colorado. The Browns Park Formation is downthrown about 600 m on the east side of the north-trending Sand Mountain fault, as is measured by the elevation difference between Pilot Knob and Smith Creek (Buffler, 1967). Fault displacement diminishes to the north, suggesting the fault either decreases in throw or becomes an east-dipping monocline.

3.2 EASTERN MOUNTAIN PROVINCE

3.2.1. FRONT RANGE

The Front Range of Colorado is a north-trending, uplifted block of Precambrian igneous and metamorphic rocks over 250 km long and up to 70 km wide. These mountains are the easternmost range in Colorado, abruptly rising from the plains at an elevation of 1,500 m to a towering 4,270 m at their crest. The Front Range has been repeatedly uplifted during the late Paleozoic, Laramide orogeny, and Neogene. Many of the faults that bound the Front Range or cut across it have Precambrian origins.

Uplift of the Front Range since the Cretaceous is the on order of 6,000 m. At least 500 m of this uplift is of Neogene age, based on offset of the late Eocene erosion surface and overlying Oligocene rocks. Style of deformation along the flanks of the Front Range varies with geographic location. Structures on the eastern flank are more clearly defined than those on the western flank. Large, moderate-to-high angle reverse faults and steep, locally overturned folds are typical of the eastern flank from about Boulder southward. North of Boulder the range front is characterized by block-faulted Precambrian basement rock that drape folds overlying sediment. Structure of the western flank of the Front is complex and is not always clearly exposed. Several large Laramide thrust faults are developed along much of the western flank, as are a few high-angle faults of Neogene age.

3.2.1.1. GOLDEN FAULT

The Golden fault (fault number 66), a N.25°W.-trending, steeply west-dipping reverse fault, borders the east flank of the Front Range in the Golden-Morrison area and accounts for approximately 2,680 m of uplift (Van Horn, 1976). Figure 18 is a low-sun-angle, vertical aerial photograph of the area near the Golden fault. The mountainous area on the west side of the photograph is the eastern flank of the Front Range. Clear Creek, a major east-flowing stream, leaves the Front Range near the center of the photograph and continues to the east between North Table Mountain and South Table Mountain, two mesas that are capped by early Tertiary lava flows. The Dakota hogback, a prominent physiographic feature along much of the Front Range, is seen only in the upper and lower parts of the photograph. It is cut out by the Golden fault (which is indicated by the white arrows) in the center of the photograph.

Figure 19 is a geologic map of a part of the area shown in Figure 18. The Front Range lies west of the Precambrian-Paleozoic contact and the Golden fault runs generally north-south, just east of and approximately parallel to the Front Range. Paleozoic and Mesozoic rocks on the west side of the fault usually dip 40° to 50° east, whereas bedding is steeper and locally overturned on the east side of the fault. Much of the piedmont east of the Front Range is covered by Quaternary deposits ranging in age from Nebraskan to Holocene.

The Golden fault is exposed in Chimney and Tucker Gulches. At Chimney Gulch three fault traces with an apparent dip of more than 45°W place Pierre Shale against the Fountain and Lyons Formations (Scott, 1972; Van Horn, 1976). An unusual relationship is exposed along Tucker Gulch where a faulted slice of Benton Shale is juxtaposed between two older units, the Fountain Formation and Dakota Group.

Fault length is thought to be about 30 km, but it is not precisely known. The south end of the fault is lost in the Pierre Shale (Smith, 1964; Scott, 1972). It may continue southward for several kilometers and could possibly connect at depth with the Jarre Creek fault (fault number 194) near Louviers in Douglas County. At its northern end, the Golden fault may join the Livingston shear zone (not shown on Plate 1), and extend northward into the Front Range for an additional 34 km (Wells, 1963, 1967; Van Horn, 1972; Hurr, 1976), or it may merge northward with fold structures.

3.2.1.2. GRABEN NEAR GOLDEN

Scott (1970) reported that a small graben of Quaternary age, thought to be related to the Golden fault, was exposed in an exploratory trench in NE1/4, SW1/4 sec. 28, T.3S., R.70W., 1.2 km northwest of downtown Golden (see Figures 18 and 19 for trench location). Scott described two vertical shear zones trending N.20° to 30°W. that displace Kansan or Yarmouth age Verdos Alluvium and overlying colluvium about 1.5 m. Figure 20 is a photograph of this exposure. To further evaluate this feature, two trenches, up to 60 m long and 10 m deep, were excavated through the graben by the Colorado Geological Survey. The following discussion summarizes the geology exposed in this excavation and presents interpretations based on observed structural and stratigraphic relationships.

3.2.1.2.1. TRENCH STRATIGRAPHY

The stratigraphic sequence revealed by the 1976 C.G.S. excavation is summarized in Figure 21. Late Cretaceous Fox Hills Sandstone and the Laramie Formation comprise the bedrock map units. The marine Fox Hills Sandstone is well-sorted, fine- to medium-grained massive sandstone interbedded with micaceous, carbonaceous, sandy shale that was deposited

Figure 18. Low-sun-angle aerial photograph of the Golden area. Arrows indicate trend of the Golden fault and diamond indicates trench location. (NASA photograph; courtesy of Keenan Lee, Colorado School of Mines)

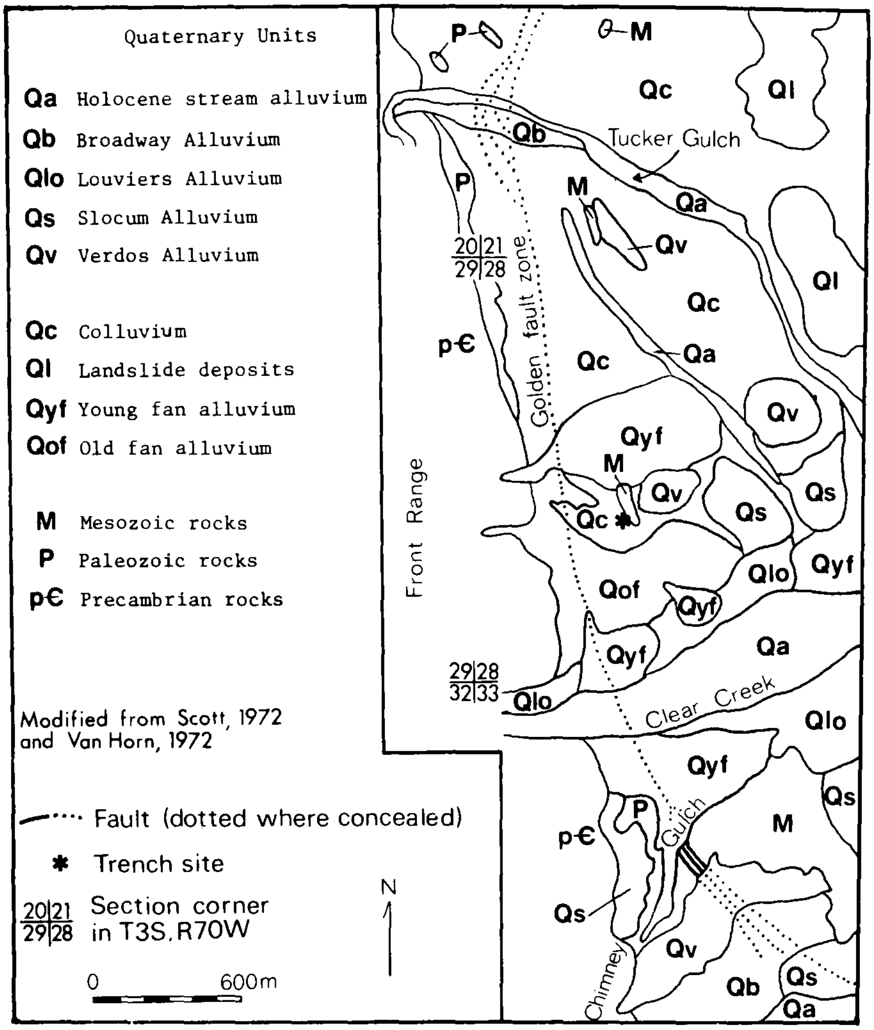


Figure 19. Geologic map of the general area near Golden.

primarily in a delta front environment (Weimer, 1973, 1976). Sandy claystone, clayey shale, and fine-grained sandstone of the non-marine Laramie Formation was deposited in a delta-plain environment (Weimer, 1973, 1976). Both formations are cut by numerous shear zones up to 23 cm wide that are marked by clay gouge, breccia and strong oxidation.

A 0.3 to 2.0 m thick, poorly sorted, coarse sandy, cobble gravel with lenses and interbeds of slightly gravelly coarse sand unconformably overlies the Cretaceous bedrock. Gravel clasts are predominantly well-rounded Precambrian igneous and metamorphic rocks, but angular cobbles and boulders of locally derived sandstone are also present. Many

Figure 20. Photograph of the graben near Golden described by Scott (1970) prior to the C.G.S. excavation in 1976. Arrows indicate limits of graben. Note gravel on upthrown side of fault and the well-developed surface soil. Large mound on left is spoil from older exploratory trench. (photograph by G. R. Scott, U.S. Geol. Survey)

of the biotite-rich granite, gneiss, and granodiorite clasts have weakened as a result of grusification. Weathering rinds are of little use in determining age relationships, because of the absence of fine-grained igneous clasts. Pedogenic calcium carbonate coats the undersides of many of the clasts and is disseminated through the sand. A marked increase in carbonate content occurs where the unit is within the surface soil

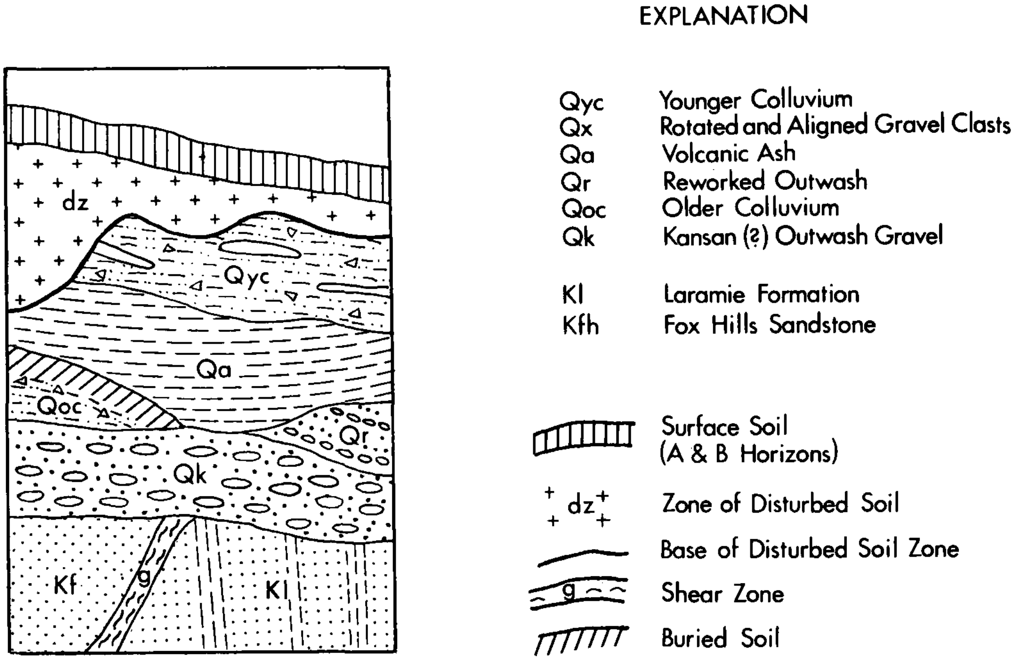


Figure 21. Schematic diagram showing the stratigraphy exposed by the C.G.S. trenching of the graben near Golden.

horizon. Relationships to overlying soils and volcanic ash, weathering characteristics, elevation above modern streams, and textural characteristics suggest this gravel is probably Kansan(?) outwash (G. R. Scott, 1977, oral comm.).

A 0 to 2.5 m thick wedge of gravelly, clayey, very fine sand extends over part of the outwash. Gravel clasts are generally pebble-sized, angular, and locally derived from nearby outcrops of fine-grained Cretaceous rocks. Textural, lithologic, and dimensional characteristics suggest it is a wedge of colluvium intermixed with slope wash that was deposited along the flank of a bedrock knob.

A 0.6 m thick buried soil is developed on the surface of this older colluvial unit. It has a 10 YR 6/4 color and a strong pedogenic "B" horizon that has clay films on sand grains and a medium coarse prismatic structure (M. West, 1976, oral commun.). The paleosol merges with the surface soil at the far west end of the trench. Degree of soil development and relationships with the overlying volcanic ash and surface soil and underlying Kansan(?) outwash suggest this paleosol is of Yarmouth age.

A thin, localized lens of gravelly coarse sand covers part of the buried soil and outwash and is found only within the sharply downdropped block. Texture and clast lithology of this unit are similar to the Kansan(?) outwash, although large gravel clasts are not present, and it physically extends from a scarp composed of outwash (Figures 23 and 25). These relationships suggest this unit is reworked Kansan(?) outwash derived from a scarp created by surface rupture on the Golden fault. It was presumably deposited immediately after fault movement.

Reworked volcanic ash that is up to 1.4 m thick overlies the reworked outwash and buried soil. Malde and Van Horn (1965), Scott (1970), Reynolds (1975), and Westgate and others (1977) describe this ash as being similar to Pearlette ashes from the Yellowstone area. G. A. Izett (1977, written commun.) correlates this ash with the Pearlette Type O ash of Naeser and others (1973) based on (1) chemical composition of glass shards, (2) assemblage of glass-mantled microphenocrysts, (3) chemical composition of clinopyroxene, hornblende, magnetite, and ilmenite microphenocrysts, and (4) paleomagnetic direction of oriented cores of the ash (Reynolds, 1975). John Boellstorff (1977, written commun.) believes the relative abundances of glass-mantled microphenocrysts of augite, rutile, hypersthene, zircon, and green hornblende, and the total number of heavy minerals in the ash suggest that it may not correlate with the Pearlette Type O ash.

Fission-track age dates of six zircon grains from the reworked ash by C. W. Naeser and G. A. Izett (1977, written commun.) average 0.66 ± 0.22 m.y. John Boellstorf (1977, written commun.) fission-track dates the ash at 0.7 ± 0.07 m.y. using two glass shards. These determinations indicate the ash is 0.6 to 0.7 m.y. old.

A younger colluvial and slope wash deposit up to 3 m thick overlies the volcanic ash. The deposit is thickest in the graben and pinches out both east and west of the graben. It consists of a heterogeneous mixture of poorly sorted, clayey, fine sand with thin lenses of well-sorted fine sand, coarse sand, reworked volcanic ash, and gravelly clay. Thin layers of reworked ash within the unit serve as excellent marker beds to document fault offset. Deposition of this colluvium and slope wash initiated shortly after reworking of the ash and may have continued at a slow rate for a considerable period of time.

An extensive surface soil is present over the entire trench site. M. W. West (1976, oral comm.) describes this soil as having a 5 to 10 cm pedogenic A horizon, a 20 to 50 cm strong textural B horizon with 7.5 YR colors, angular blocky and prismatic pedogenic structure, and abundant clay films on sand grains and ped surfaces, and a Cca horizon up to 160 cm thick with Type III carbonate development. Thickness of the B horizon of this soil changes markedly across the graben. Generally, the soil thickens appreciably on the downthrown side of the fault (Figure 22). This sudden thickening is thought to result from variation in soil development caused by textural differences across the fault, however, fault displacement could also cause such a change. The age of this soil based on degree of soil development, weathering characteristics, and relationships to the buried soil and older stratigraphic units probably is late Illinoian or Sangamon (Scott, 1963; Machette, 1975; Van Horn, 1976).

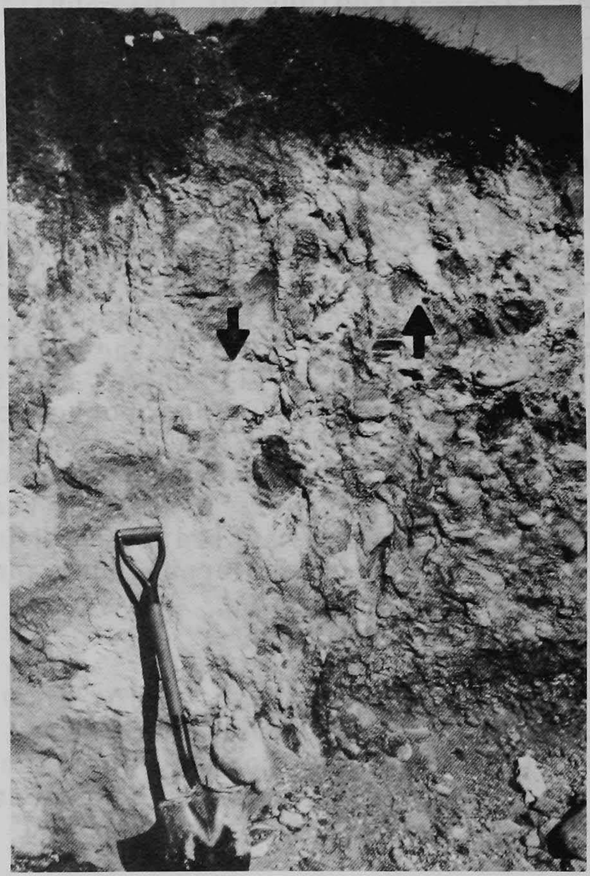


Figure 22. Photograph showing the relationship between the surface soil and fault G5 on the east end of the graben. Arrows indicate direction of fault movement. Note thickening of soil on downthrown side and aligned gravel clasts along the fault.

Within and directly beneath the Cca of the surface soil is a disturbed zone where the original soil and parent material have been altered by oxidation and bioturbation. Development of the disturbed zone occurred simultaneously with development of the surface soil, after the most recent fault movement.

3.2.1.2.2. TRENCH STRUCTURE

The C.G.S. excavations reveal a structurally complex picture that was not fully exposed in the shallow trench observed by Scott (1970). Figure 23 is a generalized geologic cross section derived from the mapped walls of both trenches. The overall structure is a graben with little relative displacement across it. The most striking feature of the cross section is the sharply down-dropped block bounded on the east by fault G5. The gravel-bedrock contact is displaced 5.5 m along this N.25°W.-trending fault and all units except the Sangamon(?) soil are offset by it. A zone rotated and aligned clasts extends from the gravel on the upthrown block to gravel in the graben floor. Pedogenic carbonate occurs on all sides of clasts within the disturbed zone, but only the bottoms of clasts in undisturbed outwash. Carbonate accumulation is greater on clasts within the surface soil horizon. Well developed slickensides preserved in clay gouge along fault G5 indicate a small component of right-lateral slip on a predominantly normal 83°SW dipping fault.

Fault G3 is a N.15°W.-trending reverse fault that dips 53°SW. The gravel-bedrock contact is offset 3.4 m along this fault, but the displacement dies out in younger colluvium as it nears the surface. This termination could result from displacement absorption in the less competent materials or movement contemporaneous with deposition of the younger colluvium. Relationships between faults G2, G3, G4, and G5 and many of the Quaternary units are shown in Figures 24, 25, 26, and 27.

Fault G1 trends N.20°W., dips 83°SW, and bounds the west side of the 14 m wide graben. Other bedrock faults lie west of fault G1, but none of these within the trenched area displace Quaternary deposits (See Figure 23). Displacement along fault G1 is in a reverse-slip sense and ranges from 0.15 to about 1 m (Figure 27). Fault G4, a less apparent but yet very significant fault, lies within the sharply down-dropped block. It strikes N.32°W., dips 74°SW, and displaces the gravel-bedrock contact about 0.4 m in a normal-slip sense. Only the bedrock and Kansan(?) outwash are cut by fault G4 (Figures 24 and 25). The overlying reworked gravel, volcanic ash, and younger colluvium show no evidence of disturbance by fault G4. Fault G6 lies just east of the sharply down-dropped block. The base of the outwash is offset 4 to 30 cm along this brecciated zone. Fault G2 is a 1 m wide bedrock shear zone into which disoriented clasts of Kansan(?) outwash have fallen. The base of the gravel does not appear to be offset across this feature, suggesting that it opened as a tension fracture with no vertical movement. Fault G2 does not offset the overlying volcanic ash.

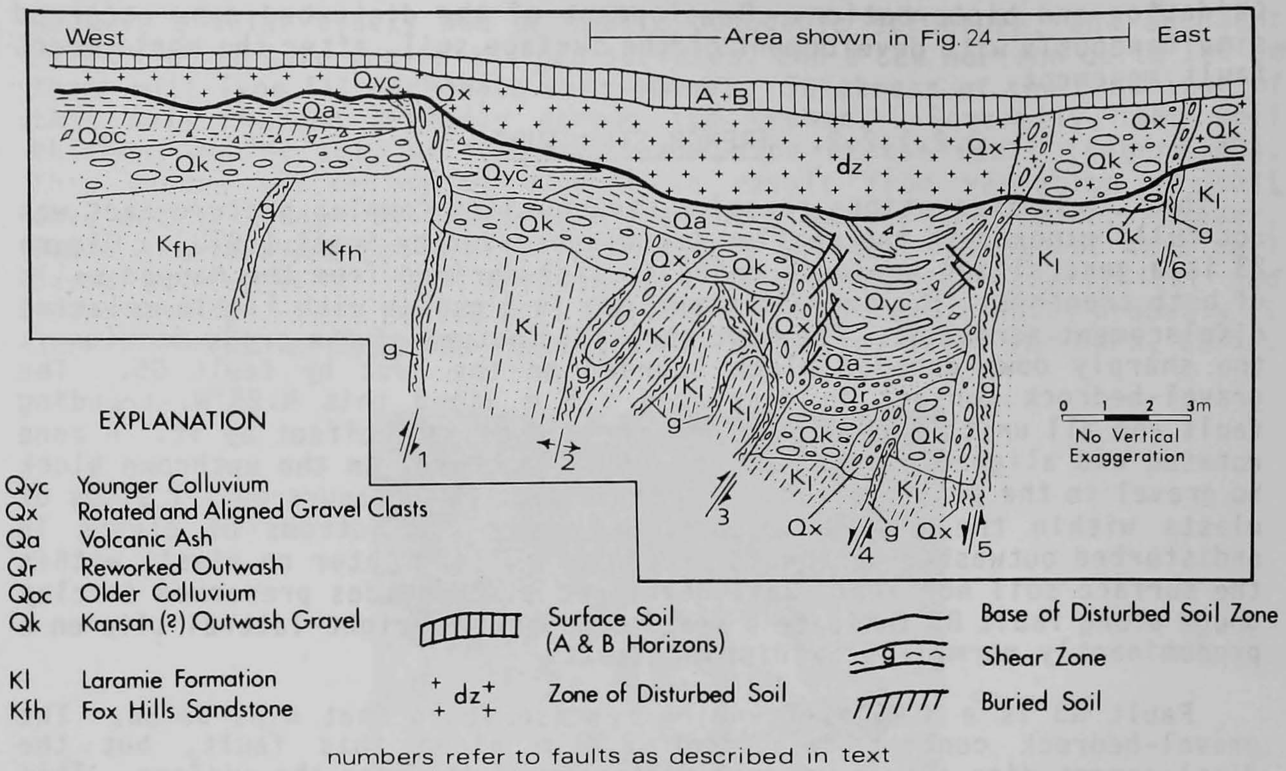


Figure 23. Generalized cross section showing the relationships exposed by trenching the graben near Golden.

Figure 24. Photograph of the east side of the graben near Golden looking north (see Figure 23 for location of photograph). Note faulted Kansan(?) outwash (Qk), especially the 5.5 m offset along fault G5 and the zone of aligned gravel clasts (Qx). See Figure 21 for an explanation of the symbols.

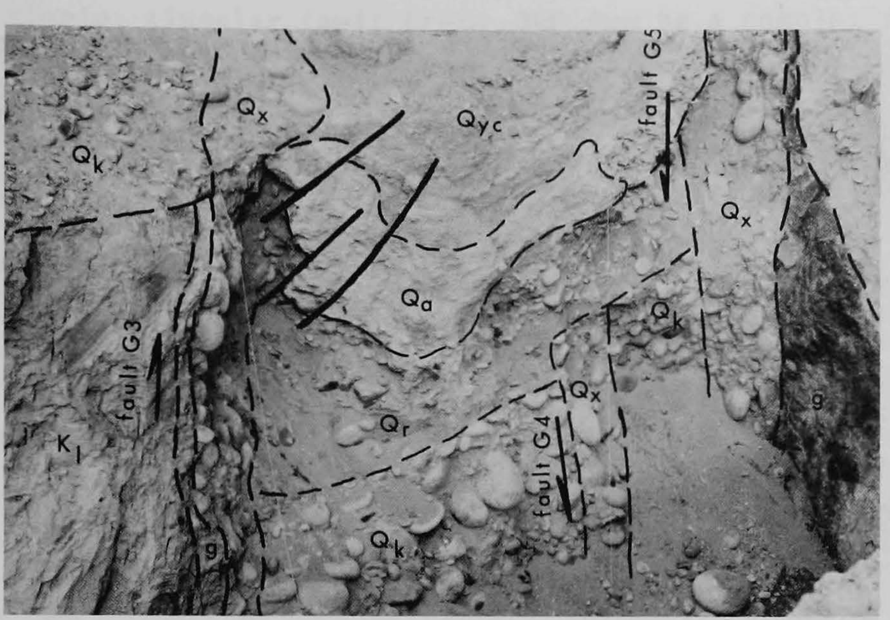


Figure 25. Close-up photograph of faults G3 and G5. Note gouge (g), reworked outwash (Qr), and shearing in the ash (Qa). See Figure 21 for an explanation of the symbols.

Figure 26. Close-up photograph of reverse fault G3. Note that the Laramie Formation is reverse faulted over the Kansan(?) outwash (Qk). See Figure 21 for an explanation of the symbols.

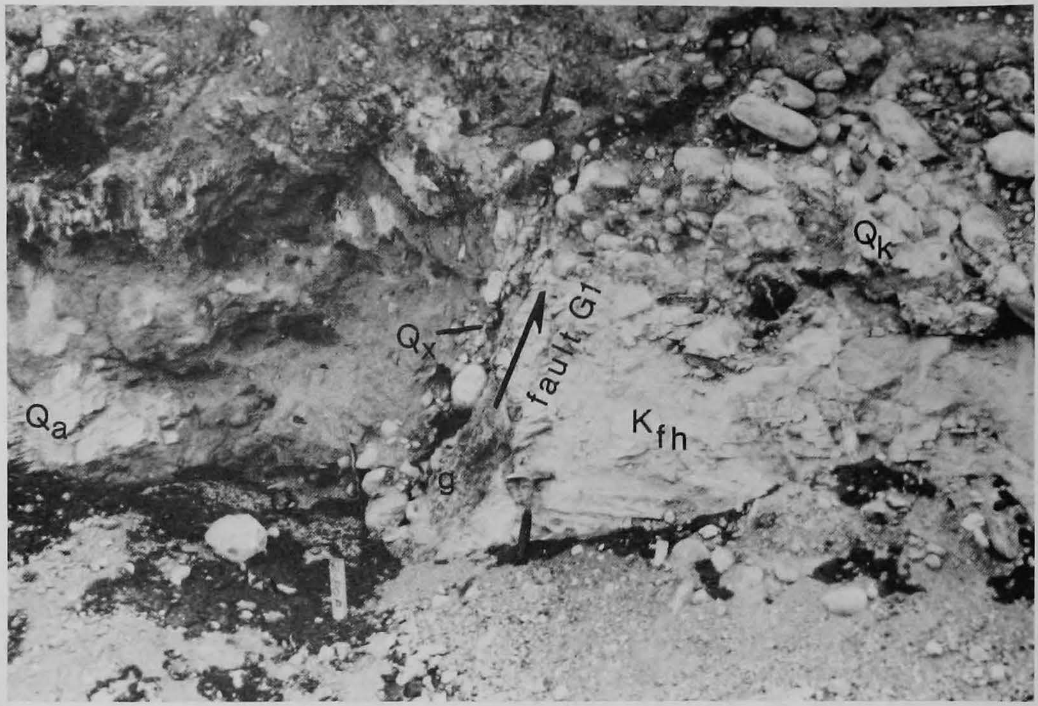


Figure 27. Photograph of fault G1. Note shearing in bedrock and aligned gravel clasts. See Figure 21 for an explanation of the symbols.

Mechanisms other than Quaternary faulting might have possibly created the features observed in the C.G.S. trenches. These include subsidence over a burnt coal bed, channel erosion and subsequent infilling, and landsliding. Channel erosion is eliminated as possible causative mechanisms by the structural and stratigraphic relationships observed in the trenches. Landsliding can not be totally discounted, but the character of deformation seen in the trench, the absence of horizontal slip planes, and the apparent continuity of bedrock stratigraphy to the north and south strongly discredit this mechanism. Subsidence is probably the only feasible alternative explanation of the graben, but the authors believe tectonism may best explain the observed deformation.

The mapped trace of the Golden fault, as shown by Van Horn (1972), is 210 m west of the graben described herein. Van Horn indicates the fault is concealed and therefore approximately located from Chimney Gulch to Tucker Gulch (Figure 19). Our excavation site is situated about midway between the two exposures, at a distance of over 1.6 km from either exposure. Geologic mapping by Scott (1972) and Van Horn (1972), drill hole data studied by Berg (1962) and Smith (1964), and seismic reflection surveys by Schuck (1976) and Money (1977) indicate the Golden fault is not always a simple, singular fault trace, but may be a complex fault zone up to a thousand meters wide. Recent laboratory experiments by Friedman and others (1976) suggest this type of deformation is typical of high-angle reverse faults. The principle structure exposed by the trench is a complex small graben with very little overall down-to-the-east movement.

3.2.1.2.3. SUMMARY OF QUATERNARY GEOLOGIC HISTORY OF THE TRENCH SITE

A summary description of the Quaternary geologic history of the trench site, as interpreted from the excavations and nearby geomorphic features, is as follows: During the early Quaternary a low-relief erosion surface developed on faulted and overturned Late Cretaceous rocks. Main-stream outwash gravels were deposited by Clear Creek at the trench site during or shortly after the Kansan(?) glaciation and a wedge of colluvium extended over part of the gravel. A moderately well developed soil formed during the Yarmouth(?) interglacial period before the first documented episode of Quaternary faulting. During the first period of Quaternary faulting at least six shear zones in the trench area ruptured and a small graben was created at the surface. Maximum displacement during this event was 2.8 m.

Immediately, these newly created scarps were eroded, and reworked outwash was deposited in the floor of the graben. Between 0.6 to 0.7 m.y. ago a volcanic ash fell on the area and was locally reworked by sheet and slope wash and redeposited in the graben. The graben was then filled with younger colluvium and slope wash deposits. During a second episode of fault rupturing at least four shear zones in the trench area were reactivated with a maximum displacement of 2.7 m. Scarps created by this rupturing were eroded and more colluvium was deposited within this new graben. A surface soil began to develop during the Sangamon(?) interglacial period and has continued development to the present.

Thus, the graben has moved at least twice since the Yarmouth(?) interglacial period. One rupture post-dates a paleosol of Yarmouth(?) age developed on colluvium overlying Kansan(?) outwash gravels, but pre-dates deposition of a 0.6 to 0.7 m.y. old volcanic ash. A second rupturing post-dates the volcanic ash and overlying colluvium, but is believed to pre-date development of a surface soil of Sangamon(?) age.

Detailed studies of the Golden fault and the graben near Golden are currently being conducted by Dames & Moore as a part of a seismic hazard investigation for the Rocky Flats nuclear processing plant. Final conclusions from this study were not publicly available when this report was published.

3.2.1.2. RAMPART RANGE FAULT

The Rampart Range fault (fault number 145) is a high-angle reverse fault that extends for about 50 km from Perry Park to Colorado Springs. This fault has been subject to considerable controversy over the years as to the nature, amount, and recency of movement. An impressive fault-line scarp is developed over much of the fault length. The Dawson Arkose is in fault contact with Precambrian Pikes Peak Granite along part of the fault. A minimum throw of 3,000 m during the Cenozoic is indicated by this stratigraphic juxtaposition (Varnes and Scott, 1967; Harms, 1959; Epis and others, 1976a). Neogene movement of at least 450 m is documented by offset of the Oligocene Wall Mountain Tuff and the late Eocene erosion surface (Epis and Chapin, 1975).

Quaternary movement on the Rampart Range fault has been described by Scott (1970). In the N1/2 of sec. 33, T.12S., R.67W. the fault trends N.25°W. and crosses the Kansas or Yarmouth age Douglass Mesa Gravel. Scott (1970) describes a 7.6 m displacement of the gravel at this location. Direction of the movement in the Quaternary was downward on the southwestern side, apparently opposite that of earlier movements. Scott (1970) also describes a south-trending swale in the gravel that may follow a branch of the fault zone. Holocene stream alluvium deposited over the fault is not offset, indicating there has been no fault movement since alluvial deposition during the Holocene.

3.2.1.3. UTE PASS FAULT

The Ute Pass fault zone (fault number 144) extends from south of Colorado Springs, where it bounds the east flank of Cheyenne Mountain, northward through Woodland Park to the vicinity of Deckers. Fault characteristics change significantly along its length. At its south end east of Cheyenne Mountain, the fault is a west-dipping reverse fault with dips as low as 30° (Epis and others, 1976a). Northward, the fault steepens in dip and at Woodland Park the fault zone consists of several nearly vertical faults that form a graben. Total fault displacement is on the order of a few thousand meters (Kupfer and others, 1968; Harms, 1959, 1964). At least 300 m of Neogene movement is indicated by offset of the late Eocene erosion surface and overlying late Tertiary deposits (Epis and Chapin, 1975; Taylor, 1975a; Tweto, 1976a).

Several features suggestive of Quaternary activity are developed along the fault east of Cheyenne Mountain. A prominent scarp is developed in Verdos Alluvium along a bedrock fault in sec. 30, T.15S., R.66W. (Scott and Wobus, 1973). The nature of this feature is not known with certainty, but a tectonic origin is supported by the tilted block of Verdos Alluvium exposed in a roadcut in E1/2 SE1/4 sec. 25, T.15S., R.67W., on strike with the prominent scarp. Several subtle, anomalous lineaments are apparent on aerial photographs of secs. 1, 12, and 13, T. 15S., R.67W. Many of the lineaments are marked by discontinuous scarps in a large sheet of rockfall debris. It is difficult to explain these colinear scarps in rockfall debris by any mechanism other than fault rupture.

Scott and Wobus (1973) believe that the large rockfall event on the east flank of Cheyenne Mountain may have been initiated by earthquake shaking during the Yarmouth(?) interglacial period. Such an earthquake could have resulted from movement on the Ute Pass fault. If the scarps preserved in the rockfall debris are of tectonic origin, then the Ute Pass fault may have moved at least twice during the Quaternary. One movement is required to produce the catastrophic rockfall event, and a second movement to explain the scarps in the rockfall debris.

Highly deformed beds of oxidized, reworked grus are exposed along a small creek in SE1/4 of sec. 23, T.14S, R.67W. Bedding is folded into a series of small folds with a maximum amplitude of about 15 cm. Mechanisms other than fault movement could explain the observed deformation (i.e. mass movement, subsidence, periglacial frost action), but a tectonic origin cannot be ruled out. Many small exposures along the mountain front reveal Precambrian rocks in vertical or near vertical contact with Quaternary deposits. Some of these contacts may be the result of fault offset.

Evidence of Quaternary movement on the Ute Pass Fault is not definitive. In view of the many pieces of circumstantial evidence, however, it is likely that the fault has moved at least once and possibly twice during the Quaternary, probably during the Yarmouth interglacial period or early in the Illinoian glacial period. Slocum Alluvium does not appear to be offset by the fault, hence there probably has been no appreciable movement since Illinoian or Sangamon time.

3.2.1.4. WILLIAMS FORK VALLEY

Numerous Neogene faults displace the Miocene and younger rocks in Williams Fork Valley (Tweto and Reed, 1973a; Tweto, 1973b; Tweto and others, 1976b; Tweto, 1979a). Figure 28 is a vertical aerial photograph of the Williams Fork Valley that shows a few of the faults and their relationship to some of the geologic units. The Williams Fork Mountains lie to the west of the valley, separating the Williams Fork Valley from the Blue River Valley. The Williams Fork Mountains are upfaulted along a 41 km long high-angle fault (fault number 53) that bounds the west side of the valley. In several locations along the fault, the Miocene Troublesome Formation is in fault contact with Precambrian rocks, suggesting considerable Neogene movement. Much of the east side of the valley is also bounded by high-angle, probably normal, faults of Neogene age (fault group 54). As on the west side of the valley, the Troublesome Formation is displaced by many of these faults, indicating the Williams Fork Valley is a graben downdropped during the Neogene.

The valley floor is broken by north- and northeast-trending faults (fault group 55), most of which are downdropped to the west (Tweto and Reed, 1973a). These cross-valley faults are marked by prominent topographic breaks up to 75 m high that offset the Troublesome Formation and possibly the pre-Bull Lake Quaternary gravels, but not the Bull Lake and younger deposits. Several of the faults pass through pre-Bull Lake Quaternary deposts and the base of the gravels lies at different elevations across the faults, suggestive of fault displacement. Age of the various gravels, however, is not accurately known and the apparent fault displacement could actually be due to miscorrelation of deposits of different ages.

A series of parallel, nearly linear, N.75°E.-trending stream drainages are cut into both Miocene and Quaternary gravels in T.1S., R.78W. and

Figure 28. Vertical aerial photograph of the Williams Fork Valley. Prominent fault scarps in Troublesome Formation and pre-Bull Lake deposits indicated by arrows. Cross-valley lineaments of uncertain origin indicated by "?". Quaternary gravels indicated by "Qg", Miocene Troublesome Formation indicated by "Tt", and Precambrian rocks indicated by "pЄ." (photograph by Army Map Service; held by U.S. Geol. Survey)

T.2S., R.78W. (designated by question marks on Figure 28). Tweto and Reed (1973a) map two of these lineaments as faults that displace pre-Bull Lake gravels. The origin of these features is uncertain. They could indeed be Quaternary faults, but their cross-valley orientation, linearity, and parallelism are suspicious. A better explanation might be that the features are a type of "joint" inherited from the underlying bedrock similar to that described by Plafker (1974). The existence of migmatite bodies in the hills east of the valley that have a strike orientation parallel to that of the "joints" lends credence to this hypothesis.

3.2.1.5 OTHER FAULTS

Two faults of Neogene age lie near the western flank of the southern Front Range. The north-trending Oil Creek fault (fault number 143) displaces the late Eocene erosion surface and overlying Oligocene deposits about 306 m (Epis and others, 1976a). The 1979 Divide earthquake apparently occurred on or near the Oil Creek fault. Taylor (1975a) documents a minimum of 400 m of Neogene uplift on the north-trending Fourmile Creek fault (fault number 140) and infers up to 1,000 m of uplift since deposition of Oligocene volcanic rocks, based on elevation differences of the pre-volcanic surface across the fault. There is no documented geological evidence to indicate that either of these faults have moved during the Quaternary.

Several faults in the central and northern parts of the Front Range are thought to be of Neogene age. The Floyd Hill fault (fault number 169) is 41 km long, northwest-trending fault zone with considerable Neogene movement (Scott, 1975a; Sheridan and Marsh, 1976). Near Shaffer Hill, in sec. 13, T.4S., R.72W., the fault zone consists of three roughly parallel N.35 W.-trending strands. Remnants of Tertiary boulder gravel cap bedrock hills separated by the fault strands. The gravel cappings are consistently downthrown to the northeast across the faults. A total of 210 m of post-gravel offset is indicated by displacement of the base of the gravel. Taylor (1975b) describes similar gravels in the Blackhawk quadrangle as being of Pliocene or Miocene a age. If this age assigment is correct, then considerable Neogene movement of the Floyd Hill fault is indicated. Scott (1975a) believes the late Eocene surface is offset as much as 600 m by the Floyd Hill fault.

A similar situation near the Livermore Embayment in Larimer County has been observed by the staff and students of the University of Colorado geology department (W. A. Braddock, 1976, oral commun.). Geologic mapping in this area has revealed an anomalous 50 m elevation change in the base of a Pliocene gravel deposit where it crosses a large east-trending fault zone (fault number 171) in sec. 3, T.9N., R.72W., west of Livermore. This elevation change was detected by contouring the elevation of the base of gravel and it is subject to possible errors due to the inability to accurately locate the base of the gravel. If the gravel is offset by the fault, activity during the Neogene is indicated.

Additional evidence of Neogene fault activity is found in other areas within the Front Range. Scott (1975a) describes 300 m of Neogene movement on the Kennedy Gulch fault (fault number 170), based on displacement of late Tertiary gravel deposits. A roadcut exposure in the North Fork of the Big Thompson River, just upstream from Drake, suggests the Thompson Canyon fault (not shown on Plate 1) may have moved during the Quaternary. V. Matthews (1976, oral comm.) believes many of the faults within the Front Range are of Neogene age. These faults offset erosion surfaces many hundreds of meters, but, unfortunately, the ages of most erosion surfaces have not been accurately determined. Thus, the age of most recent movement on these faults is difficult to determine.

3.2.2. WET MOUNTAINS - SOUTH PARK AREA

A group of north to northwest-trending faults extends from the southern end of the Wet Mountains and Wet Mountain Valley northward into South Park and the south end of the Arkansas Valley. Most of these faults are older structures that were reactivated during the Neogene. Evidence of Quaternary activity has been documented only on a few of these faults. Figure 29 shows the distribution of major Neogene faults in the southern part of this area. The cross section shows the relationship between these faults and the late Eocene erosion surface. As indicated in this cross section, individual faults displace the surface as much as 3,000 m (Taylor, 1975a).

3.2.2.1. ALVARADO AND WESTCLIFFE FAULTS

Wet Mountain Valley is a graben of Neogene age bounded by the Alvarado and Westcliffe faults. The Alvarado fault (fault number 122) bounds the west side of the valley and separates it from the Sangre de Cristo Range. The east side of the valley is controlled by the Westcliffe fault, along which the Neogene basin fill is faulted against the Precambrian rocks of the DeWeese Plateau. Taylor (1975a) believes the valley is structurally continuous with Huerfano Park to the south and that both basins are reactivated Laramide structures filled with Miocene(?) alluvial deposits. The valley floor is largely covered by Quaternary glacial outwash deposits, but a few exposures of the underlying late Tertiary basin fill in the north and south ends of the valley are correlated with the Santa Fe Formation by Taylor (1975a). A minimum of 3,000 m of vertical movement on the Alvardo fault is required to account for the difference in elevation from the top of the Sangre de Cristo Range to the base of Neogene fill in the valley.

No evidence of Quaternary activity has been documented on either the Alvarado or Westcliffe faults. Kauffman and McCullock (1965), however, describe fault deformation of Holocene sediments in Huerfano Park, which is structurally continuous with Wet Mountain Valley. Interpretation of aerial photographs indicates the area studied by Kauffman and McCullock (1965) lies within a large, recently active landslide complex. Mass movement within the complex could easily produce the deformation observed by Kauffman and McCullock.

The south end of the Alvarado fault extends across the Sangre de Cristo Range near Blanca Peak and effectively separates the range into a

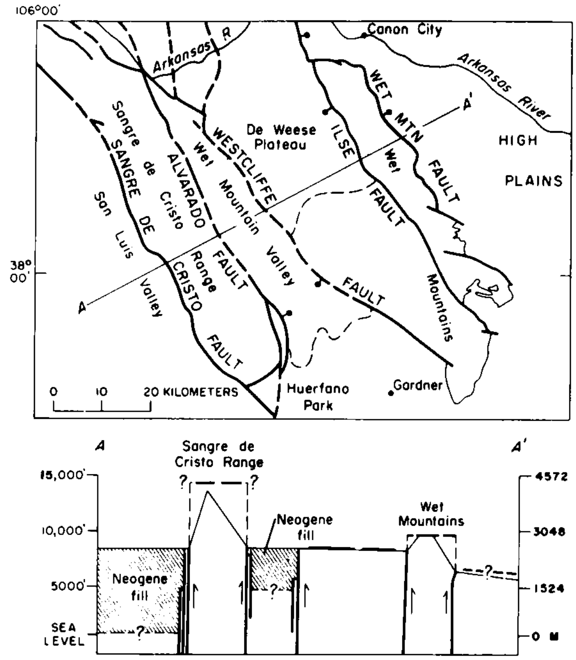


Figure 29. Neogene or potentially active faults south of the Arkansas River between San Luis Valley and Canon City. Cross section shows relationships between faults and late Eocene erosion surface which is indicated by a heavy dashed line. (from Taylor, 1975a; courtesy of the Geological Society of America)

northern and southern unit (Tweto, 1979a). Precambrian rocks in the northern unit are as much as 1,500 m higher than the Precambrian rocks found across the fault in the southern section (Culebra Range). Also, the character of the Sangre de Cristo fault abruptly changes in this area. Along the western front of the northern unit, the fault is dominantly a singular fault that lies at the base of the mountain front. To the south, movement on the Sangre de Cristo fault is distributed across a broad zone of step faults.

3.2.2.2. WET MOUNTAIN AND ILSE FAULTS

Wet Mountain Valley and the DeWeese Plateau are topographically separated from the plains of eastern Colorado by the Wet Mountains. The crestal portion of the Wet Mountains is bounded on the east by the Wet Mountain fault (fault number 126) and on the west by the Ilse fault (fault number 134). An east-trending fault that forms the southern margin of a graben containing Mesozoic rocks (Plate 1; Figure 30) abruptly terminates the northern end of the range.

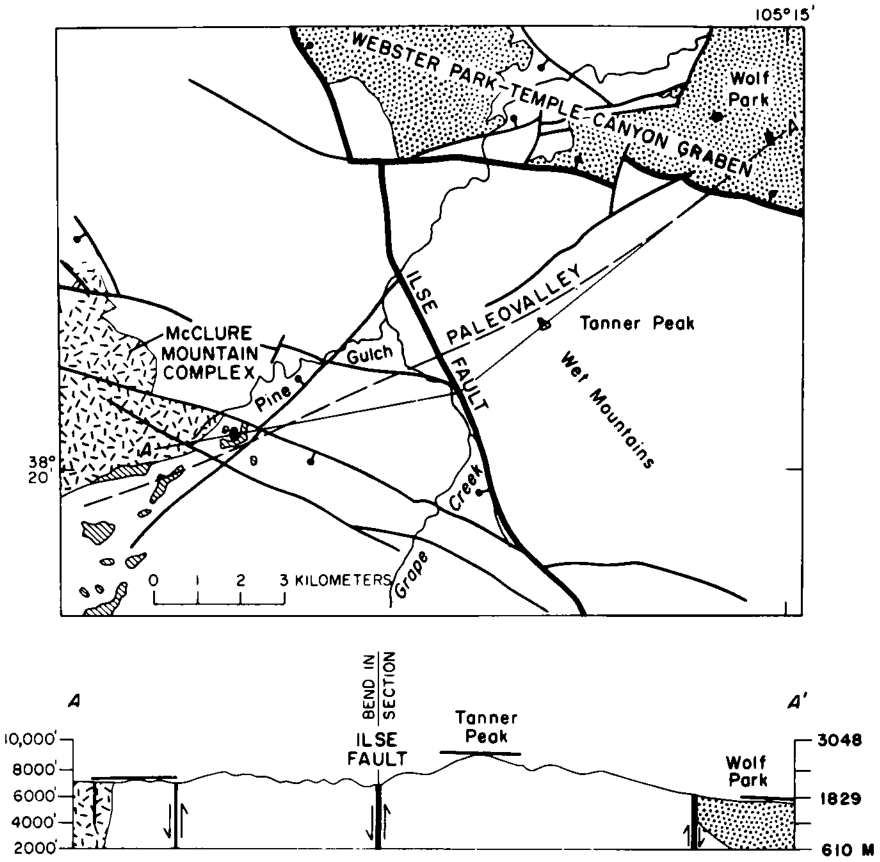


Figure 30. Geologic sketch map of the area near the north end of the Ilse fault. Diagonal line pattern indicates Miocene(?) boulder alluvium, fine stipple indicates Oligocene volcanic rocks and mud flows, coarse stipple indicates Cretaceous to Ordovician sedimentary rocks, and broken line pattern indicates Cambrian syenite. Heavy lines on the sketch map and cross section are Neogene or potentially active faults. Horizontal lines on the cross section show Miocene and Oligocene levels on paleodrainages. (from Taylor, 1975a; courtesy of the Geological Society of America)

A prominent 300 m high, 20 km long fault-line scarp marks the north end of the Ilse fault (Taylor, 1975a). Recurrent movement on the fault in the Precambrian, Laramide, and Neogene is documented by Singewalde (1966) and Taylor (1975a).

Neogene displacement on both the Ilse and Wet Mountain faults is documented by offset Oligocene and Miocene deposits and displaced paleovalleys. Taylor (1975a) describes several locations where Neogene movement can be shown. Figure 30 is a generalized geologic map of the region near Tanner Peak. Considerable Neogene fault movement can be proved both on the east and west sides of the range at this location. The top of Tanner Peak is capped by boulder alluvium containing clasts of the 29 m.y. old Gribbles Park Tuff (ash flow VII of Epis and Chapin, 1968). This alluvium is probably of Neogene age, because it contains 29 m.y. old clasts. This same deposit is also found to the west in broad channels cut into the bedrock. Differences in elevation between these locations suggest a minimum of 500 m of Neogene displacement on the Ilse fault in this region.

To the northeast, in Wolf Park, Taylor (1975a) describes two remnants of late Oligocene deposits (one of which contains the 29 m.y. old Gribbles Park Tuff) that are believed to provide a measure of the elevation of the latest Oligocene and early Miocene topographic level. The elevation difference between the base of the Neogene gravels on Tanner Peak and these volcanic remnants indicate 1,130 m of Neogene movement on the Wet Mountain fault.

Exposures near Locke Park, 13 km south of Tanner Peak, suggest 370 m of Neogene movement on the Ilse fault. Topographic positions in this region imply movement on the Wet Mountain fault is similar in magnitude to that observed near Tanner Peak. Further south, near Wixson Divide, offset paleodrainages indicate about 370 m of displacement along three branches of the Ilse fault zone, comparable to that observed to the north. Again, no remnants of the paleochannels are found east of the range and the post-Miocene displacement, which is thought to be similar in magnitude to that found to the north, must be inferred from differences in topographic levels.

Evidence of Quaternary activity exists on several faults just east of the Wet Mountain fault near Good Pasture. Scott and Taylor (1973) show a fault (fault number 127) in the center of sec. 17, T.23S., R.67W. that displaces Verdos and Slocum Alluviums (Figure 31). Both deposits are thin gravel cappings that overlie bedrock on the west or upthrown side of the fault. Scott and Taylor (1973) explain this anomalous position by a reversal in the direction of fault movement. They believe the west side of the fault moved downward during the Quaternary. Reconnaissance field investigation during this study did not resolve the problem.

Additional suggestions of Quaternary fault activity occur on the Red Creek fault (fault number 127) north of Goodpasture. Geomorphic evidence along this fault strongly suggests fault movement during the Quaternary or at least after development of the modern stream system. Figure 32 is an aerial photograph of this area that shows the influence of the prominent northwest-trending faults on stream development. Many of the ephemeral streams have cut deep canyons into the Dakota Sandstone and Purgatoire Formation on the upthrown side of the Red Creek fault, whereas only minor canyons are incised on the downthrown side. This is suggestive of fault

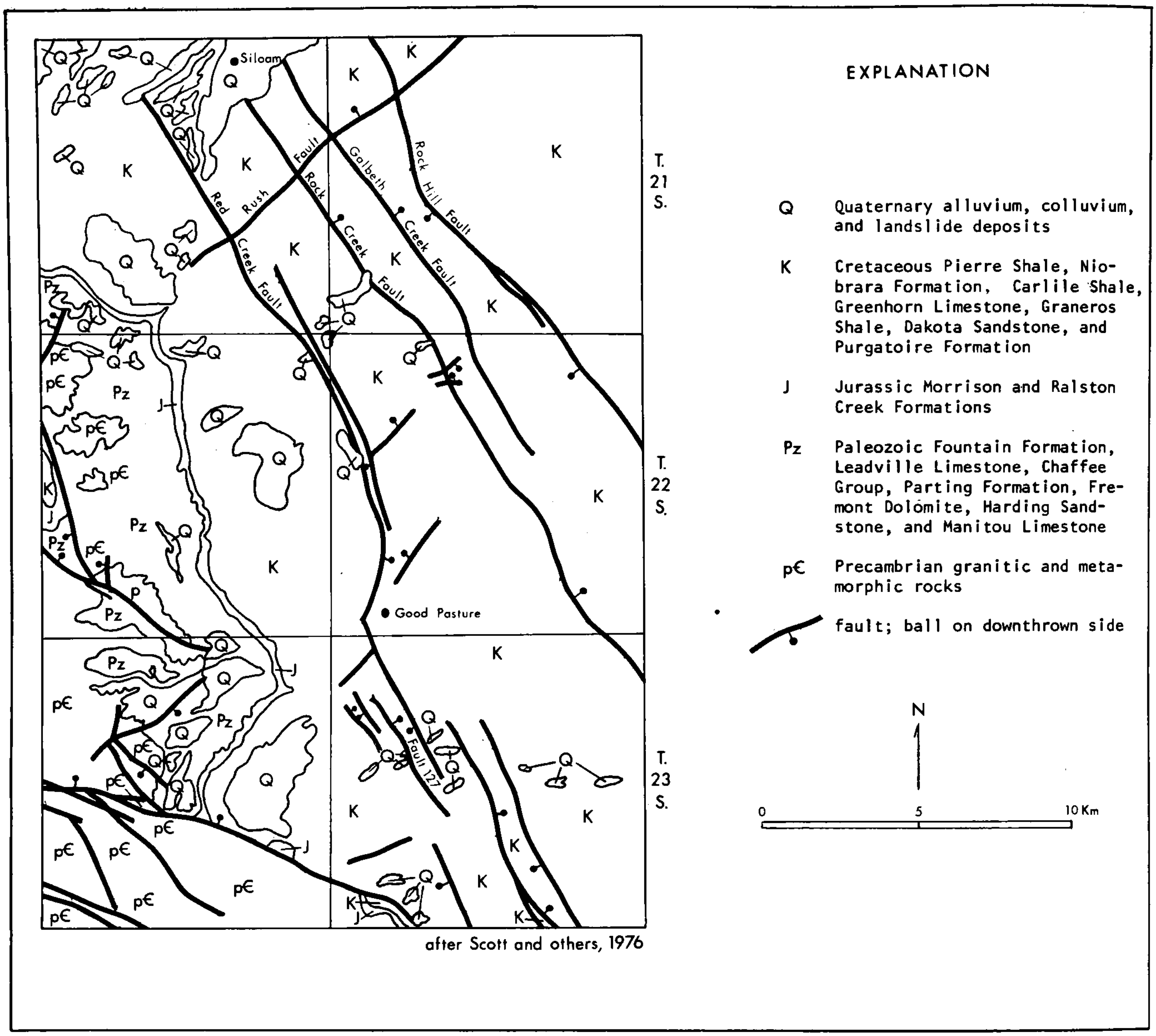


Figure 31. Geologic map of the area near Goodpasture, Pueblo County. Noted faulted Quaternary deposits along fault 127.

movement after establishment of the stream system. Malek-Aslani (1951) noted similar relationships a few kilometers to the south that he believes are the result of recent fault movement.

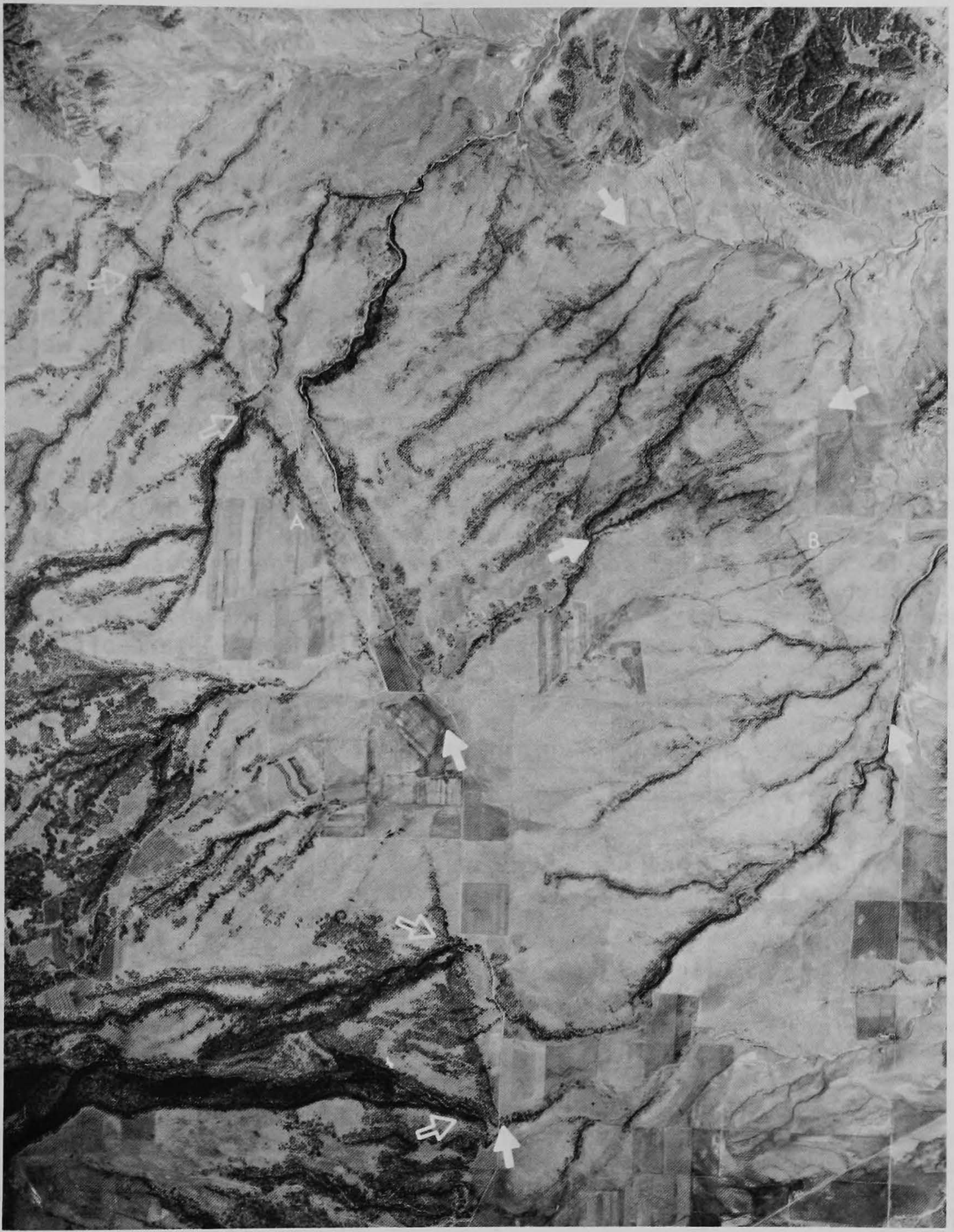


Figure 32. Vertical aerial photograph of the area north of Goodpasture. Note prominent faults indicated by solid arrows ("A" = Red Creek fault; "B" = Rock Creek fault). Incised streams on upthrown side of fault are indicated by open arrows. (photograph by Army Map Service, held by U.S. Geol. Survey)

3.2.2.3. CHASE GULCH FAULT

The Chase Gulch fault system lies in the eastern part of South Park. It recently was studied in detail by Shaffer (1980) because of the fault's close proximity to Aurora's proposed Spinney Mountain Reservoir. Most of the information presented herein is summarized from Shaffer (1980).

The Chase Gulch fault system consists of two faults, an east-side fault (fault number 177) and a west-side fault (fault 178). The east-side fault represents the main trace of the Chase Gulch fault and the west-side fault is subsidiary to the east-side fault. The east-side fault trends N.40°W. and dips east a minimum of 50°. Displacement on the east-side fault is in a normal-slip manner, whereas the west-side fault has moved in a reverse-slip fashion. The Chase Gulch fault system bounds the west side of a Neogene graben that is flanked by the Front Range on the east and by Spinney and Sulphur Mountains on the west. Gravity and borehole data indicate a minimum of 600 m of Neogene fill in the graben.

Detailed geomorphic and trench investigations by Shaffer (1980) reveal evidence of late Quaternary activity on the Chase Gulch fault system. Surface scarps 1.2 to 1.8 m high mark the trace of both the east-side and west-side faults. The scarps are laterally continuous except where disrupted by modern drainages and erosional surfaces. The most recent movement on both faults appears to have occurred between the late and early Pinedale glacial periods. Early Pinedale deposits are offset about 2.4 m by the west-side fault. Bull Lake deposits are displaced about 15 m by the west-side fault and about 9 m by the east-side fault.

3.2.2.4. OTHER FAULTS

The Texas Creek fault (fault number 135) extends northward from the Westcliffe fault to just south of Waugh Mountain. Precambrian Boulder Creek Granodiorite is downdropped about 3,000 m on the west side of the fault (Epis and others, 1976a). Crosscutting relationships with Verdos Alluvium and Bull Lake deposits (Scott, 1970; Scott and others, 1976; Epis and others, 1976a) indicate there has been no appreciable Quaternary movement on the Texas Creek fault. The Rosita fault (fault number 129) displaces the Miocene igneous rocks of the Rosita volcanic center, but is covered by Verdos Alluvium and possibly the upper part of the Santa Fe(?) Formation (Scott and others, 1976).

The region north of the Arkansas River has experienced considerable Neogene crustal deformation along several generally north-trending faults. Figure 33 is a schematic section from the southern Sawatch Range northeastward to near Castle Rock. The Eocene erosion surface, Oligocene Wall Mountain Tuff, and Eocene, Oligocene, Miocene, and Pliocene sedimentary rocks are displaced by high-angle faults throughout this region. Maximum Neogene displacement occurs on the Sawatch fault (discussed in the section on the Rio Grande rift province), but considerable movement is documented on the Currant Creek fault, Oil Creek fault, Ute Pass fault, Rampart Range fault, Chase Gulch fault system, Elevenmile fault, and faults 155, 156, and 157 (Scott, 1970; Epis and Chapin, 1975; Taylor, 1975; Epis and others, 1976a; Shaffer, 1980).

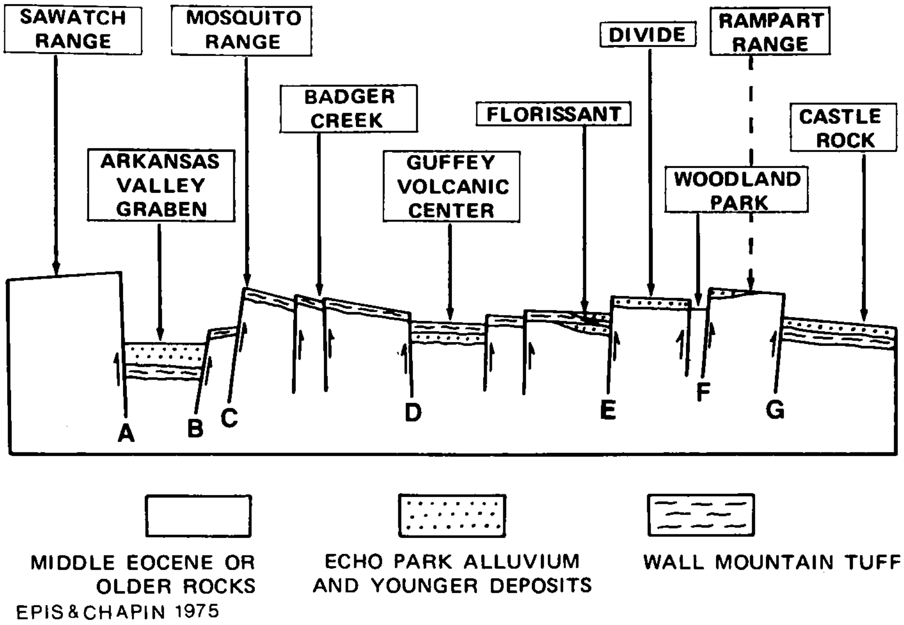


Figure 33. Schematic section from the Sawatch Range northeastward about 200 km to near Castle Rock showing Neogene or potentially active faults and their relationship to the late Eocene erosion surface and overlying deposits. Letters indicate various faults as follows: "A" = Sawatch fault, "B" = fault 156, "C" = fault 155, "D" = Currant Creek fault, "E" = Oil Creek fault, "F" = Ute Pass fault, and "G" = Rampart Range fault. (from Epis and Chapin, 1975; courtesy of The Geological Society of America)

The Currant Creek fault (fault number 146) and associated faults disrupt the Oligocene Thirtynine Mile and Guffey volcanic centers. Over 400 m of post-volcanic movement is described by Epis and Chapin (1968) near the Thirtynine Mile volcanic center. This movement may be related to either volcanism or regional tectonism. The Currant Creek fault can be traced southward to north of the Arkansas River, where it joins the Ilse fault zone. No evidence of Quaternary activity has been documented on the Currant Creek fault.

The Elevenmile fault (fault number 176) was briefly investigated by Shaffer (1980) during the study for Spinney Mountain reservoir. Geomorphic expression of the fault suggests late Quaternary activity. Bull Lake deposits appear to be offset about 1.8 m by the Elevenmile fault and ground water is ponded behind the fault in younger alluvial deposits.

Shaffer (1980) believes no significant movement has occurred on the Elevenmile fault since the late Pinedale glaciation.

The only known Neogene thrust fault in Colorado is at Red Mountain, just east of Kremmling and north of U.S. Highway 40. Red Mountain is a thrust block of Precambrian rock that has slid over the Miocene Troublesome Formation and Cretaceous Dakota Sandstone. Izett (1975) believes Red Mountain is a Laramide klippe of Precambrian rock that moved again in the Miocene as a gravity-slide block resulting from reactivation of the Williams Range fault. The thrust at Red Mountain is not shown on Plate 1 because of its limited areal extent.

3.3. WESTERN MOUNTAIN PROVINCE

Relatively few faults of Neogene age occur in the western mountain province. Several faults in the San Juan volcanic field offset Neogene rocks, but most are related to caldera collapse and are not recurrently active tectonic faults. Several faults in the Gysum-Burns area also offset Neogene rocks, but most of these are probably associated with flowage or solution in the Eagle Evaporite. A few of the Precambrian faults of the west to northwest trend (Tweto, 1979b), such as the Cimarron fault (fault number 94) and other faults to the east that are not shown on Plate 1, show minor evidence of Neogene reactivation. A few other Neogene faults are scattered throughout the western mountain province, but none are major tectonic faults that have experienced any known significant Quaternary activity.

3.3.1. SAN JUAN MOUNTAINS

The San Juan Mountains are believed to be relatively free of Neogene faulting. Atwood and Mather (1932) suggested this region experienced repeated crustal upwarp, accompanied by thousands of meters of fault movement that began in the Miocene and continued into the late Quaternary. Recent work by T. A. Steven (1977, oral commun.) disproves this. Steven finds virtually no evidence of large magnitude Neogene fault movement in the San Juan Mountains except for faults associated with the collapse of the Lake City caldera, numerous faults in the eastern end of the San Juan Mountains, a segment of the Cimarron fault, and fault number 96. The N.30°W.-trending fault number 96 displaces the Miocene basalt that caps Cannibal Plateau about 100 m (T.A. Steven, 1977, oral commun.). Steven also believes part of the Cimarron fault (fault number 94) has moved a few meters since the Miocene. Neither of these faults show evidence of Quaternary activity. Other faults in the area are suspected of minor Neogene movement (R. G. Young, 1977, oral commun.; J. B. Johnson, 1977, oral commun.), but recent movement has not been documented.

The Lake City Caldera is a resurgent caldera that erupted the 22.5 m.y. old Sunshine Peak Tuff (Steven and others, 1974). Caldera collapse occurred shortly thereafter and the Miocene age tuff was broken by numerous faults (fault group 95). These faults apparently have not moved since caldera collapse, and are probably not capable of significant future movement.

Over 40 faults in the eastern San Juan Mountains are of Neogene age and displace Miocene and Pliocene basalt flows in the region. Additional faults in this area are suspected of Neogene activity, but movement cannot be documented because of an absence of datable erosion surfaces and Neogene rocks (T. A. Steven, 1977, oral commun.). These faults are herein considered a part of the Rio Grande rift province and are discussed in that section.

3.3.2. GYPSUM - BURNS AREA

Tweto and others (1976b) have mapped several northwest-trending faults (fault numbers 58 and 59) that displace Miocene basalt flows just north of Gypsum in Eagle County. The basalt flows are broken into a series of tilted fault blocks with dips up to 10°. Only fault 58 shows any evidence of Quaternary activity. Fault 58 bounds the northeast side of Greenhorn Mountain. A striking, linear topographic escarpment up to 75 m high marks the fault trace, both in bedrock and in a large landslide complex of Quaternary age. A few small, younger landslides within the larger slope failure complex cover discontinuous segments of the fault.

Southeast of Burns, several faults in fault group 57 have prominent topographic expression and disrupt the Dakota Sandstone and overlying pediment and landslide deposits. Only a few of these faults are mapped on Plate 1; many more are obvious on aerial photographs of the area. A strong lineament along the west end of a long, east-trending fault in this area is present in a large landslide complex of Quaternary age, suggestive of post-landslide, Quaternary activity on this fault.

Additional evidence of Quaternary movement is found on two faults exposed in a roadcut east of Burns near Blue Hill in the SW1/4 of sec. 18, T.2S., R.84W. The fault on the north end of this exposure trends N.70°E. and dips approximately 75°NW. It displaces Mancos Shale and overlying pediment gravels approximately 2 m. A pre-Bull Lake age is postulated for these Quaternary pediment gravels. A second fault is exposed just south of the above described fault and it also evidently moved during the Quaternary. The base of the pediment gravel does not appear to be offset by the second fault, but gravel clasts from the overlying pediment deposit are found within the fault zone up to 0.7 m below the base of the gravel unit. Other bedrock faults are also present in the roadcut, but their relationship with the pediment gravel is not exposed.

Southwest of Gypsum on the east side of Red Hill are a series of narrow, elongate, east-trending grabens (fault group 60) that displace a Quaternary landslide complex. The three faults shown on Plate 1 are generalized from the numerous, closely spaced faults found here. Quaternary movement on these faults is indicated by offset of the landslide deposits.

The mechanism responsible for faulting in the Gypsum-Burns area is not known. These faults do not appear to be related to any major structures or to any local tectonism. The area is underlain by the Pennsylvanian Eagle Evaporite, a formation subject to solution, flowage, and associated deformation. Numerous examples of recent deformation due to evaporite solution are found throughout this area. Large subsidence depressions are especially well developed where the Eagle Evaporite is at or near the surface in the area around fault groups 59 and 60. Fault characteristics in this area suggest evaporite flowage and solution may be responsible for the observed Quaternary deformation.

The possibility of a basement-related faulting should not be totally discounted, however. The youngest volcanic rocks in the state are found in this same region (Plate 1) and their presence may imply deep-seated crustal movements during the Quaternary in this area. Giegengack (1960) dated young basalt flows near Dotsero at 4,150 ± 300 years B.P. Volcanic rocks near McCoy have been dated at 0.6 ± 0.2 m.y. and basalt flows along the Roaring Fork River have been dated around 1.5 m.y. (Larson and others, 1975).

3.3.3. GLENWOOD SPRINGS AREA

As many as 30 faults are described by Murray (1969) on the Grand Hogback west of Glenwood Springs (fault group 61). The faults are a series of parallel, N.25°W.-striking, west-dipping, normal faults that have broken the Miocene basalt cap and overlying gravels derived from the basalt into a series of east-dipping, tilted fault blocks. Individual blocks dip 11° to 35° east, with the steepest dips on the east end of the block. The overall basalt cap has been tilted about 7°, whereas the gravel-capped blocks are tilted only about 4°. Amount of throw on each fault ranges from a few meters up to about 270 m.

Murray (1969) eliminates landsliding and deformation due to evaporite flowage as causative mechanisms and proposes flexural slip, formed in response to the unfolding of the Grand Hogback monocline. Murray believes the near-surface dips of the monocline were once 70° to 80° and that later relaxation created the 45° to 70° dips existent today. Flexural slip experiments performed with a ship curve simulated the direction and amount of fault displacement observed in the field. The offset Quaternary(?) gravels indicate possible recent movement, but because of the apparent nature of the deformation, large damaging earthquakes would seem unlikely.

3.4. PLAINS PROVINCE

The plains province includes the eastern one-third of Colorado (Figure 5). Tectonic deformation in this province has been documented during the Precambrian, late Paleozoic, and Laramide orogeny, but no evidence of major Neogene activity is present. Considerable Precambrian fault activity, particularly in the southeast part of the state, is indicated by Tweto (1980b). Warner (1980) suggests a major Precambrian fault zone may extend northeastward from the Colorado Mineral Belt across the plains. Fault and fracture zones, such as that encountered by the Rocky Mountain Arsenal disposal well (Scopel, 1964), may be common in much of the Precambrian rock that underlies the plains province.

During the late Paleozoic the Apishapa highland in southeastern Colorado was uplifted by faulting (Tweto, 1980b). Uplift occurred on the northeast-trending Las Animas arch in southeastern Colorado and the Greeley Arch during the Laramide orogeny. Only four faults in the plains province show evidence of Neogene activity. Two of these, the Fowler and Cheraw faults, are in the south-central plains region. A third, the Valmont fault, lies just east of Boulder. Historic movement on a fourth fault, the Rocky Mountain Arsenal fault, was triggered by fluid injection into a deep disposal well.

3.4.1. ROCKY MOUNTAIN ARSENAL FAULT

In 1962 a series of earthquakes initiated in northeast Denver that continued for several years. The earthquakes defined a linear northwest-trending zone that we and many other geoscientists infer to represent a deep, basement-controlled fault or fracture zone herein named the Rocky Mountain Arsenal fault (fault number 168). It is widely accepted that the earthquakes were triggered by deep fluid injection at the Rocky Mountain Arsenal disposal well. The earthquake distribution, relationships between injection pressure and released earthquake energy, and presence of intense fracturing in drill hole cores of Precambrian rock from the bottom of the well suggest tectonic stresses were released by the earthquakes along a fault or fracture zone.

Geological and geophysical studies conducted during the 1960s (Healy and others, 1966a; Hollister and Weimer, 1968) found no conclusive proof of a major fault in the sedimentary rocks that overlie the linear zone of earthquakes. De Voto (1968), however, pointed out several anomalous geomorphic features suggestive of Quaternary fault activity. Recent work by J. L. Hamilton (1979, pers. commun.), K. E. Brand (1980, pers. commun.), and the authors suggest that Late Cretaceous and Paleocene rocks may be disrupted by faulting on the north and south ends of the Rocky Mountain Arsenal fault. Thus, a great deal remains to be learned about this fault and its relationship to the earthquakes triggered by fluid injection at the Rocky Mountain Arsenal. A summary discussion of these induced earthquakes is presented in a following section on man-made earthquakes.

3.4.2. FOWLER FAULT

A fault near Fowler, herein named the Fowler fault (fault number 172), trends N.60°W. and is about 12 km long. It lies in Crowley and Pueblo Counties about 5 km northwest of Fowler and is approximately parallel to the Arkansas River. The Fowler fault is described by Scott (1970) as displacing Rocky Flats Alluvium about 18 m. Two terraces underlain by stream gravel are separated by an abrupt, linear, 18 m high scarp. Gravel in terraces on both sides of the scarp have identical textural and lithological characteristics, and have similar well-developed soils, suggesting that both terraces are capped by the Nebraskan or Aftonian Rocky Flats Alluvium. The prominent scarp coincides with three northward-dipping faults described by Scott (1970) in underlying Pierre Shale in the SW1/4 sec. 22, T.21S., R.60W. Presence of these bedrock faults supports a fault origin for the scarp. Holocene Piney Creek Alluvium is the oldest unit not displaced by the fault (Scott and others, 1976). Age of the most recent movement on the Fowler fault, therefore, is bracketed by the Nebraskan glacial period or Aftonian interglacial period and the Holocene.

3.4.3. CHERAW FAULT

A fault near Cheraw, herein called the Cheraw fault (fault number 173), is also located in the lower Arkansas River Valley region. This fault was discovered by J. A. Sharps in 1968 and described by Scott (1970). The fault trends N.45°E. and extends about 44 km from near Cheraw to Haswell. Figure 34 is a surficial geologic map of the area near the fault. Rocky Flats Alluvium is downdropped up to 12 m on the northwest side of the fault. Late Pleistocene and Holocene slopewash deposits and loess cover the fault and apparently are not displaced by it. The fault trace is marked by a weathered but yet distinct scarp, vegetation changes, linear ponds, and calcite and barite-cemented breccia (J. A. Sharps, 1976, oral commun.). Figure 35 is an aerial photograph of an area where the ponds are especially prominent along the fault.

Development of the sag ponds may be related to either of two processes. The Niobrara Formation underlies the surficial deposits near the fault. The formation is composed primarily of marl and marly shale, both of which are susceptible to solution and development of karst features. Ground-water movement is often channelized along fault zones and in carbonate-rich rocks solution features, including sinkholes, may develop along a fault. Numerous sinkholes are found throughout this region where the Niobrara Formation is present at shallow depths. Some of the ponds along the fault may thus be surface expressions of sinkholes.

Blockage of stream drainages by fault rupture may also explain some of the ponds. In this region all streams drain southeastward toward the Arkansas River in a direction nearly perpendicular to the Cheraw fault. Since the northwest side of the fault is downthrown, any sudden fault movement would tend to dam a stream and pond water at the base of the scarp. On the upthrown side of the fault the stream channel would be abandoned. Several drainages that cross the fault exhibit such characteristics and are suggestive of Quaternary movement after establishment of the drainage system.

Figure 36 is a Bouguer gravity map of the area that includes the Cheraw and Fowler faults. Gravity anomalies coincide with both faults, particularly the Cheraw fault, suggesting deep-seated control of these faults. The Las Animas arch, a broad, regional anticline extends through this area. The Cheraw and Fowler faults may be related to recent minor movement on the arch or other deep structures in this area.

A 75 km long lineament trends N.30°W. from near Stratton in Kit Carson County to near Akron in Washington County. It is an abrupt, linear scarp obvious on aerial photographs. J. A. Sharps (1976, oral commun.) has noted anomalous dip changes in the bedrock on either side of the fault and unusual relationships between the lineament and distribution of Peorian loess. The exact nature of this lineament is not known, and for this reason is not shown on Plate 1.

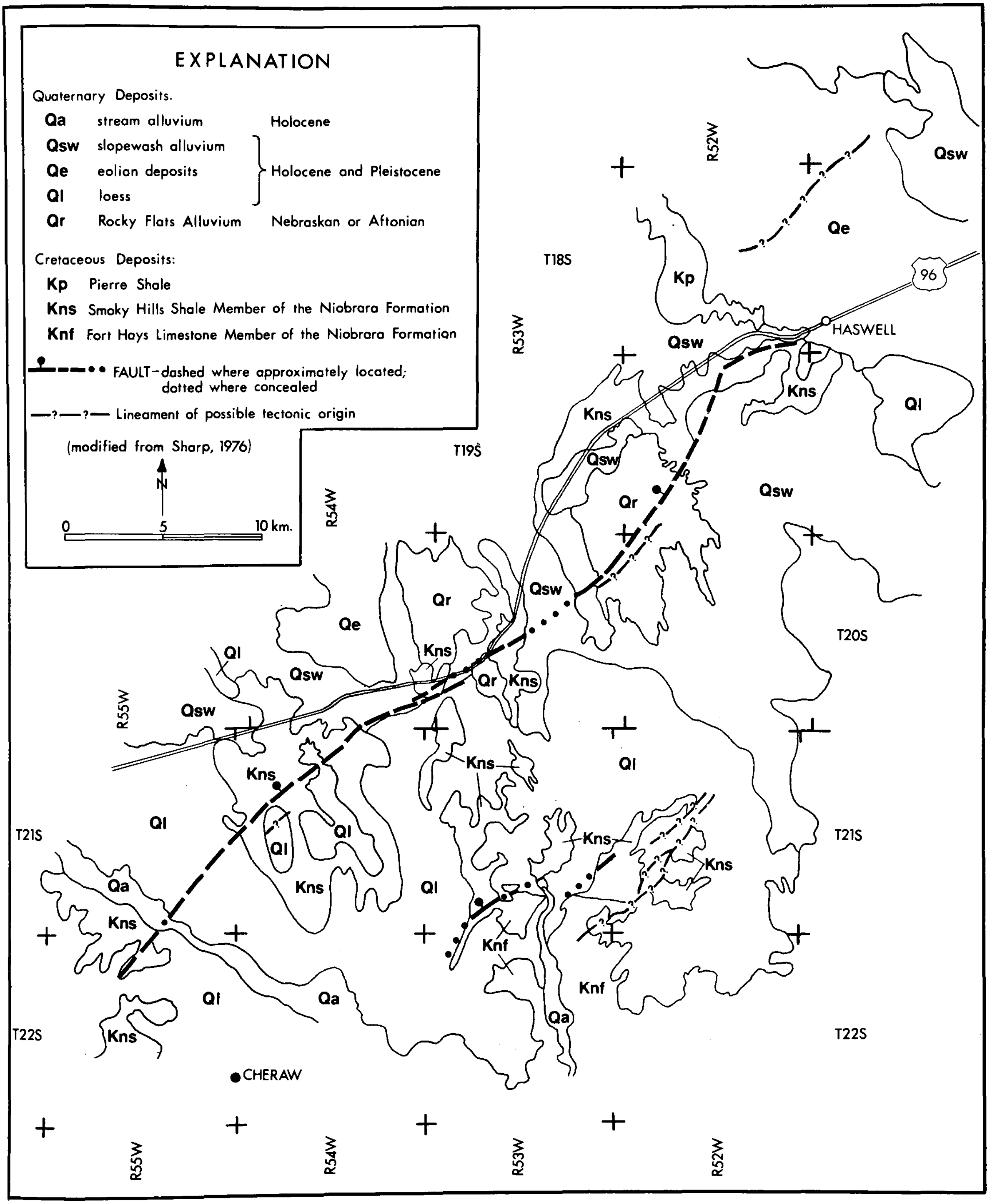


Figure 34. Surficial geologic map of the area near the Cheraw fault, Otero County.

Figure 35. Vertical aerial photograph of part of the Cheraw fault. Note prominent sag ponds (open arrows) along fault scarp (solid arrows). (photograph by Army Map Service; held by the U.S. Geol. Survey)

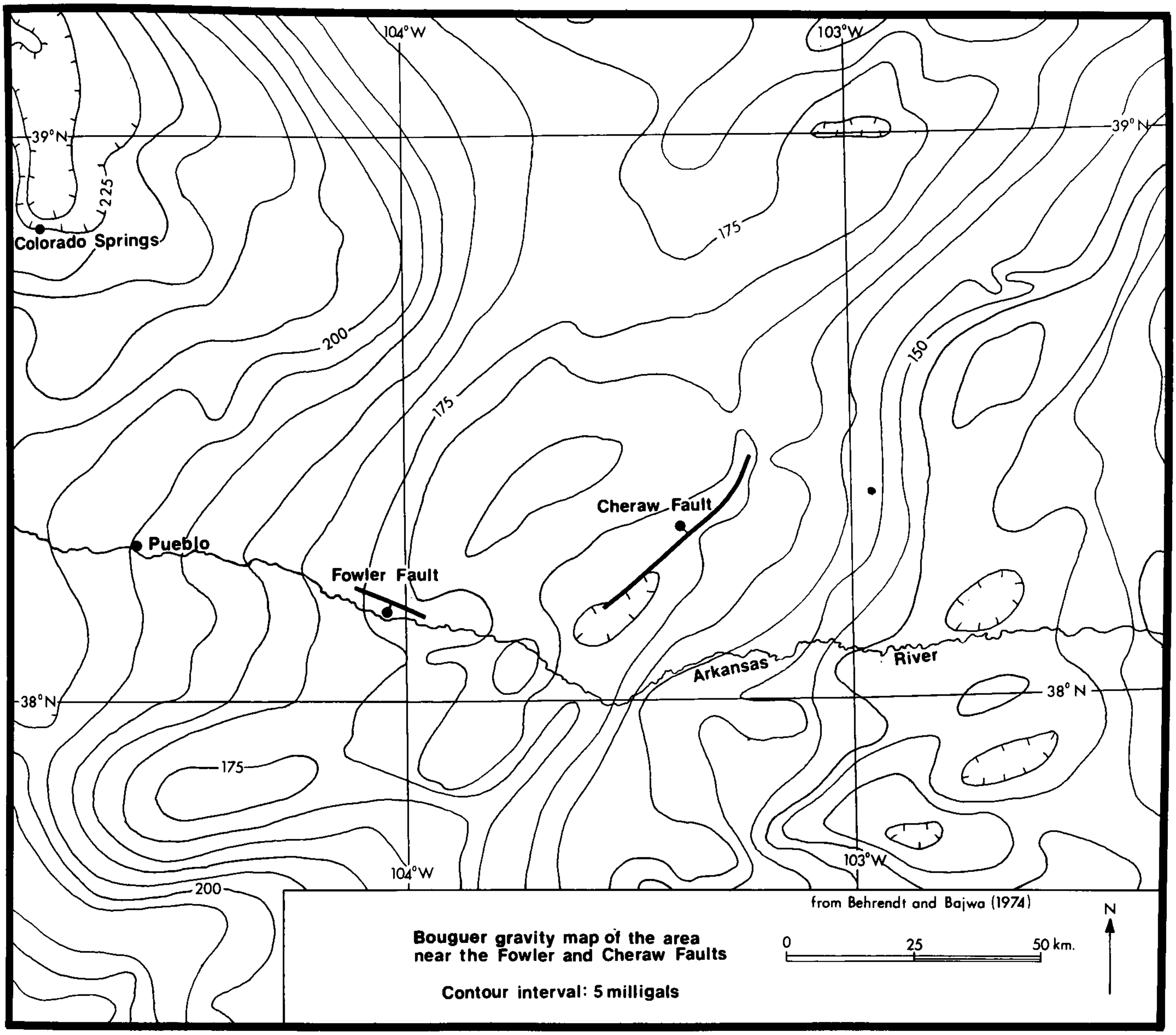


Figure 36. Bouguer gravity map of the area near the Fowler and Cheraw faults.

3.4.4. VALMONT FAULT

The Valmont fault, discovered by Frank Riley in 1957, lies about 8 km northeast of Boulder in the S1/2 sec. 24, T.1N. R.70W. The fault is mapped by Scott and Cobban (1965) and Trimble (1975) and is described by Scott

(1970) as a minor, N.50°E.-trending vertical fault that displaces Fox Hills Sandstone against the Illinoian or Sangamon age Slocum Alluvium. The south side of the fault is downthrown at least 1.5 m, although it is difficult to precisely define the exact amount of displacement (Figure 37). The fault has no surficial expression and is known only because of its exposure in a roadcut along north 75th Street. A 13 m wide zone of sheared and disrupted Fox Hills Sandstone marks the fault trace in bedrock, and gravel clasts in overlying Slocum Alluvium are disoriented (Figure 37). The bedrock-gravel contact is offset with down-to-the-south movement as much as 0.5 m along individual vertical shears.

Figure 37. Photograph of the Valmont fault. Note offset Slocum Alluvium (Qs) at main trace of fault (solid arrow). Zone of disoriented gravel clasts underlain by zone of intense shearing in Fox Hills Sandstone (Kfh). A few of the shears offset the base of the gravel. (photograph by G. R. Scott, U.S. Geol. Survey)

Scott (1970) noted the parallelism between the Valmont dike (B in Figure 38) and Valmont fault (A in Figure 38), suggesting a relationship between the two. Figure 38 also shows the locations of the Valmont fault and Valmont dike and their spatial relationship to a suite of high-angle, northeast-trending faults. Striking lineaments are developed along several of the faults included in this trend near Marshall, but these features are believed to be eroded fault-line scarps, not recent fault scarps.

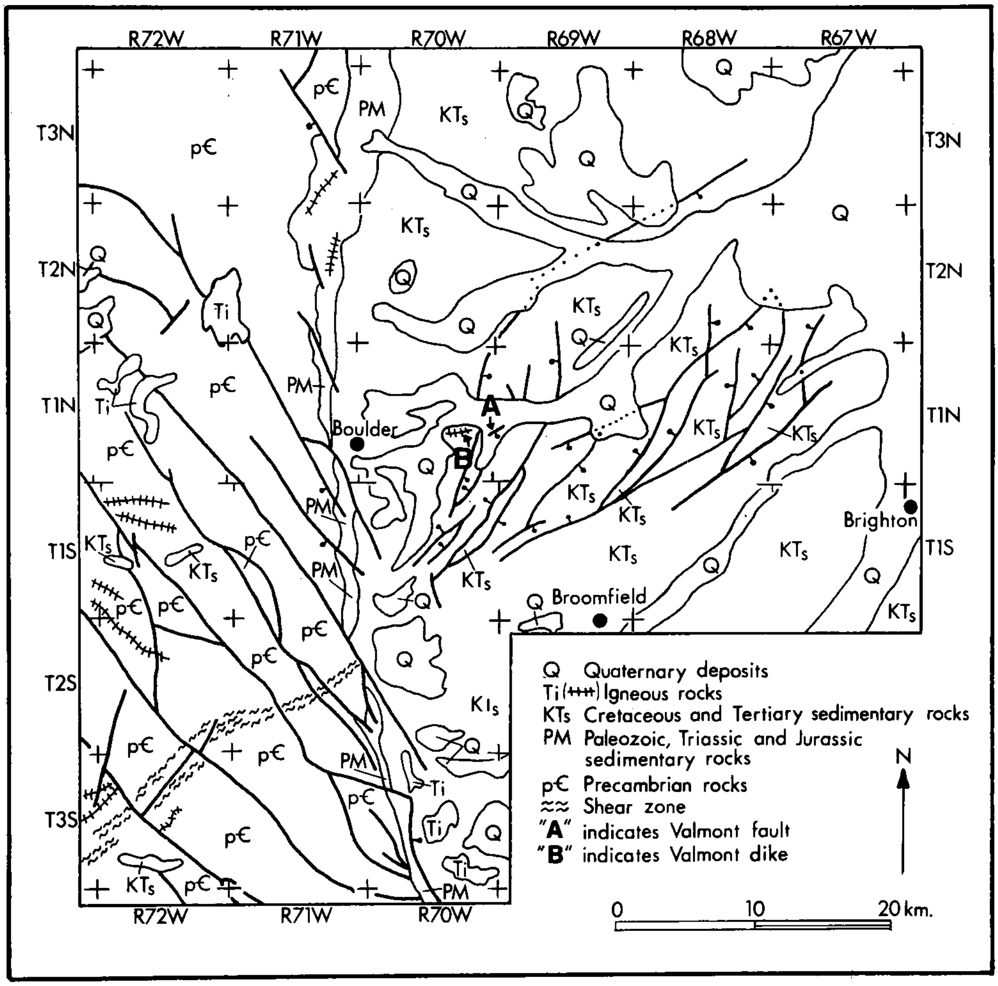


Figure 38. Geologic map of the area near the Valmont fault, Boulder County. Valmont fault indicated by "A"; Valmont dike indicated by "B". (after Tweto, 1979b)

3.5. UINTA-ELKHEAD PROVINCE

The late Cenozoic history of northwestern Colorado is similar to that of the rest of the southern Rocky Mountains (Hansen, 1965; Buffler, 1967;

Izett, 1975). A widespread, low-relief, erosional surface was carved out of terrain formed during the Laramide orogeny prior to the Miocene. Several Neogene sedimentary units, including the Browns Park, Troublesome, and North Park Formations were unconformably deposited on this eroded surface. Unconformities and conglomerates within these formations indicate recurring Miocene and Pliocene tectonism. Structure contours on the base of the Neogene deposits reveal that up to 1,000 m of fault movement is commonplace and that considerably greater uplift occurred locally (Hansen, 1965; Buffler, 1967). Many of the Neogene faults are reactivated Laramide or older faults, but commonly the direction of movement in the late Cenozoic is opposite that of earlier movement.

The prominent regional structural zone extending eastward from the Uinta Mountains, through the Elkhead Mountains, and into North Park is characterized by Neogene deformation on west- and northwest-trending, high-angle normal and reverse faults and monoclinal folds. Several distinct fault systems can be recognized within this larger zone. Long, west-northwest-trending faults near the Utah-Colorado border are associated with Neogene collapse of the crest of the Laramide Uinta arch. Numerous, short, northwest-trending faults near Cross Mountain and west of Craig break the terrain into a series of horst and graben fault blocks. A zone of generally northwest-trending faults cut through the Elkhead Mountains.

3.5.1. UINTA TREND

Long N.20°W.-trending faults in the extreme northwestern part of the state (fault numbers 1 through 9) are associated with Neogene collapse of the eastern end of the Laramide-age Uinta arch. The Cenozoic history of this area is summarized by Izett (1975), who modified the work of Sears (1924), Bradley (1936), and Hansen (1965) as follows:

> 1) After Laramide uplift, which formed the Uinta arch..., and stripping of the Paleozoic and Mesozoic sedimentary rock cover, the area underwent renewed extensive erosion and epiorogenic uplift in middle Cenozoic time.
>
> 2) A major east-trending paleovalley of the ancestral Green River...was cut along the crestline of the Uinta arch prior to 25 m.y. ago.
>
> 3) Deposition of the Browns Park Formation began about 25 m.y. ago and continued until about 9 m.y. ago along the east-trending paleovalley. Miocene sediments deposited away from the paleovalley covered uplands and extended high into mountain flanks.

4) Collapse of the eastern end of the Uinta arch formed a large east-trending graben. This collapse probably began in Oligocene time, but the downdropping took place chiefly after 9 to 10 m.y. ago. According to Hansen (1973, written commun.), the collapse along the crest of the Uinta arch totaled about 1,500 m. Local unconformities in the Miocene sequence suggest movement along faults during Miocene time. Collapse of the graben took place along the Yampa fault (as much as 1,200 m of combined Laramide and late Cenozoic movement) on the south and on a series of faults and flexures parallel to the Uinta fault on the north. Later tilting of certain blocks of the eastern Uinta Mountains took place after the deposition of the Browns Park Formation, and such collapse or relaxation faulting displays as much as 500-m throw parallel to the Laramide Uinta fault on the north flank of the Uinta Mountains.

5) Present courses of major rivers such as the Green and Yampa have been superposed in post-Browns Park Formation time.

The Mountain Home fault (not shown on Plate 1) is a high-angle south-dipping normal fault found a few kilometers west of the Utah-Colorado border (Sears, 1924; Hansen, 1965). Steeply folded and locally overturned Browns Park Formation (dated at about 12 m.y.; Izett, 1975) is in fault contact with the Precambrian Red Creek Quartzite and Uinta Mountain Group, suggesting several hundred meters of throw (W. R. Hansen, 1973, written commun. in Izett, 1975). A 30 m wide gouge and breccia zone in an exposure 5 km west of Jessie Ewing Canyon characterizes the fault in this area. No evidence of recent fault movement on the Mountain Home Fault has yet been documented, however, the Utah Geological and Mineral Survey has described evidence of recent fault activity along the Towanta lineament to the west (Utah Geological and Mineral Survey, 1977).

The Beaver Creek fault (fault number 1) lies east of the Mountain Home fault in Colorado. The Beaver Creek fault offsets the Browns Park Formation and has 458 m of vertical displacement (Hansen, 1965). Considerable fault drag is noted by Hansen (1965) east of Beaver Creek, where the Browns Park Formation is dragged upward to a nearly vertical attitude on the downthrown side of the fault.

McKay (1974) and McKay and Bergin (1974) map a system of faults (fault numbers 3 and 4) that extend eastward on strike with the Beaver Creek fault. These faults partially bound the north flank of the collapsed Uinta block. Most are well expressed topographically as fault-line scarps, but no evidence of Quaternary movement is documented on any of these faults.

A northwest-trending group of high-angle faults (fault group 2) parallels the Sparks Ranch fault, an eastward continuation of the Laramide Uinta fault. H. W. Roehler (1973, written commun. in Izett, 1975) believes there is a few hundred meters of Neogene displacement on these faults, placing the Browns Park Formation against early Tertiary and Cretaceous rocks. Movement is thought to be of Miocene and later age, as is evidenced by several angular unconformities within the the Browns Park Formation. Distinctive linear scarps are associated with many of these faults, but again, none have documented evidence of Quaternary movement.

The Yampa fault (fault number 7), a high-angle, north-dipping, normal fault, bounds the south side of the collapsed Uinta arch. This fault and faults 5 and 6 have well developed fault-line scarps up to 300 m high associated with them, but they also apparently do not disrupt Quaternary deposits.

Fault number 8 is an interesting fault, in view of the well-developed scarp preserved along its trend in the Browns Park Formation. The fresh appearance of the scarp suggests recent fault movement, but the fault does not cross any Quaternary deposits, thus making it difficult to document Quaternary activity. At a few locations along fault number 8, the topography is higher on the downthrown side of the fault, suggesting the fresh-looking scarp is actually a fault-line scarp formed by differential erosion and not recent fault movement.

3.5.2. CROSS MOUNTAIN - CRAIG AREA

Cross Mountain is a north-trending, sharply uplifted horst at the west end of Axial Basin and is composed of Paleozoic rocks. Two generally north-trending faults bound Cross Mountain, the 83° SW-dipping, normal-slip Cross Mountain fault (fault number 10) on the west and the 85°SW-dipping, reverse-slip East fault (fault number 11) on the east (Dyni, 1968). The base of the Browns Park appears to be offset about 150 m on the west side of this block.

A series of northwest-trending faults (fault group 12), just west of Cross Mountain, may be related to uplift of Cross Mountain. Maximum post-Browns Park Formation movement on these faults is probably on the order of 75 m. None of the faults show any definite evidence of Quaternary activity. However, many of the faults are marked by very sharp, steep, linear scarps up to 50 m high in the Browns Park Formation. Freshness of these scarps in the easily eroded Browns Park Formation suggests fault activity possibly as recent as the early Quaternary.

East of Cross Mountain, between Maybell and Craig are two sets of faults (fault groups 15 and 16) that offset the Browns Park Formation. Differentiation of the two groups is primarily based on strike direction, with fault group 15 generally trending N.30°W. to N.20°E., and fault group 16 averaging N.80°W. to N.45°W. Many faults in both trends are well expressed topographically by linear scarps. This is especially true for fault group 16, where individual scarps have as much as 56 m of relief along them.

A prominent lineament is present in Quaternary fan alluvium along the fault 1.5 km south of Lay. The southeastern end of this same fault offsets Cretaceous bedrock along a sharp and distinct 10 to 18 m high scarp. This location has not been field checked, therefore the origin of the feature is not known with certainty. A second fault, about 8 km southwest of Craig also may have been recently active. An extremely fresh looking, 2 to 3 m high scarp marks the fault trace in the Lewis Shale, an easily eroded deposit in which fault scarps would not be expected to remain for many years.

3.5.3. ELKHEAD MOUNTAINS AREA

A series of west-northwest trending, high-angle normal faults extend from near Farwell Mountain in the Park Range, through the Elkhead Mountains, and on into Wyoming (fault numbers 18 through 29). These faults displace the Browns Park Formation and igneous flows and intrusions dated from 7 to 11 m.y. (Buffler, 1967; McDowell, 1966; Segerstrom and Young, 1972).

Neogene tectonism in the Elkhead region is typified by long, linear zones of faulting, monoclinal folding, and localized volcanism. The most prominent zone extends from just west of Shield Mountain 29 km northwestward into Wyoming (fault number 20). This zone, termed the Willow Creek structural zone by Buffler (1972), apparently forms the southern limit of the Browns Park Formation in this area. A sharp monocline extends southeastward from fault 20. The basal part of the Browns Park Formation dips up to 50°NE along this fold. Possible eastward extensions of the Willow Creek structural zone are the King Solomon and Silver City Creek faults (fault numbers 21 and 22).

A second, conspicuous structural zone, the Slater Creek structural zone (Buffler, 1967), runs northwest from Slater Park (T.10N., R.37W.), along Slater Creek, and on into Wyoming, a distance of 54 km. This zone is a broad asymmetrical downwarp marked by faults 18 and 19, folding, igneous activity, and an abrupt 300 m drop in the base of the Browns Park Formation. The origin of this elevation change may be due to faulting, folding, or a combination thereof.

The Hahns Peak area is a prominent, complex, structural high. The area appears to be a large horst block bounded on the north by the King Solomon fault (fault number 21) and Silver City Creek fault (fault number 22) and on the south by the Grouse Mountain fault (fault number 25). Several laccoliths and altered intrusives are found within the horst and may in part be responsible for the upwarp (Buffler, 1967; Segerstrom and Young, 1972). Remnants of the Browns Park Formation overlie parts of the horst. Core drilling on the north side of the King Solomon fault revealed 180 m of post-Browns Park Formation offset (Segerstrom and Young, 1972). Segerstrom and Young infer that a westward deflection of the Dakota Sandstone in the NW1/4 sec. 2, T.10N., R.85W. indicates 180 m of left-lateral displacement. Buffler (1967) proposes about 610 m of Neogene offset, based on elevation differences between outcrops of Browns Park Formation on either side of the fault.

Segerstrom and Young (1972) also believe the King Solomon fault was active during the early Cenozoic. They postulate 610 m of vertical displacement along the west end of the fault during this period, but the direction of movement was down on the south side, opposite that of Neogene movement. Presence of Mesozoic rocks on the east end of the fault is accounted for by scissors faulting (Segerstrom and Young, 1972).

The Silver City Creek fault forms the north side of a narrow graben that is bounded on the south by the King Solomon fault. Displacement on the Silver City Creek fault is unknown. Alignment of the Silver City Creek and King Solomon faults with the Willow Creek structural zone suggest possible interrelationships. If these structures are connected, the Willow Creek structural zone is a major, regional structure over 48 km long.

The Grouse Mountain fault (fault number 25) is similar to the King Solomon fault except it is downthrown about 150 m to the south. (Segerstrom and Young, 1972). Colinear alignment of the Grouse Mountain fault with the Slater Creek structural zone suggest it may be a major regional structure over 96 km long. The Grouse Mountain fault also forms the north side of the shallow graben in which Steamboat Lake lies. This graben is bounded on the south by the Steamboat Lake fault (fault number 26) which has a maximum vertical displacement of 53 m. The Spillway fault (fault number 27) lies within the graben and has displacement similar in magnitude to the Steamboat Lake fault.

Several faults in the Elkhead region are marked by very distinctive, well-defined, topographic escarpments and vegetation changes. Many, however, are not associated with obvious fault controlled topography. None of these faults show unquestionable evidence of Quaternary activity. Anomalous lineaments in Quaternary deposits on the east end of the Grouse Mountain fault south of Farwell Mountain in T.10N., R.84W. and on fault number 29 south of the Middle Fork of the Elk River in T.9N., R.84W. are possibly due to recent fault movement.

3.5.4. NORTH PARK AREA

The Spring Creek fault (fault number 36) trends N.65°W. through the center of North Park, just north of the North Park syncline. This fault and fault number 35 are believed to be of Neogene age, based on their structural relationship with faults that offset the Miocene North Park Formation (found only along the axis of the North Park syncline) and Oligocene, Miocene, or Pliocene volcanic flows in the Medicine Bow Mountains (Tweto, 1976b). Distinct lineaments are present in Quaternary deposits along several parts of the Spring Creek fault zone, but Quaternary activity has not been documented. Geophysical studies by Behrendt and others (1969) reveal about 1,500 m of throw on the Spring Creek fault, of which a significant portion may be of Neogene age. Parallelism between the Elkhead trend, the Spring Creek fault, and a Precambrian fault in the Front Range suggest possible interrelationships.

A N.15°W.-trending fault zone (fault group 35) appears to be structurally related to the Spring Creek fault. Similarities in geomorphic expression between fault number 35 and the Spring Creek fault, and their apparent structural association imply fault number 35 may be of Neogene age. Pre-Bull Lake gravels appear to cover a part of the fault, therefore the most recent movement probably pre-dates deposition of these Quaternary gravels.

Independence Mountain is a Laramide thrust block of Precambrian rocks in the northwest part of North Park (Tweto, 1976b). Since the Laramide orogeny it has been elevated at least 100 m along high-angle faults, as evidenced by elevation differences of the North Park Formation across the faults (de la Montagne, 1957; Hail, 1965). Fault number 33, which is on the west side of Independence Mountain, has a minimum vertical displacement of 122 m and a similar fault to the north has about 250 m of throw (de la Montagne, 1953). Fault number 33 is marked by springs and seeps, travertine deposits, linear topography, and a two meter high scarp, suggestive of recent fault movement.

3.6. COLORADO PLATEAU PROVINCE

Much of western Colorado is within the Colorado Plateau province. Neogene faulting is generally rare in this province except for faults associated with the Uncompahgre Plateau or the collapsed salt anticlines. Historic movement on one fault in this province, fault number 64, was triggered by waterflooding at the Rangely oil field. During an experiment in earthquake control at the Rangely oil field (Raleigh and others, 1976) earthquakes occurring on this fault were turned on and off by controlling injection pressures. A summary description of this experiment is in a following section on man-made earthquakes.

3.6.1. UNCOMPAHGRE REGION

The Uncompahgre uplift is a large, northwest-trending asymmetrical block about 160 km long and 50 km wide composed of Precambrian igneous and metamorphic rocks overlain by Mesozoic sedimentary rocks. This uplift extends from the San Juan Mountains northwestward into Utah and is bounded on the southwest by the Dolores and San Miguel Rivers. The southeastern end of the uplift is lost in the San Juan Mountains, whereas the northwestern end plunges into the Uinta Basin. The Gunnison and Uncompahgre Rivers flow along the northeast side of the uplift.

The Uncompahgre uplift rose during the Neogene from the crest of an older, much larger highland that was a prominent structural feature during the late Paleozoic (Cater, 1966). Distribution and thickness of late Paleozoic sedimentary formations derived from the highland suggest the ancient upwarp was bounded by large faults on the southwest, while the northeast limb, which extended further east than the present uplift, gently dipped to the northeast (Cater,1970). Structural relief along the southwestern flank during the Paleozoic may have been as great as 2,440 m (Cater, 1970), as inferred from the abrupt wedge of Cutler Formation near Gateway. Cater (1970) describes about 1,220 m of structural uplift since deposition of the Upper Jurassic Entrada Sandstone in this same area.

The modern Uncompahgre uplift is a northeast-tilted block, structurally similar to its predecessor but much smaller. The southwestern flank and part of the northeastern flank near Grand Junction are bounded by abrupt, locally faulted monoclines (Lohman, 1965; Cater, 1970). Cater (1966, 1970) presents evidence suggesting the modern Uncompahgre uplift has experienced considerable movement during the Pliocene and Quaternary, and that many of the faults and monoclines which bound the uplift were activated during this period.

The Uncompahgre highland has experienced uplift and subsequent erosion repeatedly during the past. Following the Laramide orogeny extensive erosion reduced this general area to a widespread erosion surface of low relief. Development of this surface preceded broad epiorogenic uplift that initiated in the Miocene (Hunt, 1956). As the region slowly moved upward, streams began downcutting rapidly. Many ancestral rivers established their courses during this period, including the Gunnison River which flowed across the uplift through Unaweep Canyon.

Cater (1966) describes the uplift of the Uncompahgre region and the abandonment of the Unaweep Canyon as follows:

> The Uncompahgre uplift probably started forming not long before the Gunnison River deserted Unaweep Canyon. Only about 600 to 700 feet (183 to 214 m) of differential uplift had occurred along the faulted monocline forming the southwest flank of the uplift by the time the river had left the canyon. This is indicated by the greater depth beneath the Triassic Wingate Sandstone to which Unaweep Canyon was carved on the uplifted side of the monocline. An additional 1,300 to 1,400 feet (397 - 427 m) of differential uplift occurred along this monocline after the canyon was abandoned. The amount of this uplift is measurable between the ancient stream gravels immediately below the mouth of Unaweep Canyon and the canyon floor on the uplifted side of the monocline. Unless the rate of prediversion uplift was considerably slower than the rate of postdiversion uplift, it seems unlikely that uplift started before mid-Pliocene time. Uplift, as a matter of fact, could not greatly predate abandonment of the canyon because structural and topographic displacement of the Uncompahgre Plateau coincide; that is, the plateau surface is eroded to only about the same

stratigraphic level as the mesa lands to the southwest, which are more than than 2,000 feet (610 m) lower. This condition would not be likely to exist had uplift occurred in the distant past, particularly so because the sedimentary rocks capping the plateau in the vicinity of Unaweep Canyon are relatively soft. It is concluded that uplift began no earlier than the mid-Pliocene and probably continued into the Pleistocene.

River gravels were deposited by the ancestral Gunnison River northeast of Gateway at the lower end of Unaweep Canyon along West Creek. These river gravels are overlain by two fanglomerate sequences. Dating of the fanglomerates establishes a minimum age for the abandonment of Unaweep Canyon. Cater (1966) correlates these two deposits with the Harpole Mesa Formation of Richmond (1962).

The Harpole Mesa Formation consists of three members that Richmond (1962) correlates with the Nebraskan, Kansan, and Illinoian glaciations. Two volcanic ashes are found within the Harpole Mesa Formation. The middle member contains a volcanic ash, the Pearlette Type O ash, named for its exposure along Onion Creek (Izett and others, 1970). The Pearlette Type O ash is derived from Yellowstone and is believed to correlate with the Lava Creek Tuff, dated at 0.6 m.y (Izett and others, 1971; Izett and others, 1972; Naeser and others, 1973). The lower member of the Harpole Mesa Formation contains a volcanic ash correlated with the Bishop Ash, dated at 0.7 m.y. (Richmond, 1962; Izett and other, 1970). In view of these ages the middle and lower members of the Harpole Mesa Formation are now believed to correlate with, respectively, the Yarmouth interglacial period and the Kansan glaciation (G. M. Richmond, 1977, oral commun.).

Cater (1966) correlates the older fanglomerate exposed near Gateway with the Lower Member of the Harpole Mesa Formation and the younger fanglomerate with either or both the Middle and Upper Members of the Harpole Mesa Formation. Abandonment of Unaweep Canyon by the Gunnison River is therefore believed to have happened prior to the Kansan glaciation. Since up to 427 m of uplift occurred after canyon abandonment, it is likely that uplift persisted well into the Pleistocene and may be continuing at the present.

Faults of late Cenozoic age that flank the Uncompahgre uplift are shown on Plate 1 (fault numbers 65 through 89). All of these faults should be considered when evaluating earthquake potential for a specific site. However, only the better known faults are discussed in this report.

3.6.1.1. NORTHEASTERN FLANK

Fault number 74 is a N.81°W.-trending normal that which dips 49°SW. It is of special interest because it is the only fault associated with the northeast flank of the Uncompahgre uplift that can be physically shown to have moved during the Quaternary. The fault is exposed in a roadcut along

U. S. Highway 50 in the center of the N1/2 of sec. 35, T.4S., R.3E., about 14 km west of Delta. Klein and Osterwald (1974) describe the feature as a Quaternary fault that displaces Mancos Shale and overlying pediment gravels.

Pediment gravels that cap this exposed section consists largely of well rounded, basaltic cobbles derived from Grand Mesa and are believed to correlate with the pre-Bull Lake Quaternary deposits of Yeend (1969). The base of the gravel is offset about 1.2 m, whereas the underlying Mancos Shale is offset a minimum of 3.1 m. Fault drag in the Mancos is well developed on the downthrown side of the fault, but is subdued on the upthrown side. The fault plane is a very sharply defined, nearly planar surface marked by clay gouge up to 1 cm thick. Slickensides in the gouge indicate a nearly vertical, dip-slip movement. A 1.5 cm thick brecciated zoned with gypsum-filled fractures is found in the hanging wall at the gouge-bedrock contact. Gravel clasts within the pediment deposit have been rotated by fault movement.

There is no obvious surface expression of fault number 74. It cannot be traced from the roadcut with any certainty. A deeply incised canyon west of the roadcut is on strike with the fault and may coincide with it. A reconnaissance field check did not uncover any stratigraphic offset across the canyon. R. G. Young (1977, oral commun.) has noted a west-trending fault defined by geophysical studies that lies north of Delta. It is possible that this fault and fault number 74 are related.

The northeast flank of the Uncompahgre uplift near Grand Junction is upwarped along a complex zone of high-angle faults and monoclines. Plate 1 shows the generalized distribution of structures in this complex zone. Figure 39 shows additional details and interrelationships of the various structures. Fault number 65 represents three faults and two monoclines southwest of Grand Junction. This 15 km long zone is one of two major structural systems found in this area. The second structural system (fault group 68) includes two monoclines and one fault.

Structural features associated with fault group 65, from northwest to southwest, include the Flume Canyon fault, a short unnamed monocline, the Kodels Canyon fault, Lizard Canyon monocline, and Redlands fault. The second system, fault group 68, consists of the Ladder Creek monocline, Bangs Canyon fault, and East Creek monocline. The following descriptions of these features are largely summarized from Lohman (1965).

The Flume Canyon fault has a maximum displacement of about 92 m in Flume Canyon and dies out both northeastward and southwestward. It merges with a short, unnamed symmetrical monocline at Devils Canyon in the SW1/4 of sec. 25 T.1N., R.3W. The monocline merges with the Kodels Canyon fault about 0.8 km east. The Kodels Canyon fault extends eastward about 1.6 km into Fruita Canyon where it gradually becomes a faulted monocline, the Lizard Canyon monocline. A maximum displacement of 107 m on the Kodel Canyon fault is found in Kodel Canyon. The asymmetrical Lizard Canyon monocline has two folds in its upper limb. The higher limb is mapped by Lohman (1965) as the Fruita Canyon monocline, while actually it is only a part of the Lizard Canyon monocline. The Lizard Canyon monocline merges with the Redlands fault near the mouth of Monument Canyon.

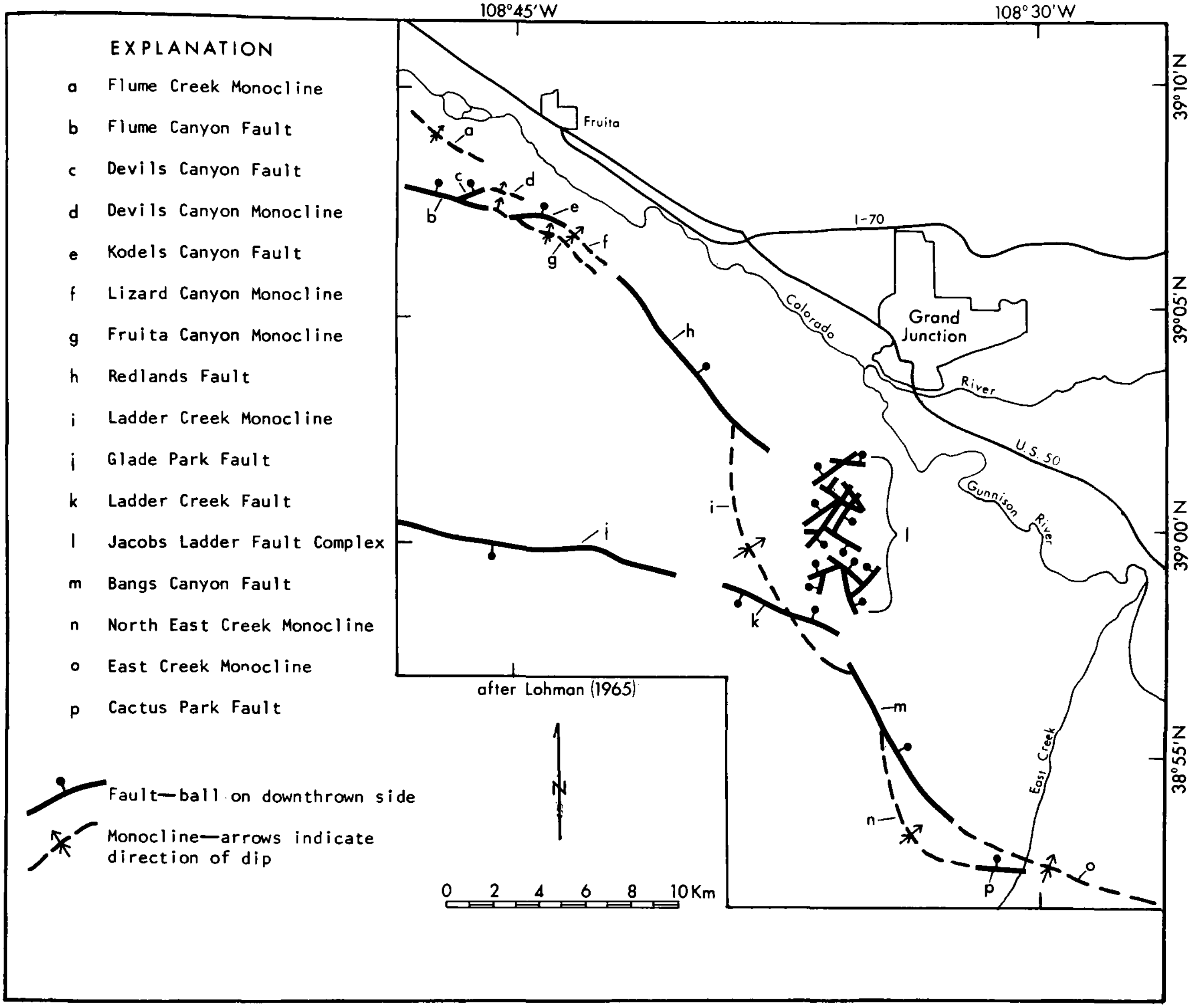


Figure 39. Major structural features on the northeast flank of the Uncompahgre uplift near Grand Junction.

Directly north of the Flume Canyon fault are the Devils Canyon and Flume Creek monoclines. The symmetrical Devils Canyon monocline parallels the Flume Canyon and Kodel Canyon faults. Its western end joins the Flume Canyon fault along a short northeast-trending fault. Its eastern end bends toward the Lizard Canyon monocline, but they do not appear to join at the surface. Lohman (1965) believes the Devils Canyon monocline was formed later than the larger structures and that its formation may have been accompanied by renewed deformation on the major structures.

A major fault, the Redlands fault, bounds the uplift at the Colorado National Monument. A maximum throw of 244 m (Lohman, 1965) is developed in the SE1/4 of sec. 21, T.11S., R.101W. Unlike most other faults in the area, the 10 km long Redlands fault is both a normal and reverse fault at different locations along its strike. In most places it is vertical or near vertical. However, at two locations it is a reverse fault that dips 45°SW. These locations are at the mouths of Gold Star Canyon and a smaller canyon in the SE1/4 SW1/4 of sec. 30, T.1S., R.1W. Lohman (1965) believes the Redlands fault may have originally been a normal fault that has since been rotated due to renewed deformation of the uplift in the manner suggested by Kelly (1955).

A second major structural zone splits off from the Redlands fault near its southeastern end and extends southward as the Ladder Creek monocline. This monocline continues southward and gradually bends southeastward in a concave-to-the-east manner. The Ladder Creek monocline crosses the east-trending Ladder Creek fault and merges with a normal fault that abuts against the southeast-trending Bangs Canyon fault of fault group 68. The Bangs Canyon fault has a throw of approximately 305 m (Lohman, 1965) and is thought to be a near vertical normal fault, but nowhere is the fault plane observed or measurable. To the south the Bangs Canyon fault merges with the East Creek monocline, the longest, uninterrupted monocline in this area.

The Glade Park fault (fault number 66) and Ladder Creek fault (fault number 67) are anomalous, small-displacement, east-trending faults that generally are downthrown on the south side. Both faults are aligned, which suggests they may be continuous, but field investigation and aerial photograph interpretation indicate they are not continuous at the surface and are separated by about 2.4 km of undisturbed terrain. Maximum throw on either fault is less than 7.6 m (Lohman, 1965). The Ladder Creek fault is of interest because it apparently is a scissors fault, with the sense of displacement changing from down-to-the-south on the west to down-to-the-north on the east end. The flank of the Uncompahgre uplift is apparently offset by the Ladder Creek fault, suggesting this fault may be younger, at least in part, than structures along the northeast flank of the uplift.

The Jacobs Ladder fault complex is shown in part on Figure 39, but not Plate 1 because of its intricate fault pattern and short length. The area is capped by the indurated, erosion-resistant Burro Canyon Formation and Dakota Sandstone, and is underlain by the weak, easily eroded Morrison Formation. This complex of minor faults and folds is situated near the offset of the flank of the uplift, east of the Ladder Creek fault and at the focus of the Ladder Creek monocline. The Jacobs Ladder fault complex may be structurally related to either or all of these features. Lohman (1965) believes the deformation may have resulted from brittle fracturing of the indurated caprock that accompanied plastic deformation of the underlying incompetent rocks.

The Cactus Park fault (fault number 70) is an east-trending, nearly vertical normal fault that merges westward with the North East Creek monocline. An excellent exposure of this fault in a roadcut in the SE1/4 of sec. 36, T.13S., R.100E. indicates the fault zone consists of a wide, vertical breccia and gouge zone. It does not displace the Holocene deposits north of the roadcut.

3.6.1.2. SOUTHWESTERN FLANK

One of the more prominent features of the southwestern flank is the Ute Creek graben, bounded by two roughly parallel, northwest-trending faults. The southwest-bounding fault (fault number 80) has a maximum post-Triassic displacement about 260 m near Pine Mountain in sec. 11, T.51N., R.18W. (Cater, 1970). Maximum post-Triassic displacement on the northeast-bounding fault (fault number 79) is about 400 m, developed sec. 33, T.15S., R.10W. (Cater, 1970).

Cater (1970) believes the Ute Creek graben may still be active today. Stratigraphic displacement of the Triassic Chinle Formation nearly equals the topographic displacement, indicating there has been only minor erosion since development of the graben. If the graben has been inactive for several million years, erosion should have lowered the uplifted block considerably. Cater (1970) interprets this to indicate the graben was active during the late Pliocene and Pleistocene.

Fault number 82 lies in T.48N., R.13W. and T.48N., R.12W. and trends N.70°W. Bedrock in the area consists of gently northeast-dipping Dakota Sandstone and Burro Canyon Formation, underlain by the Brushy Basin Member of the Morrison Formation. In places where the Brushy Basin Member lies at the surface, it is covered by abundant landslides, earthflows, and other types of slope failures largely of Quaternary age. Fault number 82 passes through the Brushy Basin Member and overlying Quaternary deposits at Roubideau Creek. Near the creek there is a scarp in the surficial landslide deposits that suggests fault movement since development of the Quaternary landslide complex (Figure 40).

Recent movement on this fault appears to be downward on the southwest side. However, apparent drag in the bedrock suggests down-to-the-north displacement. This anomaly may be the result of a change in direction of movement or possibly due to scissors-type movement.

The Ridgway fault (fault number 179) bounds the southern end of the Uncompahgre uplift. Recent investigations of the Ridgeway fault and associated faults by the U.S. Water and Power Resources Service indicate Quaternary activity (Sullivan and others, 1980). A pre-Wisconsin Quaternary gravel exposed in a gravel pit in the NW1/4 sec. 3, T.4S., R.8W. is offset 0.3 to 3 m by several small branch faults. A microearthquake survey conducted in the area during late 1978 and early 1979 located a number of events that centered on the Ridgway fault. A total of 66 events were recorded in the vicinity of the Ridgway fault, and the majority of these events occurred in two distinct swarms. The geologic evidence of Quaternary activity, combined with the microseismic

Figure 40. Vertical aerial photograph of fault 82 (solid arrows) where it crosses Roubideau Creek. Note hummocky landslide-covered terrain (Qls) on the Brushy Basin Member of the Morrison Formation. An apparent scarp (open arrows) is developed in these Quaternary landslide deposits along fault 82. (photograph by Army Map Service; held by U.S. Geol. Survey)

data, indicate the Ridgway fault should be considered an active fault (Sullivan and others, 1980).

3.6.2. SALT ANTICLINE REGION

The collapsed salt anticlines of the Colorado Plateau are very unusual structural features. The structures consist of northwest-trending, salt-cored anticlines that have collapsed along their crests in a graben-like manner during the Neogene. They are found in the deepest part of the Pennsylvanian Paradox basin, southwest of the Uncompahgre uplift. Position and orientation of the anticlines are believed to be controlled by large subsurface faults that displace the pre-Paradox Formation rocks as much as 1,525 m (Cater, 1970). Considerable evidence suggests the collapsing salt anticlines have been active in the Quaternary and may well be active today (Hunt, 1956; Cater, 1970).

There are many salt structures in the world and they have been studied with considerable interest for many years. Two properties of salt are responsible for the development of salt structures; its ability to flow and its low density. Earlier workers thought it necessary for the salt to be buried at least 2,000 m before it could be mobilized (Stille, 1925, Nettleton, 1943). Detailed geological mapping in east Paradox Valley by Elston and Landis (1960) revealed numerous unconformities both within and above the Hermosa Formation, suggesting salt mobilization prior to deep burial.

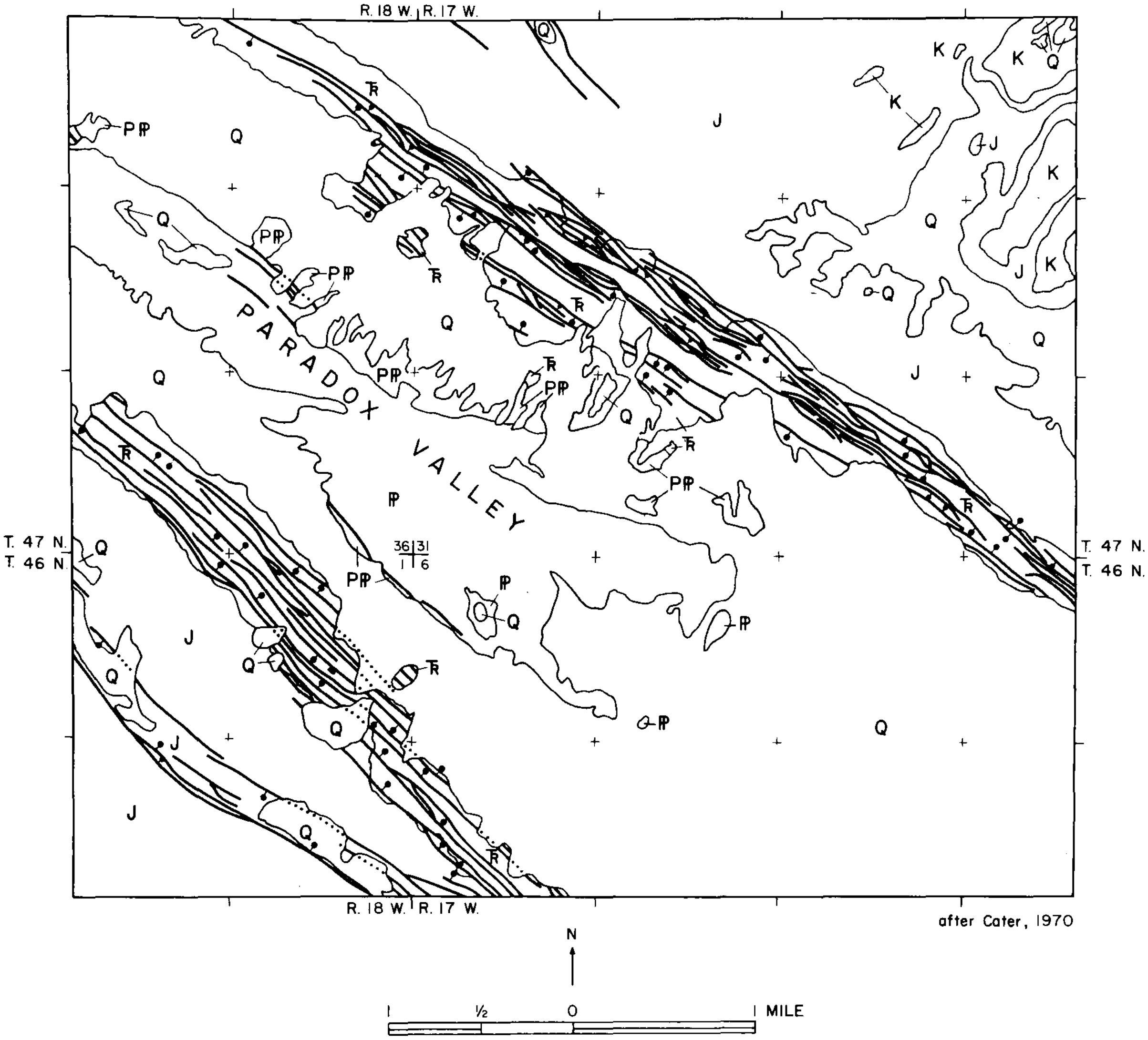
Cater (1970) explains this seemingly anomalous beginning as being initiated by tectonic movements. He believes the controlling subsurface faults were active during post-Paradox time, and the accompanying displacements exposed the salt core to the surface. This theory is supported by the parallelism of the anticlines with other prominent structures features of the Colorado Plateau (Kelley, 1955b). Hence, the anticlines developed more or less contemporaneously with deposition of the overlying sediments. The salt upwarps probably persisted until late in the Jurassic, after which they were covered by younger sediments.

Further folding occurred following deposition of the Mesa Verde Formation. This disruption was probably not a result of salt tectonism, but rather renewed movement on the deep-seated subsurface faults. Original collapse of the salt-cored anticlines occurred during or immediately after this period of deformation. The downdropping may have resulted from relaxation of the stresses that caused folding.

A second and more significant period of collapse initiated in the Miocene during epiorogenic uplift of the Colorado Plateau. Anticlines were breached and the cores exposed to the surface by deep erosion accompanying the regional uplift. Upon exposure, the cores experienced rapid solution and flowage, and renewed collapse began. Collapse continued into the Quaternary, as is indicated by fault scarps that bound the valleys and by faulted and folded late Pleistocene and Holocene alluvial deposits in Paradox, Big Gypsum, and Sinbad Valleys in Colorado and in Salt, Castle, and Fisher Valleys in Utah (Baker, 1935; Hunt, 1956).

Collapse was and is not a simple graben-like downdropping of the crestal portion of the anticline. Plate 1 shows the complexity of faulting in a very generalized way (fault groups 90, 91, 92, and 93). Similar faults in Sinbad Valley are not shown on Plate 1. Collapse occurred along many faults, most of which, but not all, parallel the strike of the crest of the collapsed anticlines. Most faults are downthrown on the valley side, but several are antithetic. Figure 41 shows the geology of a part of the Paradox Valley in considerably more detail. Note the profusion of faults that shatter the valley walls.

Some of the faults associated with collapse of the salt anticlines are probably active today. In that they result from salt flowage and solution, it is likely that none are capable of generating earthquakes larger than magnitude 4 or 5. Movement on many of the faults may occur as creep. This should be considered in the engineering design and siting of critical facilities in the area. It is not known if the large subsurface faults that control the location of the anticlines are still active. Any recent movement on these faults could easily be masked by deformation on the multitude of faults along which continued collapse is occurring. These deep, subsurface faults should be carefully investigated before any critical or sensitive man-made structures are sited in the region.



Q Quaternary alluvial, eolian, and landslide deposits

K Cretaceous Burro Canyon Formation

J Jurassic Brushy Basin and Salt Wash Members of the Morrison Formation, Summerville Formation, and Entrada Sandstone, and the Jurassic/Triassic Navajo Sandstone

T Triassic Kayenta, Wingate, Chinle, and Moenkopi Formations

pIP Permian and Pennsylvanian Cutler and Rico Formations

IP Pennsylvanian Paradox and limestone members of the Hermosa Formation

fault; dotted where concealed, ball on downthrown side

Figure 41. Geologic map of part of Paradox Valley.

4. COLORADO SEISMICITY

4.1. EARTHQUAKE HISTORY

The earthquake history of an area is very important in the evaluation of future seismicity because past earthquakes suggest both the location and size of future earthquakes. There are, however, serious limitations in using the historic earthquake record by itself to predict future seismicity. Allen (1975) discusses such limitations and suggests the coordinated use of recent geologic history and earthquake history. The following sections discuss the seismic history of Colorado. A later section attempts to relate this data to young geologic features in the state. Information on Colorado's historic earthquakes is listed in Appendix 3 and epicentral locations are plotted on Plate 3.

Colorado has a relatively short earthquake history dating back only some 110 years. The first reported earthquake occurred on December 7, 1870, when an observer at Fort Reynolds, 32 km east of Pueblo, noted moderate shaking of the structure he was in. Father Armand W. Forstall installed the first Colorado seismometer at Regis College in 1909. This instrument has provided valuable data, but the system has generally operated at low gain and is capable of detecting only large events. A seismograph was in operation at the University of Colorado at Boulder from 1954 to 1959. Events were recorded on 35 mm film from one vertical and two horizontal seismometers. These records, along with those from Regis College, are the main sources of pre-1961 instrumental data in Colorado.

In December of 1961 the Colorado School of Mines installed a three-component seismograph in the Cecil H. Green Observatory at Bergen Park, about 14 km southwest of Golden. This system has been in continuous high-gain operation since installation and is now the primary source of instrumental data on Colorado earthquakes. The Bergen Park station, designated GOL by the worldwide standardized seimograph network (WWSSN), is thought to be capable of locating Colorado earthquakes to within 15 km of their epicenter (Simon, 1972a). During part of 1971 and 1972 the Colorado School of Mines and NOAA jointly operated a seven-station, state-wide monitoring network. Colorado earthquakes were located with much greater accuracy (1 to 5 km) during this period (Simon, 1972a).

Appendix 3 lists earthquakes felt in Colorado from 1870 to 1961 and the larger, instrumentally recorded earthquakes from 1962 through 1979. Plate 3 shows the geographic distribution of the more significant events and their relationship to Neogene or potentially active faults. As seen in Appendix 3 and on Plate 3, several moderate-sized earthquakes and numerous small earthquakes have been felt and/or recorded during the 110 year period.

The November 7, 1882 earthquake is of special interest because of its apparent proximity to Denver. Felt reports indicate the earthquake shook much of Colorado, southern Wyoming, and adjacent states, but reported intensities do not consistently define an epicentral region. Most reports suggest the earthquake centered in the north Denver Metro area, where

Modified Mercalli (M. M.) intensities of VII were felt (see Appendix 1 for description of this scale). High M.M. intensities were also reported along the Union Pacific Railroad in southern Wyoming, but these are thought to be exaggerated accounts (Hadsell, 1968). Strong ground shaking was also reported in the Roan Cliffs area. It is also interesting to note that several newspaper accounts of this earthquake refer to a previously felt earthquake in the Denver area that occurred a few years earlier.

A Richter magnitude can be estimated for this 1882 event using maximum observed intensity (VII) or size of the felt area (1,200,000 km^2). A magnitude of 5.0 $\pm$ 0.6 is indicated by the intensity, whereas the size of the felt area suggests 6.7 $\pm$ 0.6 (Hadsell, 1968).

In 1961 a small event occurred in this same general north Denver area. Felt reports for this earthquake indicate a M.M. intensity of III. The epicenter is thought to be near that of the 1882 event (Hadsell, 1968; National Oceanic and Atmospheric Administration, 1980).

On November 15, 1901 a M.M. intensity VII event shook Buena Vista. Slight damage occurred in Buena Vista and the water in Cottonwood Lake was reportedly agitated. Somewhat smaller, intensity VI earthquakes shook Mount Gunnison on September 9, 1944 and Lake City on August 3, 1955. On October 11, 1960 a magnitude 5.5 earthquake shook the Ridgway-Montrose area. This event is one of the larger earthquakes that has occurred in Colorado during the historical period.

In 1961 a deep injection well was drilled at the Rocky Mountain Arsenal, northeast of Denver. Fluid injection began in 1962 and a series of earthquakes initiated shortly thereafter. Evans (1966a) was the first to publicly suggest a correlation between injection rates at the well and the earthquakes. Follow-up investigations supported his conclusion (Healy and others, 1966b; Hollister and Weimer, 1968). This sequence of earthquakes is fully discussed in a following section on man-made earthquakes.

In 1966 an impressive swarm of earthquakes shook the Dulce, New Mexico area, just south of Pagosa Springs. A magnitude 5.5 event with M. M. intensities up to VII initiated the sequence on January 23. Numerous aftershocks, several of which were larger than magnitude 4, followed during ensuing years. Seismic activity continues in this area today (Sanford and others, 1979).

Minor damage was reported in Trinidad, Aguilar, Segundo, and Trinchera when a magnitude 4.5 earthquake rumbled over a 48,000 km2 area in southeastern Colorado on October 3, 1966.

An interesting earthquake that generated considerable newspaper coverage occurred near Divide on January 6, 1979. A variety of felt reports including an unusual audible acoustic response accompanied the earthquake. The earthquake apparently centered on or near the Oil Creek fault.

From January, 1966 through August, 1973 over 4,900 events were recorded at GOL. These events were located by Simon (1969, 1972a) using the records from GOL and UBO, a seismograph at the Uinta Basin Observatory in Vernal, Utah, that is operated by Geotech Corporation for the Advanced Research Projects Agency. This earthquake information has been summarized by Presgrave (1977). The location and number of total events (natural and man-made) recorded at GOL during the 7 and 2/3 year period is presented in Figure 42. The size of the circles roughly defines the estimated error involved in locating each event.

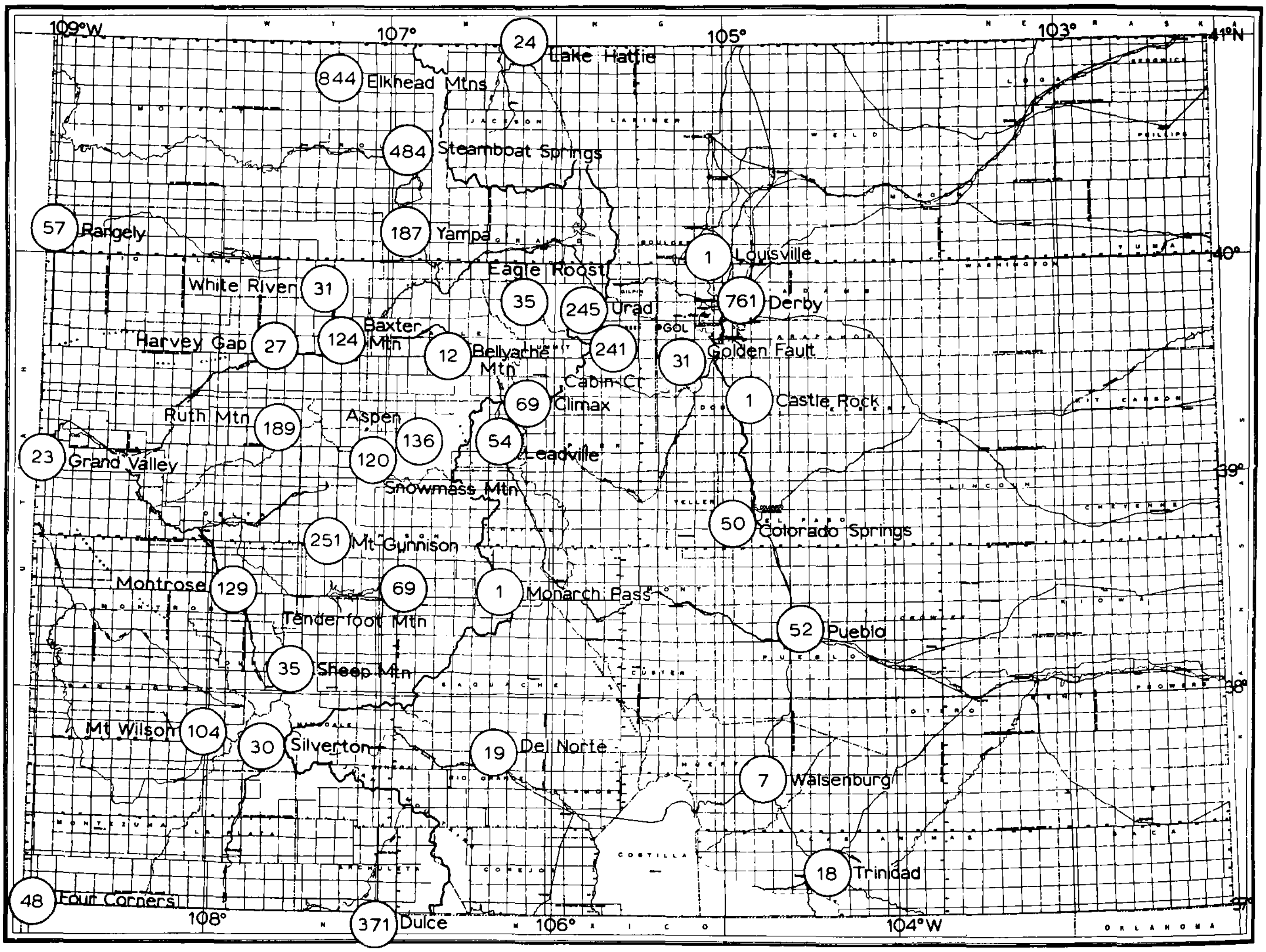


Figure 42. Location and number of total events recorded at GOL from January, 1966, through August, 1973. (from Presgrave, 1977)

The majority of events lie west of the Continental Divide. Several areas, including much of eastern Colorado and parts of northwestern and southwestern Colorado, appear to be relatively aseismic. An area encompassed by 105°W to 106°W longitude and 37°N to 39°N latitude, which includes the Sangre de Cristo fault, is anomalously aseismic. Areas with apparent high seismic rates include Derby, Dulce, Elkhead Mountains, Steamboat Springs, Mount Gunnison, Urad, and Cabin Creek.

A part of these events is almost certainly man-made (Simon, 1969, 1972a, 1972b). Presgrave (1977) attempted to eliminate the man-made events from the total events by subtracting those events recorded during common blasting times from the total number of events shown on Figure 42. This modified version is shown in Figure 43. A marked decrease in the number of events thought to be earthquakes is apparent at Cabin Creek, Urad, Elkhead Mountains, Steamboat Springs, and Mount Gunnison.

This technique improves the GOL data, but does not eliminate all man-made events. For instance, Hadley (1975) demonstrated that virtually all events in the Cabin Creek area were man-made. A microseismic investigation conducted during this C.G.S. study indicates that many of the events located in Elkhead Mountains and Steamboat Springs are actually blasts at large coal mines south and southwest of Steamboat Springs. Of areas having seemingly high seismic rates, only at Derby and Dulce are the majority of recorded events definitely tectonic earthquakes.

There is also an inherent bias in the apparent seismic rates due to detection thresholds. At locations near GOL, such as Derby, events as small as magnitude 1.0 can be detected, whereas at greater distances earthquakes of magnitude 2.5 may not be seen in the records (R. B. Simon, 1977, oral commun.). Presgrave (1977) attempted to remove this bias from the data in Figure 43 by normalizing the number of events to a threshold magnitude of 2.5 (Figure 44). Significant changes in seismic rates result from applying such a normalizing technique. In Figure 43 the greatest number of events occur at Derby. The number of Derby events are greatly reduced on Figure 44 and Dulce becomes the most active area in the state. The Four Corners area also has a striking increase in seismic activity after normalization of the data.

The distribution of earthquakes recorded by the joint NOAA/CSM network is shown on Figure 45. A total of 48 events of magnitude 2.0 to 4.5 were located with a 1 to 5 km accuracy during the second half of 1971 (Simon, 1972a). Several features about the earthquake distribution shown on this map are of interest. Six magnitude 3.5 to 4.5 events were located at Derby, and this is consistent with other GOL records. Four events in the same magnitude range also occurred just south of Antonito. These events were unique in that at no other time were earthquakes known to have occurred here (Simon, 1969, 1972a; Hadsell, 1968). Because of this, Colorado School of Mines personnel field checked the area and found the events were probably due to road construction blasting (R. B. Simon, 1977, oral commun.).

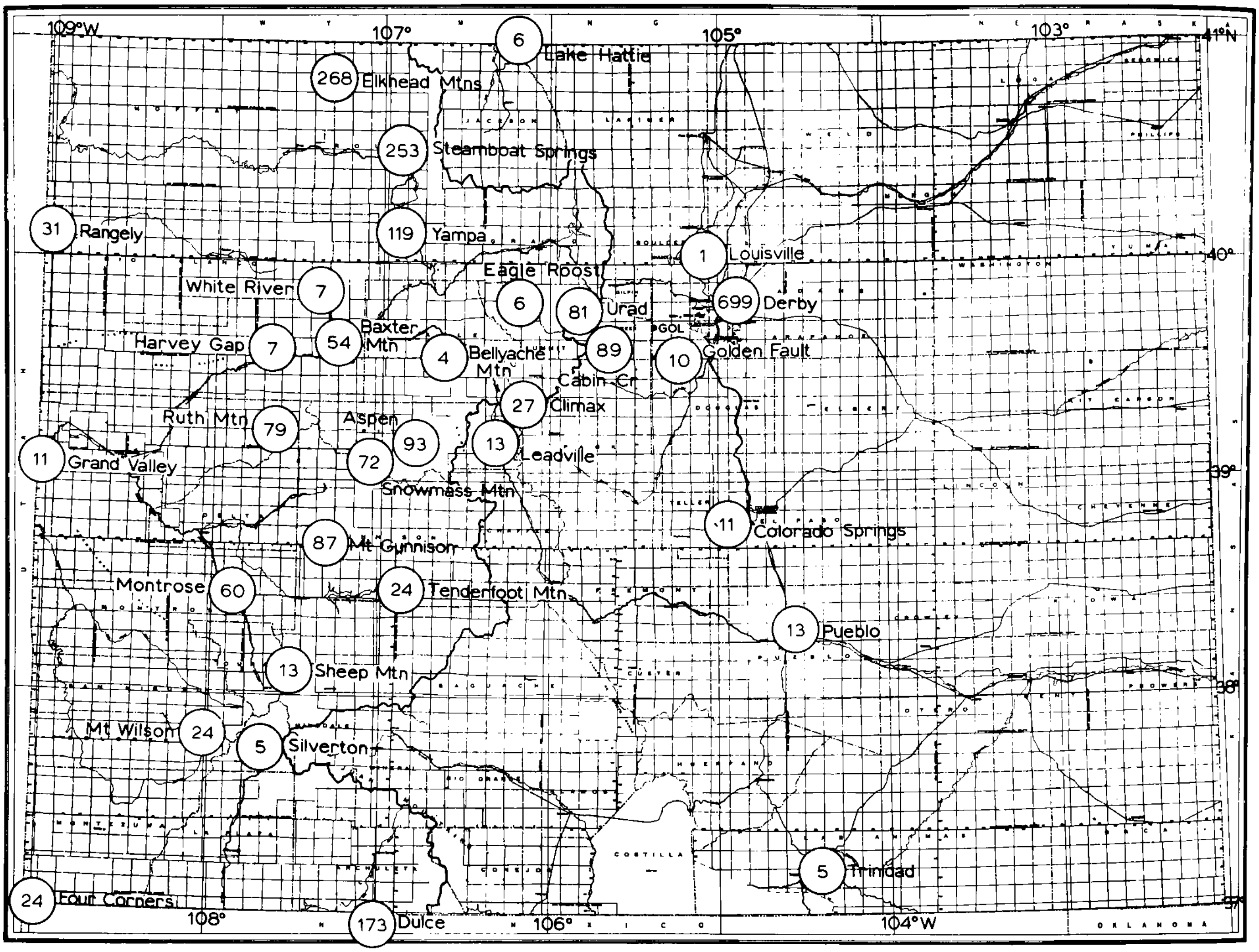


Figure 43. Location and number of events thought to be earthquakes recorded at GOL from January, 1966, through August, 1973. (from Presgrave, 1977)

Two smaller events were located in the upper Arkansas River Valley near the Sawatch fault by the joint network. No earthquakes were located here during years when GOL and UBO records were used. A magnitude 3.5 to 4.5 event was centered along the northeast flank of the Uncompahgre uplift. A smaller earthquake occurred near Gateway on the southwest flank of the uplift. Several small events were located near the northeast flank of the Uncompahgre uplift between Montrose and Ridgway. A large number of events centered in the region southwest of Steamboat Springs near the large coal strip mines. This agrees with the findings of the C.G.S. microearthquake survey and supports our conclusion that many of the events

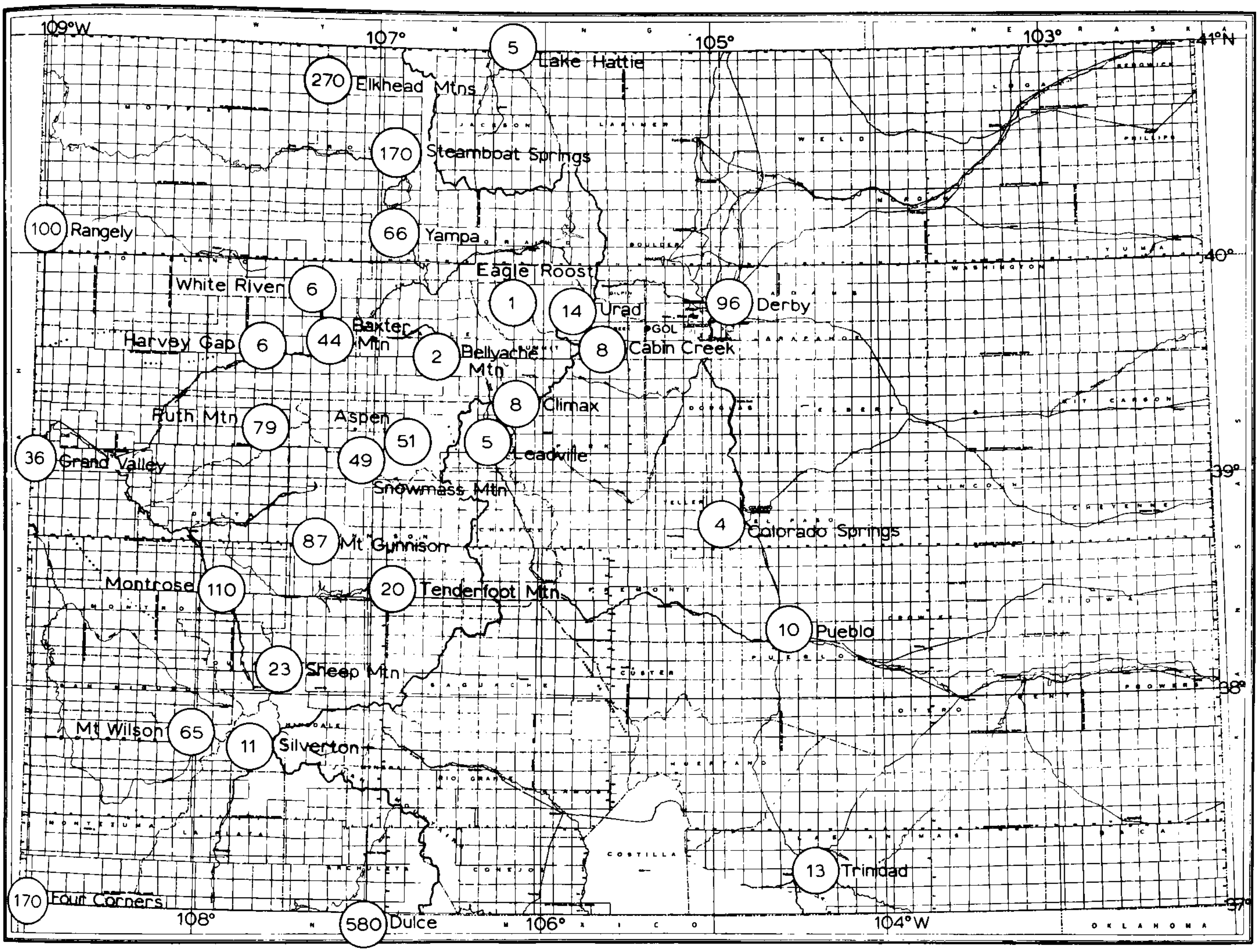


Figure 44. Location and number of events normalized to a threshold of magnitude 2.5 recorded at GOL from January, 1966, through August, 1973. (from Presgrave, 1977)

assigned to the Elkhead Mountains and Steamboat Springs areas by GOL are probably mine blasts originating southwest of Steamboat Springs.

4.2. MAN-MADE EARTHQUAKES

Colorado is one of the few states in our country where earthquakes have been generated or triggered by man. The most obvious cases of

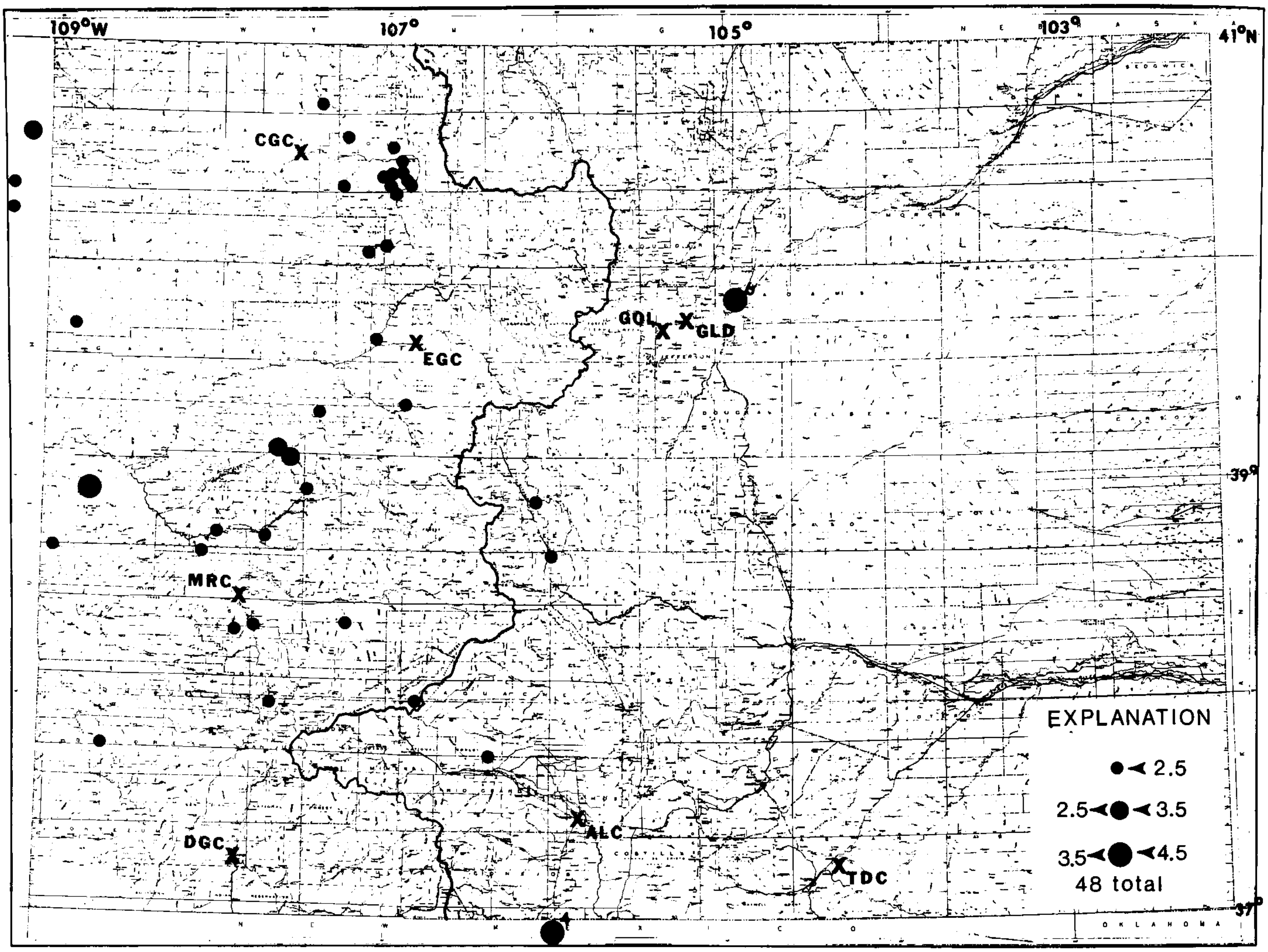


Figure 45. Location and size of events recorded by the joint NOAA/CSM network during the second half of 1971. (from Simon, 1972a)

man-generated earthquakes involve experimental nuclear explosions to stimulate natural gas recovery from low permeability sandstone reservoirs. Three such explosions have been detonated in or very near Colorado: Projects Gasbuggy, Rulison, and Rio Blanco. More subtle, but yet widely accepted cases of man-induced seismicity involve fluid injection deep into the subsurface. At the Rangely oil field scientists were actually able to turn on and off earthquakes by controlled fluid injection. Damaging earthquakes were inadvertently triggered by liquid waste injection into a deep disposal well at the Rocky Mountain Arsenal during the 1960s. A few water reservoirs in Colorado are suspected of inducing earthquakes, but this relationship has not yet been satisfactorily proven. One questionable case of reservoir-induced seismicity was studied, but the supposedly-induced earthquakes were found to be related to construction.

4.2.1. ROCKY MOUNTAIN ARSENAL EARTHQUAKES

In 1962 a series of earthquakes initiated in the northeast Denver area that created considerable scientific interest and concern for the safety of Denver's citizens. The sequence of earthquakes began on April 24, 1962, with a magnitude 1.5 event. Fortunately, the Colorado School of Mines had recently established a seismograph station (GOL) near Bergen Park that was capable of detecting such a small earthquake. During the following years over 1,500 earthquakes, some of which caused damage, were located in the northeast Denver area. Minor activity continues in this area today.

Initially, the earthquakes were very small and only a few were felt. Through October 1965, over 1,000 earthquakes occurred, but only 16 events were greater than magnitude 3.0 (Major and Simon, 1965). Two graduate students from the Colorado School of Mines studied the earthquakes during this period (Pan, 1963; Wang, 1965). Wang (1965) discovered that many of the earthquakes centered in a region about 75 km long and 40 km wide. It was later pointed out that most events located by Wang were within 8 km of a liquid waste disposal well at the Rocky Mountain Arsenal.

The director of the Regis College Seismological Observatory, Father Joseph Downey, was one of the first to suggest there was a possible relationship between the earthquakes and the Rocky Mountain Arsenal disposal well (Healy and others, 1968). The disposal well was located near the center of the the Denver Basin, completed on September 11, 1961, and drilled to a depth of 3,670 m (Scopel, 1964). Pressure injection of liquid waste into fractured Precambrian rock near the bottom of the well began during March of 1962, just prior to initiation of the earthquake series.

In November of 1965, D. M. Evans, a consulting geologist from Denver, publicly announced there was a direct relationship between the disposal well and the Denver earthquakes. His conclusions were principally based on the earthquake distribution reported by Wang (1965) and the striking correlation between the number of earthquakes per month recorded at GOL and the volume of waste injected into the well (Figure 46). Because of the increased awareness of the potential for damaging earthquakes and the possible relationships between the earthquakes and the Rocky Mountain Arsenal disposal well, the U.S. Geological Survey, in cooperation with the Colorado School of Mines, was directed to evaluate the earthquake series (Healy and others, 1966b).

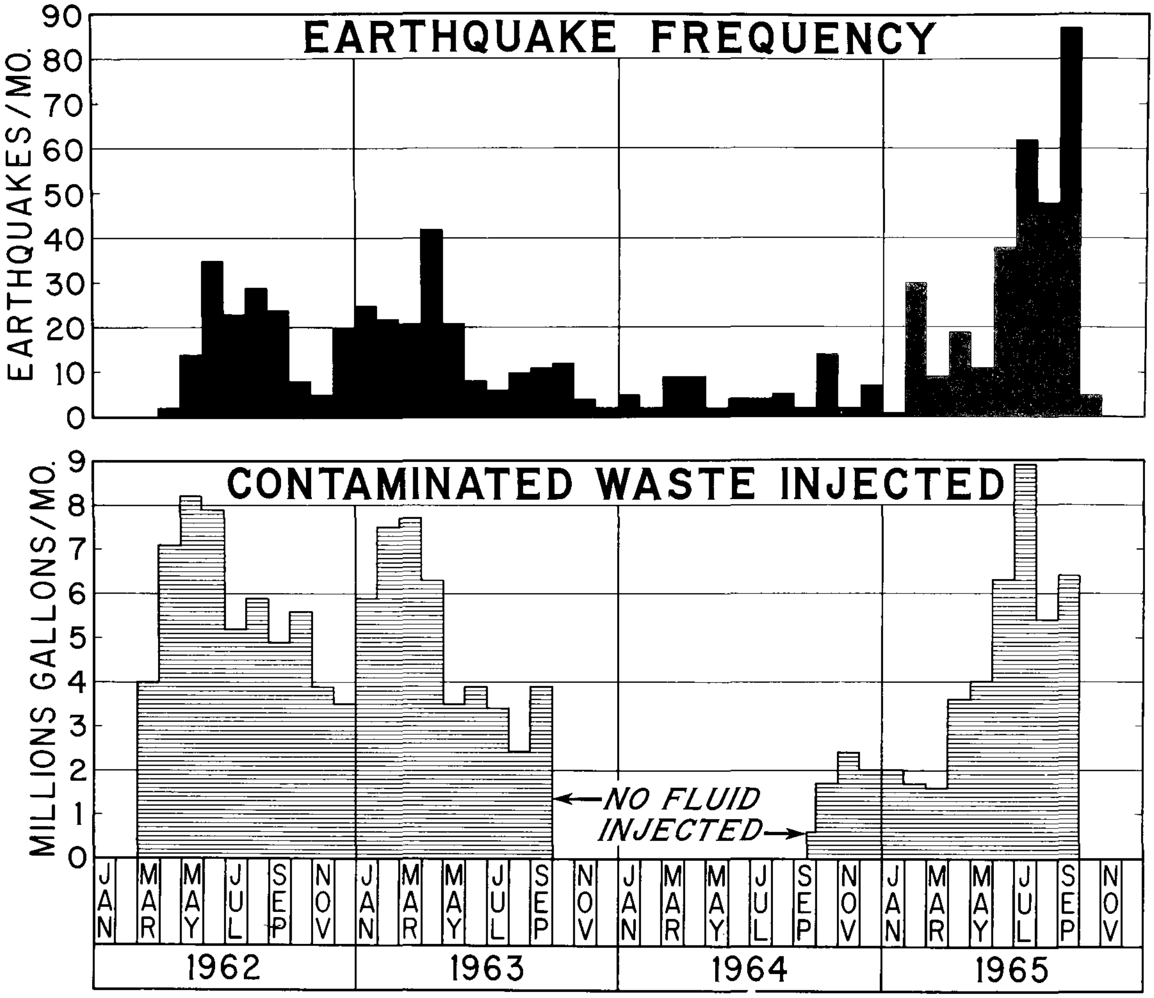


Figure 46. Chart showing the number of earthquakes per month recorded in the northeast Denver area (upper chart), and the monthly volume of injected liquid waste at the Rocky Mountain Arsenal well. (from Evans, 1966a)

Determination of the pre-injection seismic history of the area was a principal element of the U.S. Geological Survey's preliminary investigation. The occurrence of earthquakes prior to injection would lessen the correlation suggested by Evans. Seismic records from Regis College were examined, but because of high background noise small magnitude earthquakes could have escaped detection. Records from GOL were of limited value because the station began operating only a few months before injection initiated. Study of seismic records from a short-period seismograph run by Warren Longley at the University of Colorado at Boulder between 1954 and 1959 revealed 13 events that could have been Denver area earthquakes. However, all events occurred during normal working hours and probably were construction blasts (Krivoy and Lane, 1966).

Hadsell (1968) reviewed historic reports and newspaper accounts of the pre-instrumental period and found two felt reports that possibly occurred in the general vicinity of the Rocky Mountain Arsenal. A large earthquake of intensity VII shook the northern Metro Denver area on November 7, 1882, but this event could only be approximately located. On October 11, 1916, a small intensity III event was also reported in the northern Denver Metro area (Plate 3). Because location control is poor for these two earthquakes, it is uncertain if they occurred near the Rocky Mountain Arsenal. Thus, there is no absolute evidence to indicate any pre-injection seismic activity near the Rocky Mountain Arsenal, but the two felt earthquakes are suspected of having occurred nearby.

Another part of the U.S. Geological Survey's study involved establishment of a very dense seismic network to accurately locate hypocenters. The network operated about 6 hours per day for a 2-month period in January and February of 1966. Sixty-two earthquakes located during this period occurred in an ellipsoidal zone about 10 km long and 3 km wide that included the disposal well. The long axis of this zone trends N60°W and the earthquakes ranged in depth from 4.5 to 5.5 km. These earthquakes define the active part of a fault or fracture zone herein named the Rocky Mountain Arsenal fault (fault number 168). Fault-plane solutions indicate a right-lateral strike-slip motion on a nearly vertical plane that is parallel to the zone of epicenters (Healy and others, 1966a, 1968). The U.S. Geological Survey (Healy and others, 1966b) concluded that there were definite temporal and spatial relationships between the earthquakes and the disposal well.

Because of the suggested connection between the well and the earthquakes, fluid injection at the well was terminated on February 20, 1966. The earthquakes, however, did not cease. Numerous additional small earthquakes occurred during the following months, and the largest, most damaging earthquakes happened over a year after injection was halted. This continued activity appears to reduce the correlation between fluid injection and the earthquakes, but Healy and others (1968) propose a conceptual fracturing model that actually suggests the larger earthquakes should occur after cessation of injection.

Probably the most comprehensive evaluation of the Rocky Mountain Arsenal earthquakes involved geophysical, geologic, and hydrologic studies by the Colorado School of Mines (Hollister and Weimer, 1968). The report contains several papers by numerous geoscientists. Major and Simon (1968) provide the most complete listing available of the earthquakes that occurred up to September 1, 1967, based on records from the Colorado School of Mines network, University of Colorado station, and Regis College station. One of their principal conclusions was that the past occurrence of many small earthquakes did not preclude the possibility of a larger event in the future. Hadsell's compilation of historic earthquakes based on felt reports was valuable not only for the Rocky Mountain Arsenal study, but it also increased our knowledge of the pre-instrumental earthquake history of the entire state. Other papers in this report provided useful data on physical characteristics of the reservoir rock, structure, stratigraphy, and hydraulic characteristics of nearby exposed Precambrian rocks in the Front Range, Quaternary geology at the Rocky Mountain Arsenal, and the vertical relationships between rock elasticity and fluid pressure.

Most workers who have studied the Rocky Mountain Arsenal earthquakes believe the fluid injection triggered the earthquakes (Healy and others, 1968; Hollister and Weimer, 1968). Considerable evidence has been introduced that indicates tectonic stresses existed in the area prior to injection and that the earthquakes partly released this stored energy. Healy and others (1968) point out two factors leading to a tectonic origin for these earthquakes: 1) the pre-1967 earthquakes have a frequency-magnitude relationship comparable to that found in tectonically active areas, and 2) the earthquake distribution, consistent fault-plane solutions, and presence of fracturing in cores from the well all suggest a zone of vertical fracturing. Studies of stress drops of the larger earthquakes by Wyss and Molnar (1972) indicate only part of the available tectonic stresses have been relieved. Hsieh and Bredehoeft (1979) present a reservoir analysis that suggests fluid pressures play a critical role in triggering the earthquakes, but that tectonic stresses were responsible for most of the energy released by the earthquakes.

Two primary questions concerning the sequence of earthquakes at the Rocky Mountain Arsenal remain to be definitely answered: 1) can damaging earthquakes occur in the future at the Rocky Mountain Arsenal, and if so, what is the potential for surface rupture, and 2) are there other areas in the Denver Basin or in Colorado where a similar phenomenon could occur? The final answers to these questions can only be resolved through detailed studies.

Tectonic stresses apparently played an important role in this series of earthquakes and we tend to agree with other researchers who suggest the earthquakes would have eventually occurred naturally without being triggered by fluid injection. Similar tectonic stresses may also be present at other as yet unknown areas within the Denver Basin. Release of this stored energy will probably occur along other pre-existing fracture or fault zones. The maximum magnitude of such earthquakes would likely be at least as large as those that occurred at the Rocky Mountain Arsenal (M = 5 to 5 1/2) or the 1882 earthquake (intensity VII). Fluid injection into other tectonically stressed areas could unintentionally trigger similar earthquakes, but they may also occur naturally in the future.

4.2.2. RANGELY EXPERIMENT

One positive result of the Rocky Mountain Arsenal earthquakes was increased awareness of the potential value of underground fluid injection in controlling earthquakes. In 1967 W. W. Rubey suggested that the Rangely oil field in northwest Colorado might be a favorable location suitable for conducting earthquake-control experiments (Raleigh and others, 1976). Waterflooding, the injection of water at high pressure to aid secondary recovery of oil, initiated at Rangely field in 1957. A seismograph array at Vernal, Utah, established 5 years later in 1962, began recording small earthquakes that centered near the oil field immediately after installation.

The U.S. Geological Survey set up a portable seismograph array at the Rangely oil field in the fall of 1967 to evaluate the feasibility of conducting an earthquake-control experiment (Pakiser and others, 1969). Forty earthquakes were recorded during a 10-day monitoring period and all occurred within the oil field in areas of high fluid pressures due to waterflooding. Upon agreement with the leaseholders and Chevron Oil Company, the field operator, a detailed experiment was planned. During the first year background data on seismic activity would be recorded. This was followed by a period during which fluid pressure near the earthquakes would be lowered by backflowing water from selected injection wells. If the reduction in fluid pressure resulted in decreased seismic activity, injection pressures would be increased and the cycle repeated.

Rangely oil field is located on a closed, doubly plunging anticline in Mesozoic and Paleozoic sedimentary rocks. The primary reservoir rock, the Pennsylvanian and Permian Weber Sandstone, is about 350 m thick and lies about 1,700 m below the land surface. Only one fault lies within the field (fault number 64). Detailed structure contour mapping on the top of the Weber Sandstone based on drill hole information (Figure 47) indicates the fault has only 10 to 15 m of vertical displacement (Raleigh and others, 1976) with an unknown amount of horizontal displacement. The fault is not a major fault, and it appears to have been inactive since before deposition of the Mancos Shale or fault displacements must have been distributed over a wide zone within the Mancos Shale. No surficial evidence of recent ground rupture has been documented for this fault.

The earthquake-control experiment initiated in October of 1969 with the installation of a U.S. Geological Survey seismograph network. Four selected injection wells were used in the experiment. Between October, 1969 and November 10, 1970 the bottom-hole pressure in these holes was increased from 235 to 275 bars (Raleigh and others, 1976). Over 900 earthquakes were recorded during this period, and 367 of these events occurred within 1 km of the four injection wells. The earthquake epicenters clustered in two dense groups (Figure 47). One group centered very near the injection wells at a depth of 2.0 to 2.5 km and a second group with focal depths averaging 3.5 km occurred to the southwest just beyond the oil field. Both groups were parallel to the mapped extent of the minor fault previously described. Fault-plane solutions suggest strike-slip movement on the fault in a right-lateral sense with a small component of dip-slip.

On November 10, 1970 the injection wells were shut in for three days and then backflowed for six months to reduce pressure (Raleigh, 1972). Within a short time period the rate of earthquake activity decreased from 20 to 40 per month to less than one per month. Reinjection initiated in May of 1971, but it was not until August of 1972, that bottom-hole

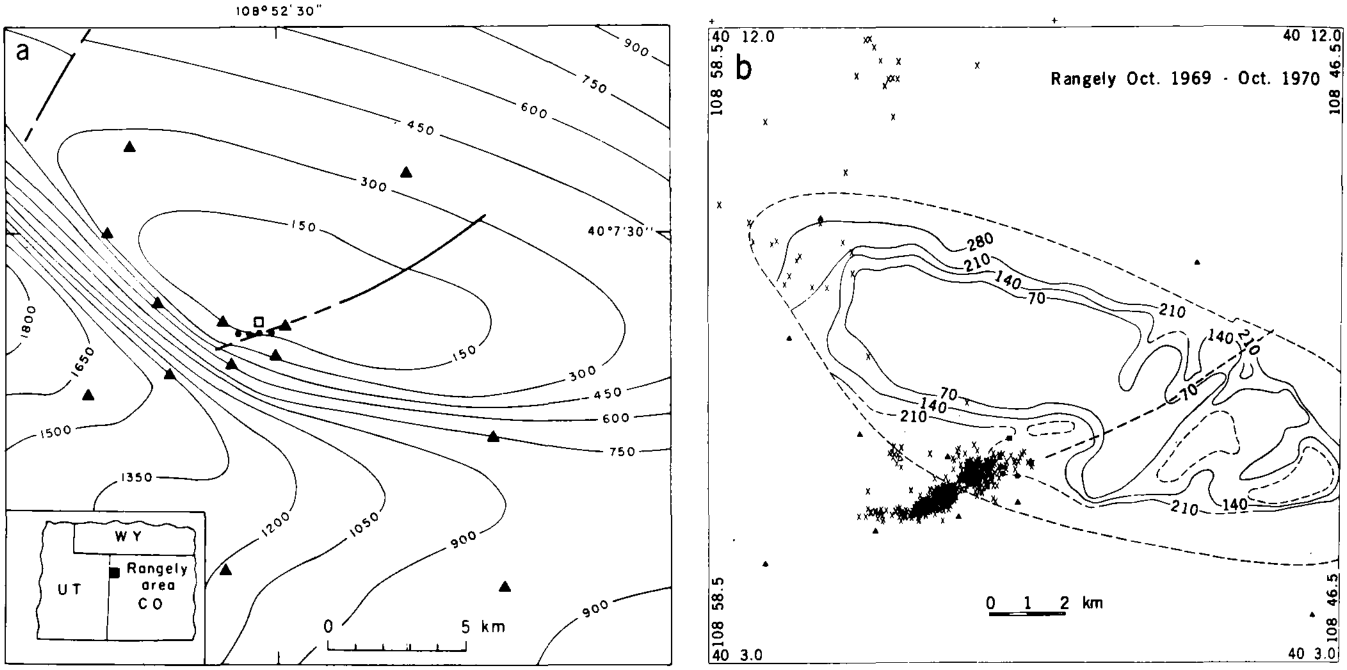


Figure 47. Structure contour map (in meters below sea level) on the top of the Weber Sandstone at Rangely oil field (left side). Earthquakes occurring between October, 1969, and November, 1970, are indicated on the right side by "X". Contours on right side are bottom-hole, 3-day shut-in pressures as of September 1969. (from Raleigh and others, 1976; copyright 1976 by Amer. Assoc. Advancement Science)

pressures returned to original levels. Earthquake activity during this period remained at very low levels. During the following few months bottom-hole pressures slowly increased to 275 bars and the monthly average of earthquakes raised to six. When pressures further increased to 280 bars, an average of 26 earthquakes occurred per month. On May 6, 1973, the injection wells were shut in and backflowing initiated. Earthquake activity immediately dropped. None were recorded near the wells after that day and only one per month were recorded along the fault zone to the southwest.

The Rangely experiment proved that earthquakes can be triggered by increases in fluid pressure and that pore pressure and effective stress concepts as proposed by Hubbert and Rubey (1959) can account for the phenomenon. The experiment supports the hypothesis of Evans (1966a) that the Denver earthquakes were related to waste injection at the Rocky Mountain Arsenal and indicates that earthquakes may be triggered in areas of relatively low historic seismicity. In both cases evidence indicates that most induced earthquakes tend to occur along pre-existing faults or fracture zones and that natural tectonic stresses were also present.

Thus, special care must be used when underground liquid waste injection or oil-field waterflooding are planned near faults or fracture zones in areas that may be subject to even very low stress rates. Determination of the natural state of stress by, for instance, hydraulic fracturing and the in situ rock strength may enable prediction of safe injection pressures (Raleigh, 1972).

4.2.3. NUCLEAR EXPLOSIONS

Three nuclear explosions have been detonated in drill holes in or very near Colorado as a part of the Plowshare program to explore the feasibility of using atomic energy for industrial applications. All three experiments were joint government-industry tests to stimulate natural gas recovery from low permeability sandstone reservoirs. The tests include Project Gasbuggy, Project Rulison, and Project Rio Blanco. They were successful in part, including increased gas recovery from the reservoirs, but several problems, particularly economics, have prevented widespread usage of this technique.

Locations of the Rulison and Rio Blanco tests are shown on Plate 3. Project Gasbuggy took place just off the map south of Pagosa Springs. Each blast caused a considerable amount of ground motion and was assigned a body-wave magnitude between 5 and 5 1/2. They were felt over a wide area, but did minimal serious structural damage. A large number of microearthquakes located within about a 1,000 m of the blast immediately followed each explosion, but rapidly diminished in frequency within a few days. None of the explosions appear to have significantly altered natural seismicity rates. The following paragraphs briefly describe the three projects.

Project Gasbuggy was conducted just south of Colorado about 88 km east of Farmington, New Mexico on December 10, 1967. The experiment consisted of a single 29-kiloton nuclear explosive that was detonated at a depth of 1,292 m. The blast occurred in the Lewis Shale about 12 m below the base of the Pictured Cliffs Sandstone, a low permeability gas reservoir. A chimney 102 m high with a 24.4 m radius resulted from the explosion. N.O.A.A. (1980) reported a body-wave magnitude of 5.1 for event.

A single 43-kiloton nuclear explosive was detonated at the Rulison gas field during Project Rulison on September 10, 1969. The test site was located about 9.6 km southeast of the town of Grand Valley in Garfield County, Colorado. The blast occurred in the Mesa Verde Formation about 2,568 m below ground level and generated an 82.3 m high chimney with a radius of 21.3 m. A body-wave magnitude of 5.3 is recorded by N.O.A.A. (1980) for the explosion.

Project Rio Blanco consisted of three 30-kiloton nuclear devices that were detonated simultaneously at depths of 1,752 m, 1,869 m, and 2,007 m.

The explosion occurred on May 17, 1973 about 40 km west of the town of Rio Blanco in Rio Blanco County. Numerous low permeability, lenticular sandstone beds in both the Fort Union and Mesa Verde Formations were stimulated by the blast, and fractures may have extended as far as 240 m from the drill hole. N.O.A.A. (1980) assigns a body-wave magnitude of 5.4 to the Rio Blanco test. Several nearby faults were monitored for blast-induced movement, but no displacements were recorded.

4.2.4. RESERVOIR-INDUCED SEISMICITY

It has been widely suspected for many years that some seismicity may also be related to water reservoirs in both spatial and temporal manners. A relationship between water levels at Lake Mead and occurrence of local earthquakes was recognized as early as 1945. Reservoir-induced seismicity (RIS) has been observed at many locations throughout the world since this time. Some of the more notable cases of RIS and their maximum induced earthquake magnitudes include Kariba, Africa (6.25), Koyna, India (6.5), and Kremasta, Greece (6.3).

Packer and others (1979) investigated 77 reservoirs that reportedly have induced seismicity associated with them. They evaluated 64 of these water impoundments and concluded that 45 did have RIS. 14 reservoirs had macro-seismity related to them, 15 had micro-seismicity, and 16 had both macro- and micro-seismicity. A relatively high number of deep (greater than 92 m) and/or very large reservoirs have associated RIS (Stuart-Alexander, and Mark, 1976; Packer and others, 1979). Only 11 impoundments have induced earthquakes of magnitude 5 or greater. Active faulting is found near 9 of these 11 reservoirs, and inconclusive evidence of active faulting occurs at the remaining 2 impoundments (Packer and others, 1979).

No reservoirs in Colorado have documented cases of RIS, although Simon (1969, 1972b) indicates seismic events have occurred near four reservoirs in or adjacent to Colorado. They include the Harvey Gap (north of Silt), Cabin Creek (south of Georgetown), Blue Mesa (west of Gunnison), and Lake Hattie (in Wyoming northeast of Walden) Reservoirs. Hadley (1975) investigated the possibility of RIS at Cabin Creek Reservoir and found that the recorded events were related to construction activities. The other reservoirs have not been evaluated for RIS.

Though the state-of-the-art knowledge of RIS is still somewhat limited, some tenative conclusions are drawn by Packer and others (1979): 1) deep and/or very large dams have a higher probability of inducing seismicity, 2) stresses caused by reservoir loading are usually not high enough to initiate new rock ruptures; i.e. stress is usually released along pre-existing fractures and faults, 3) active faults are associated with most, if not all reservoirs that have induced earthquakes of magnitude 5 or greater, 4) in that deep and/or very large dams continue to be built, there will likely be additional cases of RIS, and 5) the potential for damaging reservoir-induced earthquakes is increasing, especially in areas of low historic seismicity where dam designs may not fully anticipate moderate to large magnitude induced events.

4.3. MICROEARTHQUAKE SURVEYS

4.3.1. ELKHEAD MOUNTAINS - STEAMBOAT SPRINGS SURVEY

For a twenty day period between July 22 and August 14, 1976, a high gain seismic array with a detection threshold of magnitude 0.0 (Figure 48) was operated by Micro Geophysics Corporation for the Colorado Geological Survey. The survey monitored a 2,200 km2 area in the Elkhead Mountains for 14 days and a 1,900 km2 area in the Steamboat Springs area for six days (Figure 48). These sites were selected for reconnaissance microearthquake investigation because of their reported high level of seismic activity (see Figure 44; Simon, 1969; Simon, 1972a; Presgrave, 1977). Measurement of the number and size of micorearthquakes and accurate determination of local earthquake epicenters were primary goals of the study.

Seven Sprengnether Instrument Co. MEQ-800-B portable seismic systems were employed for the study. Four systems consisted of a vertical seismometer, a gain-stable amplifier, an integral timing system that was synchronized daily with WWVB, and a smoked paper recorder with 0.05 mm stylus width and 120 mm/min recording speed. Three additional systems were similar to the above systems except all three were tied into a three-component seismometer consisting of one vertical and two horizontal seismometers. Figure 49 is an operating schedule for stations occupied during this study.

All earthquake-like events were identified on the records and entered in a log book. A plot of the total number of events versus hour of the day is shown in Figure 50. It can be seen that a definite clustering of events occurs between 10 A.M. and 6 P.M., and near 11 P.M. This distribution became apparent early in the investigation, and when combined with the fact that event signatures were similar to that of known blasts, led to the conclusion that many of the events were mine blasts, not local earthquakes. For this reason, the three large coal mines operating in the area were asked to log all mine blasts, including the time and size of the blast. Adequate blasting logs were obtained from August 3 (Julian day 216) to August 18 (Julian day 231). Records were kept by Seneca Coal, Ltd. for their Seneca Strip No. 2 Mine in sec. 35, T.6N., R.87W., by Pittsburg and Midway Coal Mining Co. for the Edna Strip Mine in sec. 13, T.4N., R.86W., and by the Energy Fuels Corporation for Energy Strip Mines Nos. 1, 2, and 3 in sec. 1, 32, and 33, T.5N., R86W., and sec. 25, T.5W., R.87W. Table 1 lists these records and a graph of number of blasts versus hour of the day is plotted in Figure 51.

Events detected at GOL, the Colorado School of Mines seismograph in Bergen Park, are recorded in their earthquake log book. Examination of their log book indicated that 24 events thought to originate in either the Elkhead Mountains or the Steamboat Springs area (Table 2) were detected during this period when blasting records were kept. Events occurring at a distance of 200, 210, and 220 km are assigned to the Elkhead Mountains by GOL and those at 177 km to Steamboat Springs (R. B. Simon, 1977, oral commun.).

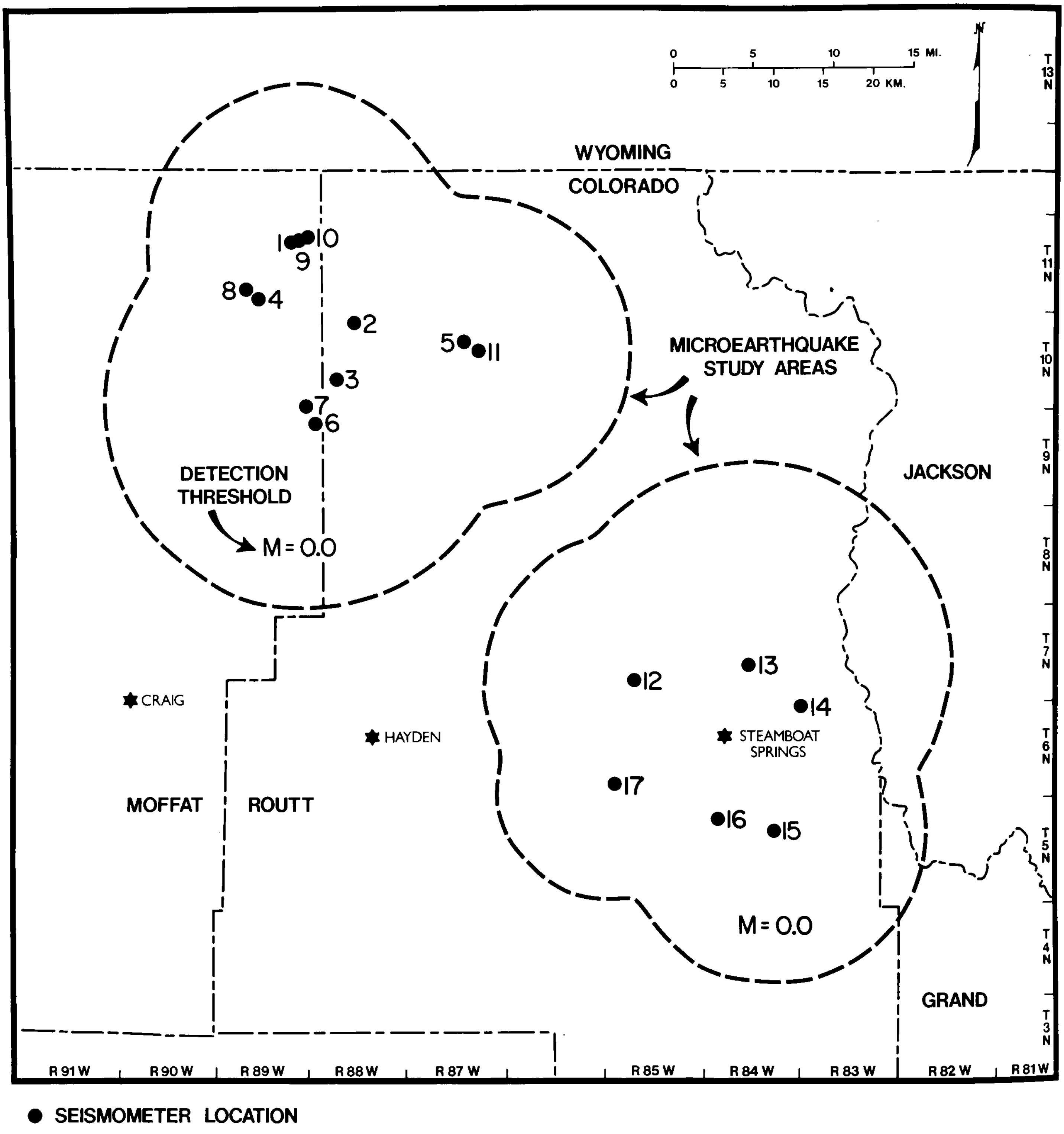


Figure 48. Seismometer location map for the Elkhead Mountains-Steamboat Springs survey.

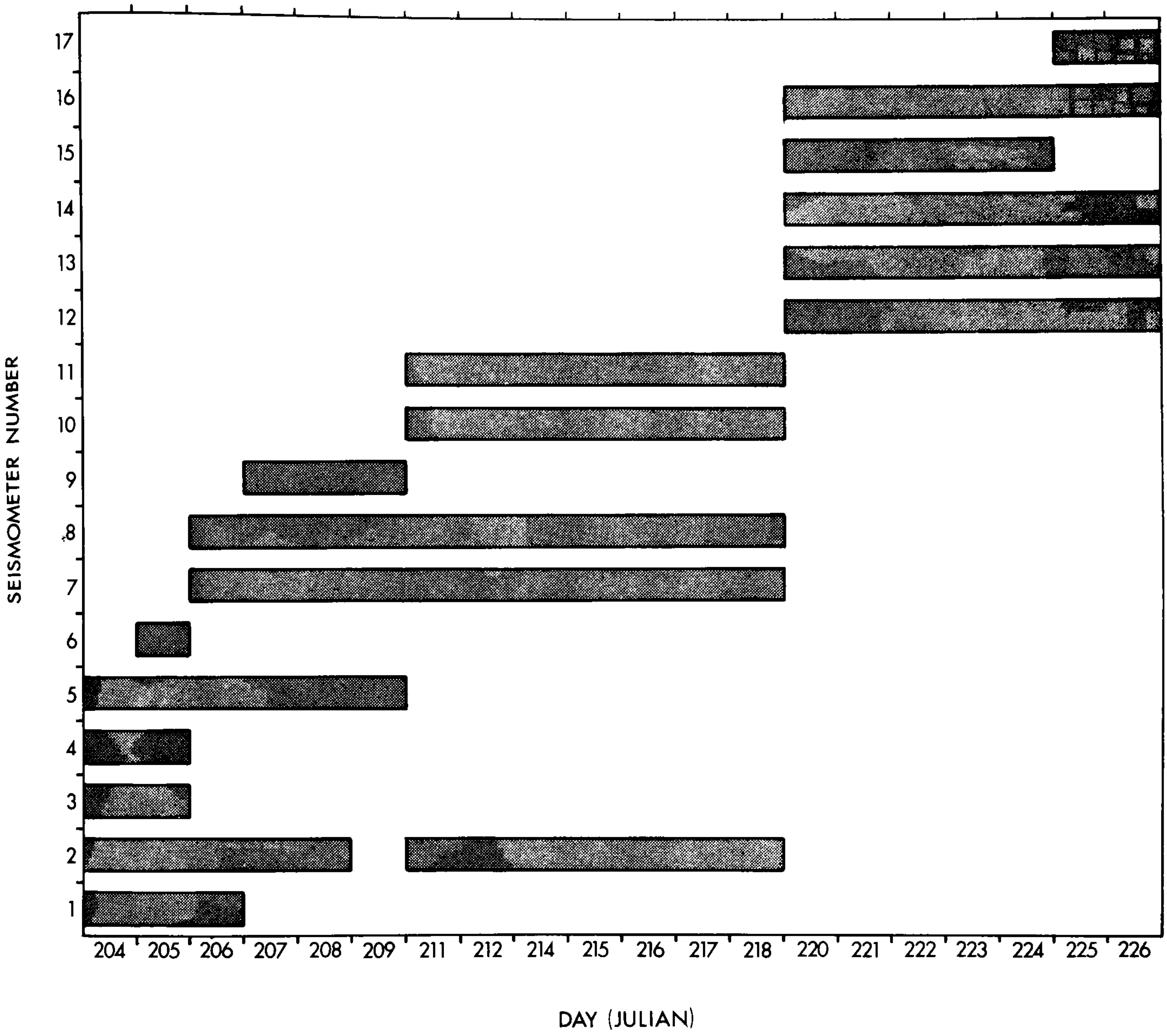


Figure 49. Seismometer operating schedule for the Elkhead Mountains-Steamboat Springs survey.

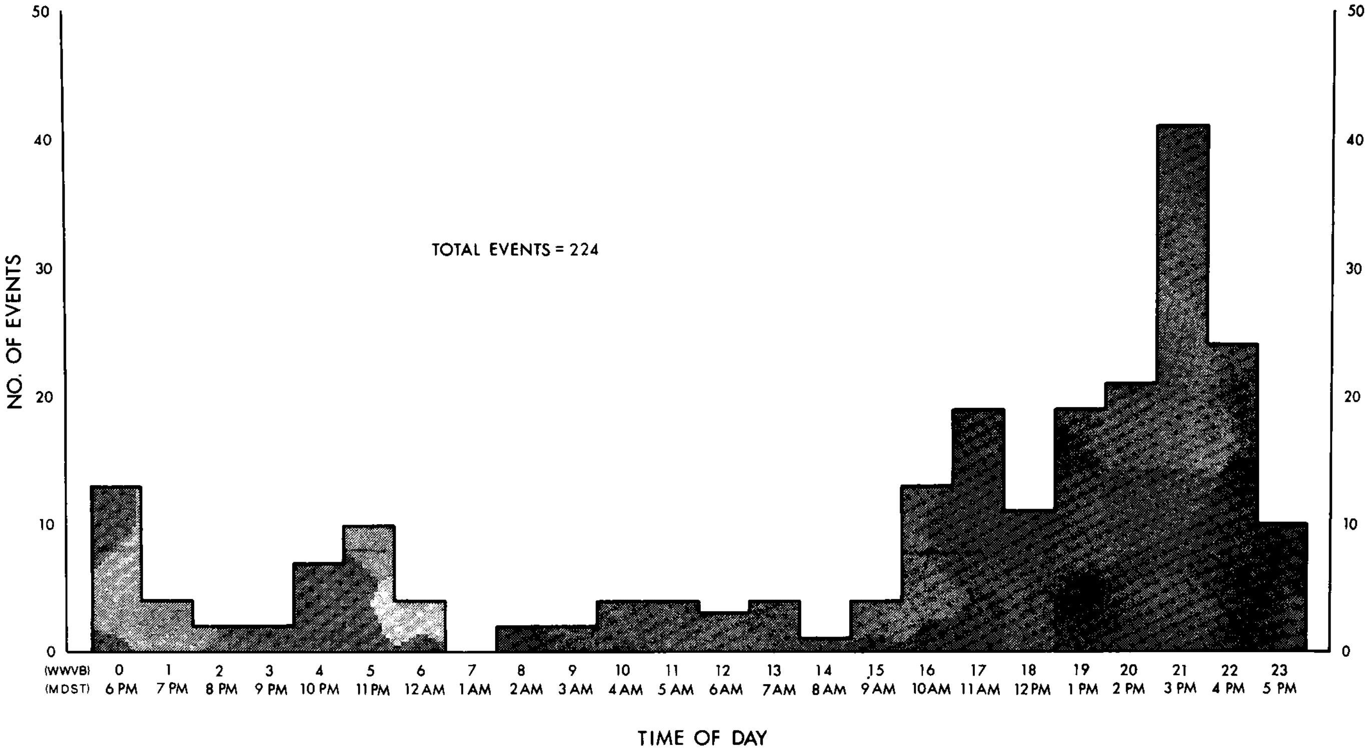


Figure 50. Total number of recorded events versus time of day for the Elkhead Mountain-Steamboat Springs survey.

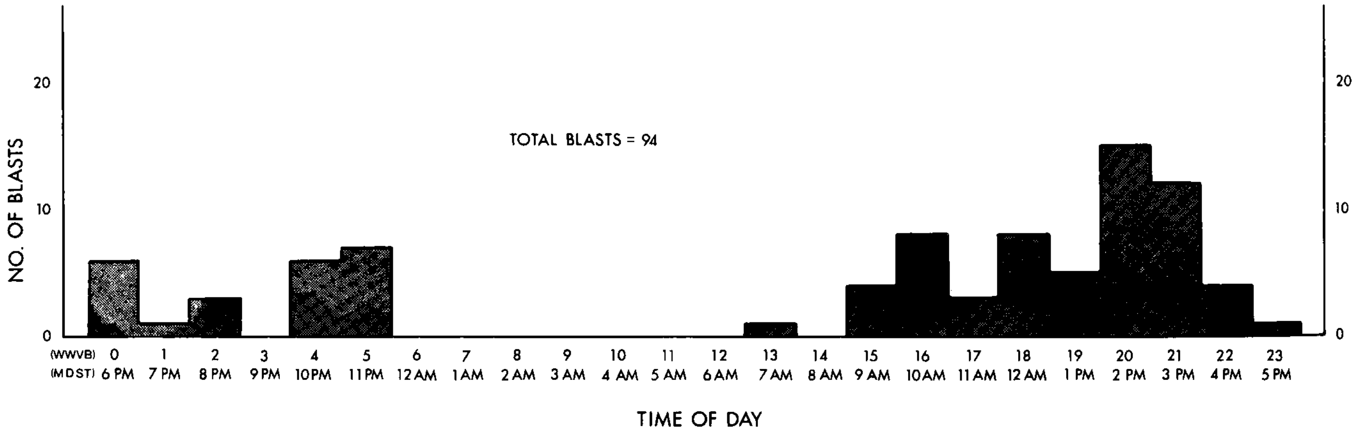


Figure 51. Total number of blasts versus time of day for the Elkhead Mountains-Steamboat Springs survey.

Table 1. Blast record for the Elkhead Mountains - Steamboat Springs microearthquake survey.

Day (Julian)	Time(WWVB) Hour	Time(WWVB) Minute	Location*	Size (pounds)	Comments
210	18	05	P	1,500	
210	21	52	P	2,000	on GOL
211	02	33	P	700	
211	02	48	P	900	
211	04	45	P	1,800	
211	18	00	S	1,800	
211	20	47	P	1,200	
211	21	00	S	1,800	
212	00	50	P	2,700	
212	04	17	P	2,700	
212	15	30	P	2,000	
212	18	00	S	1,700	
212	21	00	S	1,700	
213	21	00	P	2,250	
213	01	02	P	2,700	
213	05	00	P	3,600	
213	20	37	P	3,300	
214	04	50	P	3,400	
214	15	42	P	1,400	
215	17	00	S	6,100	
215	20	56	P	2,000	
215	21	15	S	6,100	
216	04	46	P	4,200	
216	20	45	S	25,500	on GOL
216	20	50	P	4,200	
217	20	35	P	10,500	on GOL
217	21	15	S	1,850	on GOL
218	00	23	P	1,400	
218	05	10	P	2,700	
218	18	17	P	2,500	
218	20	36	P	1,400	
219	02	35	P	3,600	
219	05	10	P	800	
219	08	44	E	7,500	
219	16	05	P	2,000	
219	21	00	S	23,500	on GOL
220	00	14	P	4,000	
220	05	11	P	3,600	
220	19	45	P	1,750	
221	04	40	P	6,000	on GOL
221	20	20	P	12,100	
222	19	55	S	4,550	
222	22	45	E	36,000	on GOL
223	00	50	P	12,100	on GOL
223	05	00	P	2,400	
223	18	20	P	2,600	
223	22	25	S	6,800	
223	22	45	P	?	
224	19	50	S	2,500	
224	23	09	E	34,000	on GOL
225	13	30	S	700	
225	20	56	E	1,600	
226	17	10	P	2,600	
226	21	40	S	45,000	on GOL
226	21	40	E	38,000	on GOL
227	00	10	P	1,400	
227	04	55	P	3,400	
227	16	00	S	1,500	
227	18	00	E	8,700	
227	20	15	S	11,000	on GOL
227	20	44	P	4,600	
227	21	15	S	200	
228	20	47	P	7,000	
229	05	07	P	5,200	
229	16	00	S	1,200	
229	18	00	S	1,200	
229	19	12	P	3,000	
229	20	45	S	1,200	
230	00	41	P	2,800	
230	05	04	P	2,200	
230	22	03	E	28,000	on GOL
231	19	06	E	1,600	on GOL

* "P" = Pittsburg & Midway Coal Mining Company
"S" = Seneca Coals Ltd.,
"E" = Energy Fuels Corporation

Table 2. Events recorded at GOL assigned to the Elkhead Mountains or Steamboat Springs area during the 1976 C.G.S. microearthquake survey.

Day (Julian)	Time(WWVB) Hour	Minute	Second	Distance (km)	Comments
206	21	14	23	220	
207	04	15	55	210	
207	19	31	48.3	200	
208	03	58	26	210	
208	23	52	20	188	
209	22	18	27	210	
210	21	52	22	220	on blast record
212	23	36	20	177	
215	22	05	54	210	
216	20	39	02	220	
216	20	46	50	177	on blast record
217	20	37	07	200	on blast record
217	21	18	32	220	on blast record
219	05	56	45	210	
219	21	01	54	210	on blast record
221	04	40	04	200	on blast record
222	22	39	08	210	on blast record
223	00	50	25	200	on blast record
224	23	12	00	220	on blast record
226	21	40	48	220	on blast record
226	21	51	15	210	on blast record
227	20	14	51	?	on blast record
230	22	04	19	220	on blast record
231	19	06	13	220	on blast record

Events detected at GOL (Table 2) correlate strikingly well with the blast records (Table 1). During the period when accurate blast records were kept (day 216 to 231) only one event recorded at GOL is not listed on the blast records. This event occurred on day 219 at 05 hr, 56 min, 45 sec, a time when blasting can be expected (Figure 51). Furthermore, the signature of this event is almost identical to that of known blasts. All nine events detected by GOL before accurate blast records were being kept also occurred during favored blasting times (Table 2). Signatures of these nine events, likewise, are virtually the same as that of known blasts. Thus, all 24 "Elkhead Mountains" and "Steamboat Springs" events recorded at GOL from day 206 to 231 (25 days) are actually mine blasts originating as much as 64 km from their assigned location (distance is from center of Elkhead Mountains epicentral area to the Pittsburg and Midway mine).

A total of 224 events were recorded by the microearthquake seismometers during the 20-day survey (Figure 50). All but 25 of these events were eliminated from consideration because their signatures were not characteristic of local earthquakes. Azimuth analysis of the remaining 25 events revealed that 20 originated from the same general areas as did the coal mine blasts and were therefore dismissed as being man-made. A few of these events could possibly be microearthquakes within the mining areas, but their signatures suggest they more likely were blasts. Of the remaining 5 events one originated southwest of the network, one from the northeast, and one from the east-northeast. Two events looked as if they may have originated from within the network. Further signature analysis by personnel of Micro Geophysics Corporation suggests that only one of these events could possibly be a local microearthquake, and it originated approximately 10 km NE of the Elkhead Mountains array.

During the 7 and 2/3 years when the locations and numbers of events recorded at GOL were published, a total of 1,328 events (Figure 42) were located in either the Elkhead Mountains or Steamboat Springs region (Simon, 1969; Simon, 1972a; Presgrave, 1977). Presgrave (1977) attempted to remove man-made events from this total by excluding the events that occured during normal blasting hours. The number of events thought to be earthquakes were thereby reduced to 521 (Figure 43). To compare seismic rates for the entire state, Presgrave normalized all events to a threshold level of M = 2.5 (Figure 44). A total of 440 magnitude 2.5 or larger earthquakes were assigned to the combined Elkhead Mountain and Steamboat Springs areas. Using this information, Presgrave (1977) calculated earthquake magnitudes for a 30-year and 200-year recurrence interval (R.I.) on magnitude versus frequency plots with a "b" slope value of 0.86. His calculated magnitudes are as follows: Elkhead Mountains -- a 30-year R.I. for magnitude 5.8 earthquakes and a 200-year R.I. for magnitude 7.0 earthquakes; Steamboat Springs -- a 30-year R.I. for magnitude 5.6 earthquakes and a 200-year R.I. for magnitude 6.7 earthquakes.

The values established by Presgrave (1977) are valid using the data from GOL and his assumptions concerning the number of man-made events. These values were plotted on magnitude versus frequency graphs to ascertain the level of microearthquake activity that should have been observed during the 20-day study, if indeed the events recorded at GOL were earthquakes. Magnitude versus frequency plots using "b" values ranging from 0.8 to 1.0 and normalized to a 20-day period are shown in Figures 52 and 53. The minimum number of magnitude 1.0 and greater earthquakes that should have been detected during our 20-day survey varies from 8 to as many as 300, depending on the "b" value of the area. Between 45 to 2,500 magnitude 0.0 earthquakes should also have been detected.

A significant difference between the predicted seismic rates based on GOL records (Presgrave, 1977) and the observed level is apparent. Either of two possible explanations could be responsible for the discrepancy. The seismic level during the 20-day study could have been anomalously low, or the assumptions made by Presgrave (1977) as to the number of man-made events could be incorrect. The striking correlation between the GOL records and the blast records (Table 1; Figure 51) suggests the latter is the most likely cause of the discrepancy. It is apparent from the blast

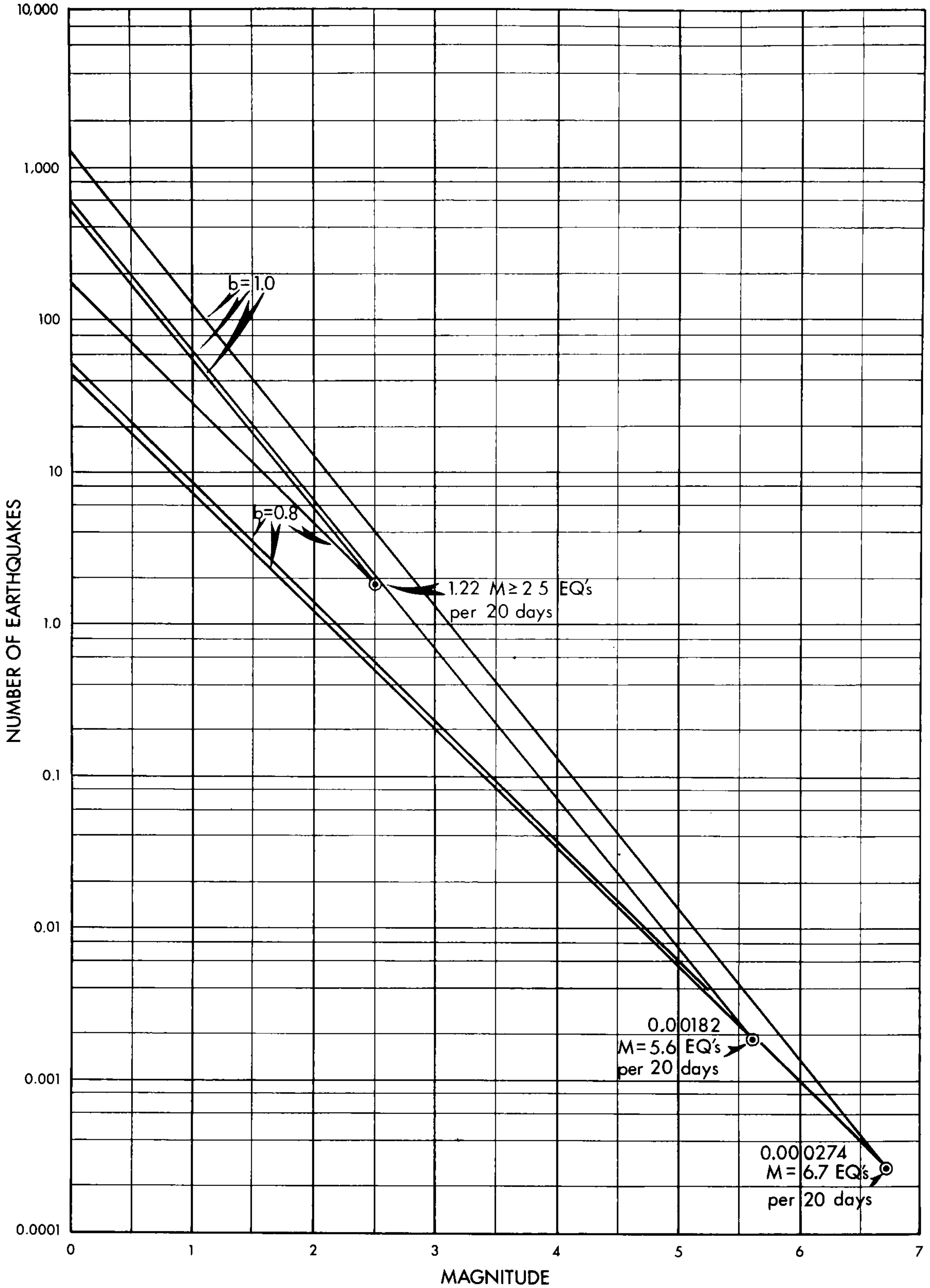


Figure 52. Magnitude versus frequency plot for the Steamboat Springs region.

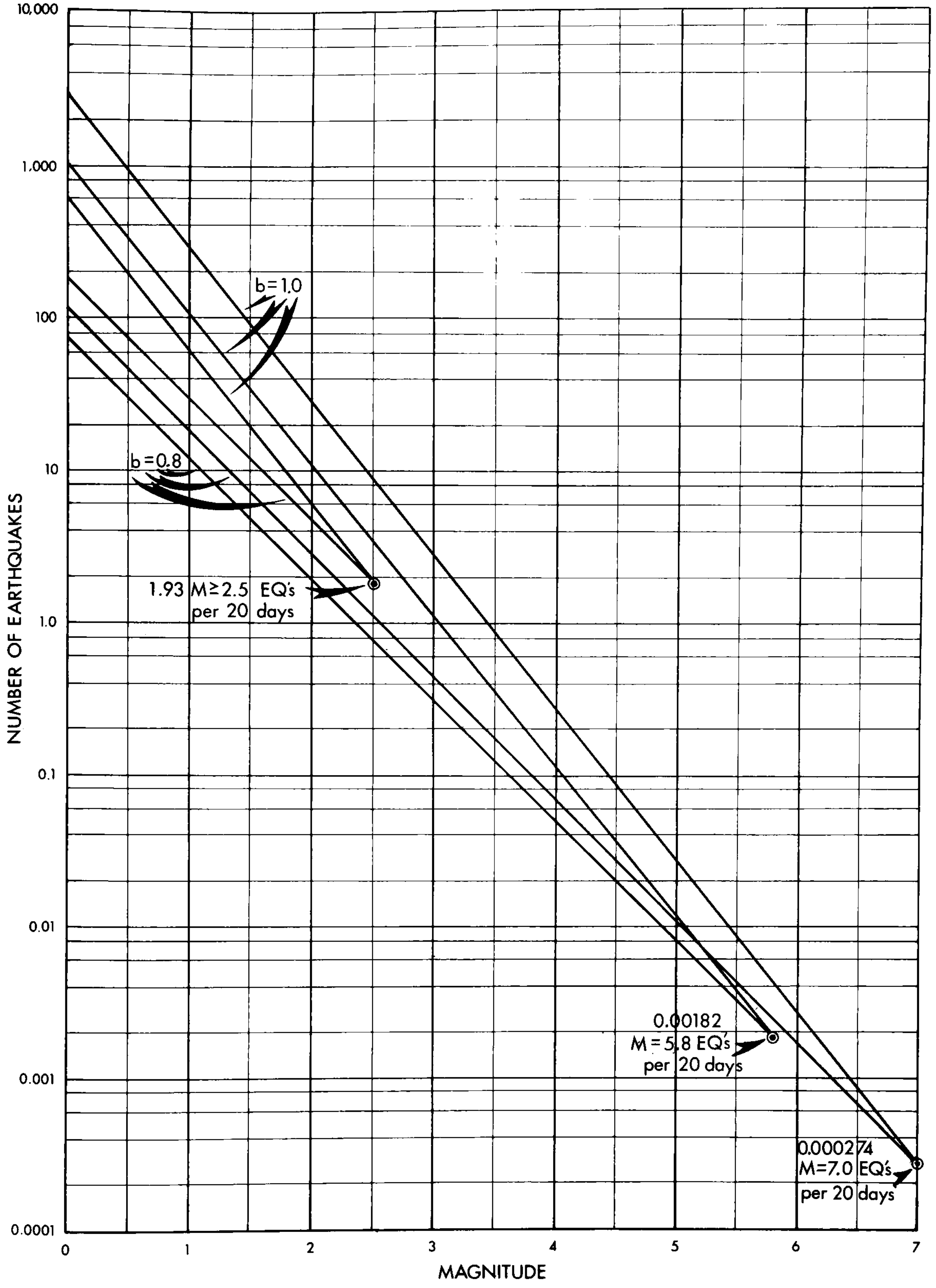


Figure 53. Magnitude versus frequency plot for the Elkhead Mountains region.

records that large blasts are not restricted to daylight hours. Many of the events recorded at GOL during the night time are actually blasts.

Nonetheless, there have been several sizeable events recorded in the Elkhead Mountains-Steamboat Springs area that probably are earthquakes (Hadsell, 1968; National Oceanic and Atmospheric Administration, 1977). These include M.M. intensity V events on March 22, 1895 and February 10, 1955, a magnitude 4.4 event on March 18, 1971, and a magnitude 3.5 event on March 31, 1974 (Plate 3, Appendix 3). If this data is plotted on either Figure 52 or Figure 53, the points would fall considerably below the predicted seismic rates derived from Presgrave (1977), but would be much closer to a plot using the one magnitude 0.0 or larger earthquake per 20 days, as recorded by our microearthquake study.

4.3.2. OTHER MICROEARTHQUAKE SURVEYS

Several other microearthquake surveys have been conducted in Colorado. Unfortunately the information from most of these surveys is not publicly available. The following section summarizes the information that is attainable.

Osterwald and others (1973) investigated seismic tremors in the region near Leyden in T.2S., R.70W., approximately 19 km northwest of downtown Denver during January, 1972. The purpose of the survey was to monitor the response of coal-mine pillars and overlying bedrock to changes in stress due to injection and withdrawal of gas in the Leyden coal mine-natural gas storage reservoir. Eight seismometers were used in the 15-day study.

Two types of seismic tremors were detected in the general area of the mine. The most abundant type, Type I, consisted of low-velocity, low-amplitude, low-frequency, amplitude-modulated wave trains up to 20 to 30 seconds long. These were detected only by seismometers above or very near the storage area. Osterwald and others (1973) interpret Type I events as resonant vibrations caused by fluid movement within the mine.

A second type of tremor, Type II, consisted of short-duration, high-amplitude waves with frequencies between 30 and 20 cycles per second. These waves were both frequency and amplitude modulated. During the study 40 Type II tremors were recorded, but only six could be located. Epicenter determinations for the six events indicate they occurred about 3 km south and southwest of the mine near the Golden fault.

The origin of the Type II tremors is not known. They could related to hydrologic pressure changes associated with injection and pumping at the Leyden mine. It is also possible that the events were microearthquakes associated with the Golden fault (F.W. Osterwald, C.R. Dunrud, 1977, oral commun.). This question cannot be fully answered until further microearthquake studies of the Golden fault are conducted.

Keller and Adams (1976) conducted an 18-day reconnaissance microearthquake survey in San Luis Valley during July and August 1974 using three Sprengnether MEQ-800 seismograph systems with vertical seismometers. The objective of the study was to collect sufficient data for a seismotectonic analysis of the area and to detect any microearthquake swarms associated with hot springs in the valley.

Only six local microearthquakes were recorded during the entire 18-day survey, a surprisingly low number considering the geological and geomorphic evidence of active tectonism in this region. Only one of these events was detected on all three seismographs and it was located near La Jara.

Microearthquake surveys in the upper Arkansas Valley have recorded several microearthquakes. Crompton (1976) detected and located three local events during a 4-day survey of the valley. Locations of these events are plotted on Plate 2. In addition to locating microearthquakes, Crompton studied the crustal structure of the area using known blasts from Climax.

AMAX Exploration, Inc., conducted microearthquake surveys in the upper Arkansas Valley to evaluate the region for geothermal potential. A. L. Lange (1977, oral commun.) supplied information on 12 events recorded during a 10-day microearthquake survey and a 10-day ground noise survey. Epicenters of these events are shown on Plate 2. The microearthquake distribution does not define distinct zones, but there is a general grouping of events along the west side of the valley near the Sawatch fault.

Microearthquake monitoring of the Chatfield and Bear Creek Reservoirs, southwest of Denver, has been conducted by the Colorado School of Mines for the Corps of Engineers (Fassett, 1974; Patrick, 1977). This study was designated to provide data for an induced seismicity evaluation. This network has not recorded any definite local earthquakes (Patrick, 1977), but six events that might possibly be earthquakes have been detected (M. W. Major, 1976, pers. comm., in Patrick, 1977).

A microearthquake survey near Ridgway was conducted by the U.S. Water and Power Resources Service (Sullivan and others, 1980). Sixty-six microearthquakes were detected in this region during their investigation. Most of these occurred in two distinct swarms of events. The distribution and depth of the events correlate strikingly well with the Ridgway fault, and lead to the conclusion that the Ridgway fault is active (Sullivan and others, 1980).

5. RELATIONSHIPS BETWEEN EARTHQUAKE HISTORY AND GEOLOGY

This section attempts to relate historic Colorado earthquakes with youthful geologic features, primarily Neogene or potentially active faults. Plate 3 combines a reduced version of Neogene faults shown on Plate 1 with the larger earthquakes listed in Appendix 3. Additional earthquakes discussed in this section are shown in Figures 43 and 45.

Any attempt to correlate seismicity with geology in Colorado must consider the limitations of the data. Geologic information is limited in that an understanding of the recent history of fault activity is achieved only through detailed investigation of individual faults or fault zones. Few faults in Colorado have been sufficiently studied to provide the specific information about recent activity needed to be able to predict earthquake potential.

The greatest limitation, however, results from the short period of adequate seismic monitoring. Pre-instrumental data does not provide accurate earthquake locations or magnitude determinations. Because of a relatively quiet, historical earthquake record, minimal instrumental studies have been conducted in Colorado. Past investigations are of good quality, but the absence of a multi-station, state-wide network hampers any attempt to accurately define seismicity in the state. Only for a short time period during 1971 and 1972 was an adequate system, the joint NOAA/CSM network, in operation. The Colorado School of Mines seismograph, GOL, has detected many events since installation in 1961, but they cannot be located with the precision of a multi-seismograph system. Furthermore, crustal structure in Colorado is extremely complex, a fact that only adds to the problem of accurately locating earthquakes. These limitations must be kept in mind when attempting to predict future earthquakes from the recent geological or seismological history of Colorado.

The series of earthquakes that occurred at the Rocky Mountain Arsenal is the best studied earthquake sequence in Colorado. It has been reasonably established that these earthquakes were triggered by fluid injection at the Rocky Mountain Arsenal disposal well (Healy and others, 1968). Distribution of the earthquakes suggest they are related to a deep-seated, northwest-trending shear zone that has not yet been recognized at the surface.

Although the earthquakes resulted from fluid injection, this area should not be considered to be free of future earthquakes. Evidence favors an interpretation that the earthquakes were only triggered by the injection-induced pressure changes and that tectonic stresses do exist in the area. In other words, fluid injection caused a "premature" release of tectonic energy. Several other earthquakes, including the large 1882 earthquake, have occurred in this general area prior to the injection, and these resulted from release of tectonic stresses.

Quaternary fault movement has been documented on a graben near Golden that is suspected of being related to the Golden fault. At least two periods of fault rupturing are indicated since the Yarmouth(?)

interglacial period. A total of 38 small events have been recorded at GOL in 1965, 1967, and 1976 that could be related to activity on the Golden fault (Table 3; R. B. Simon, 1977, oral commun.). Most events occurred on weekdays during hours when blasting could be expected. This does not mean that all the events listed in Table 3 are man-made, but there is a possibility that at least a part could be. Detailed microearthquake monitoring of the Golden fault is needed before the present activity of the fault can be established.

Table 3. Events recorded at GOL between 1965 and 1967 thought to be related to the Golden fault.

Year	Date	Time (UTM)	Year	Date	Time (UTM)
1965	Jan 05	23:26	1967	Oct 18	20:54:57
1967	Feb 23	23:17:20	1967	Nov 02	18:14:29
1967	Feb 24	18:41:16	1967	Dec 07	20:16:18
1967	Feb 27	20:03:28	1967	Dec 14	18:02:23
1967	Mar 01	23:53:04	1967	Dec 19	21:36:22
1967	Mar 04	07:56:20	1967	Dec 22	19:09:33
1967	Mar 12	12:18:07	1967	Dec 26	19:01:06
1967	Mar 12	17:24:23	1967	Dec 26	20:23:21
1967	Mar 15	16:32:14	1967	Dec 26	21:21:08
1967	Mar 16	15:59:29	1967	Dec 26	23:18:10
1967	Apr 05	15:35:10	1967	Dec 28	15:04:10
1967	Apr 05	20:06:02	1967	Dec 28	17:59:19
1967	May 03	19:07:30	1967	Dec 28	21:13:27
1967	May 11	23:04:31	1976	Jun 09	19:34:48
1967	May 22	22:50:00	1976	Jun 21	21:41:24
1967	May 22	23:02:50	1976	Jun 22	21:41:20
1967	Aug 29	06:23:18	1976	Jun 23	01:23:19
1967	Aug 30	06:25:33	1976	Jul 01	19:46:08
1967	Aug 31	06:05:02	1976	Jul 27	19:15:33

Several events have been detected by GOL at Cabin Creek and Urad (Figure 43). Most events from Cabin Creek and Urad are probably man-made blasts, not natural earthquakes. Felt earthquakes, however, have been reported at Georgetown (Appendix 3) near Urad and Cabin Creek. These events are probably natural earthquakes related to fault activity. Potentially active faults near Georgetown include a series of faults in the Williams Fork Valley, the Kennedy Gulch fault, the Floyd Hill fault, and the Frontal fault. Minor movement on any of these faults could have generated the earthquakes felt at Georgetown.

Earthquakes up to intensity VI have shaken the lower Arkansas River valley from Pueblo to the Colorado-Kansas border. The alignment of the earthquakes along the valley is probably biased by the distribution of population along the valley. Two faults in this area, the Cheraw and Fowler faults, have experienced movement during the Quaternary and could be responsible for the reported earthquakes. It is improbable that these two faults have caused all the reported earthquakes, because the highest intensities often are a considerable distance from the faults (i.e. reports from Lamar rather than Las Animas, La Junta, and Rocky Ford). A more reasonable explanation may be that part of the earthquakes are caused by stress release on a deep-seated structure or structures that are not recognized at the surface. Such deep-seated structures may also be responsible for the earthquakes near Trinidad.

GOL has detected several earthquakes thought to originate near Colorado Springs (Figure 43). These earthquakes are located by GOL directly on the Ute Pass fault, a fault suspected of Quaternary activity. They could also be related to movement on the Rampart Range fault which lies just to the north. No felt earthquakes have been reported in Colorado Springs, but the earthquakes detected by GOL indicate the need for further study in this highly populated area.

The Divide earthquake of 1979 was assigned a location directly on the Oil Creek fault. Such a close spatial relationship suggests the possibility of slight movements on the fault.

Geological data indicates the Rio Grande rift province has been the most active province in the state throughout the Neogene. Our known earthquake history, however, does not obviously support the geological findings. Parts of the structural zone, in particular the San Luis Valley, have been anomalously aseismic during the past 110 years. Even a microearthquake survey in the San Luis Valley revealed surprisingly few microearthquakes (Keller and Adams, 1976).

Certain parts of the Rio Grande rift province, however, have experienced moderate earthquakes. Two earthquakes, one accompanied by intensities up to M.M. VII, shook the upper Arkansas River Valley near the Sawatch fault (Plate 3, Appendix 3). Microearthquakes have been instrumentally located in this same part of the structural zone (Plate 2; A. L. Lange, 1977, oral comm.; Crompton, 1976). Several earthquakes have occurred the Steamboat Springs region. Two of these earthquakes were located near the Steamboat Springs fault zone (Plate 3). GOL has detected many events in this part of the rift province (Figure 44; Presgrave, 1977), some of which may be natural earthquakes.

The apparent absence of seismicity in San Luis Valley during the historical period should not mislead those preparing seismic risk analyses into believing the area has low potential for future earthquakes. We believe the geologic data strongly indicate numerous large magnitude earthquakes have repeatedly occurred along the Sangre de Cristo fault during the late Quaternary and throughout the Neogene. The current period of quiescense may be an integral part of a seismic cycle similar to that observed for many of the active faults in Nevada (Ryall, 1977).

Several moderate earthquakes have shaken northwestern Colorado. The 1891 intensity VI event felt in Axial Basin is aligned with the west-trending en echelon faults between Craig and Maybell, near Juniper Hot Springs. Quaternary movement has not been documented on this faults system, primarily because of the absence of Quaternary deposits in this area, but several features suggestive of recent movement are present on these faults.

Earthquakes occurring near Rangely have been the topic of considerable interest because of their possible man-induced nature. Two intensity IV earthquakes occurred in this same region in 1954 (Plate 3, Appendix 3) prior to initiation of waterflooding at the Rangley oil field. Occurrence of these events suggests the existence of tectonic stresses in this region, and indicates that the later earthquakes may have only been triggered by waterflooding of the Rangely oil field.

A felt earthquake in 1889 and numerous intrumentally located earthquakes have centered near Glenwood Springs (Plate 3; Figure 43). These events generally coincide spatially with relatively minor faults that disrupt the Grand Hogback. Glenwood Springs is also noted for it hot springs, and it is possible that structural features associated with the thermal waters may be related to the earthquake activity.

The joint NOAA/CSM network located an earthquake near Dotsero (Figure 45), the site of Holocene volcanism. This same network also detected events along the east-west faults of the Uinta trend just east of the Colorado-Utah border and near fault number 45 on the northeast side of the Flat Tops.

Several earthquakes have occurred near faults associated with the Uncompahgre uplift (Plate 3, Figure 45), indicating possible modern activity on this structural block. Most of these events centered near the southeast end of the uplift. In 1960 a magnitude 5.5 earthquake was widely felt in this area and caused minor damage. Several smaller events are reported in this same general vicinity. A striking correlation between microearthquakes and the Ridgway fault was discovered by the U.S. Water and Power Resources Service (Sullivan and others, 1980). Sullivan and others also believe the magnitude 5.5 earthquake was related to the Ridgway fault.

Another earthquake of magnitude 5.5 occurred near Dulce, New Mexico in 1966 just south of Pagosa Springs (Plate 3, Appendix 3). It was followed by a series of aftershocks of diminishing magnitude that still continue today (R. B. Simon, 1977, oral commun.; Sanford and others, 1979). There is no documented evidence of Neogene faulting or folding in the region near Dulce (E. H. Baltz, 1977, oral commun.; T. A. Steven, 1977, oral commun). Baltz (1965) describes the Dulce area as a structurally complex region within the Archuleta anticlinorium on the northeast flank of the San Juan Basin. Numerous faults and folds within the anticlinorium disrupt the early Tertiary and older rocks, but no evidence of late Tertiary or Quaternary deformation has been described in this immediate area. To the south the San Juan Basin is bounded by a major, recently active fault, the Nacimiento fault. Because of the historic seismicity and complex geology of the region, it is possible that evidence of recent tectonism may be uncovered in this area through detailed geological, geophysical, and seismological studies.

Many felt and instrumentally located earthquakes have centered in the San Juan Mountains. Much of this region has been the site of repeated volcanic activity during the middle Tertiary and it was tectonically active during the late Paleozoic and Laramide orogeny. Several large faults associated with older tectonism lie within the area (Steven and others, 1974; Tweto and others, 1976a), but only a very few are known to have been active during the Neogene. Faults peripheral to the Lake City caldera displace the Miocene volcanic rocks of the caldera, but are not believed to be active today. A small amount of movement has occurred on a part of the Cimarron fault and on a fault that displaces the Miocene basalts on Cannibal Plateau, but neither appear to have experienced movement during the Quaternary.

6. SEISMIC HAZARDS AND IMPLICATIONS FOR LAND USE

Several geologic phenomena associated with earthquakes can cause severe damage to man-made structures and possibly result in loss of human lives. These phenomena include surface faulting, ground shaking, associated ground failure, tsunamis and seiches, and regional subsidence or tilting.

When a fault moves, the resulting rock rupture may propagate upward and displace the ground surface. Such a displacement may be in horizontal and/or vertical directions and it may occur rapidly or very slowly. The direction of displacement depends on the type of fault (Figure 1). Strike-slip faults move horizontally, dip-slip faults move vertically, and oblique-slip faults have both vertical and horizontal components of movement. Rapid faulting occurs during major earthquakes, but slow movement, called fault creep, may gradually occur over a long period time and be associated only with microearthquakes. Fault creep usually is restricted to strike-slip faults, but there is a limited amount of poorly documented data that suggest some dip-slip faults may also experience creep.

The amount of displacement that may occur during an individual earthquake varies from less than a few centimeters to over several meters. There is a general correlation between fault length and displacement per event. Long faults often have greater displacement and may generate large earthquakes. The maximum recorded surface rupture for a single earthquake is 12.8 m of vertical displacement (Bonilla, 1970). Over 6 m of horizontal displacement occurred along the San Andreas fault in 1906 (Bonilla and Buchanan, 1970). Geologic studies in Colorado suggest up to about 3 m of vertical displacement has occurred during individual earthquakes in the recent geologic past. Not all large earthquakes cause surface faulting. Deep earthquakes may result from rupture of deeply buried rocks, and this rupture may not extend to the surface. Oftentimes, this type of earthquake only results in bending or gentle folding of shallow rocks.

Surface faulting can severely affect man-made structures by physically offsetting foundations, roads, utility lines, etc. The most simple and direct way to minimize hazards due to surface faulting is to completely avoid construction on or across active faults. Where avoidance is not possible, special designs may minimize damage due to surface faulting. In Colorado, however, the existing data base on the location of active faults is much too limited to adequately outline all zones where surface faulting may occur. Detailed, site specific fault investigations should be an integral part of design and construction phases for all critical structures such as nuclear facilities, dams, and industrial plants that handle large amounts of hazardous or toxic materials. High-occupancy structures such as institutional buildings and high-rise apartments and offices, and essential key public facilities such as police and fire stations, hospitals, water-supply and natural gas lines, and bridges should also be located to avoid active faults or be designed and constructed to minimize damage due to surface faulting.

The most widespread earthquake damage is often caused by earthquake-generated ground shaking. Factors that influence the degree of ground shaking include the actual energy released by an earthquake, proximity of the site to the source of energy release, and local rock and soil characteristics. Intensity of ground shaking for a particular earthquake is especially dependent on local rock and soil characteristics.

Seismic risk maps based on the expected ground shaking have been prepared by several workers (Ulrich, 1948; Roberts and Ulrich, 1950, 1951; Richter, 1959; Algermissen, 1969; Algermissen and Perkins, 1976; Brazee, 1976). These maps have often been used as guides for the design of low-risk structures such as single-family dwellings. Algermissen (1969) developed a seismic risk map of the United States that is widely used in a somewhat modified form by many building codes. On this map Colorado is entirely within seismic zone 1, a zone of low seismic risk in which earthquakes of intensity VI and smaller may occur. Several earthquakes of intensity VII have been recorded historically in Colorado and geological evidence suggests large earthquakes have happened in the recent past and are likely to recur in the future. We believe existing data indicates a need to design in accordance with seismic zone 2 of Algermissen (1969) in much of Colorado. Only the northeastern part of the state appears to be totally acceptable for zone 1.

Algermissen and Perkins (1976) presented a probabilistic map showing maximum expected rock accelerations in the contiguous United States for the next 50 years. The highest acceleration value assigned in Colorado was 0.07 g in the southwestern part of the state. Unfortunately, very little information on Quaternary faulting was available to Algermissen and Perkins during report preparation and, their map, therefore, is primarily based on the historic earthquake record. Brazee (1976) constructed several maps using historical intensity data. These maps are valuable as general guides to historical intensities and could be used to crudely approximate expected earthquake intensities for designing low-risk structures. The U.S. Geological Survey, in cooperation with several state and federal agencies, is preparing a map of the Arizona-New Mexico-Colorado area that uses geologic data to approximately predict the maximum credible magnitudes anticipated for selected tectonic provinces. This map, along with the data presented in section 2.3 of this report, should encourage the use of a seismotectonic approach to predict ground motion in Colorado.

Seismic design criteria for high-risk structures and essential public facilities should be developed for each particular site using state-of-the-art techniques that incorporate detailed geologic and seismologic studies. A commonly used approach involves a deterministic analysis of all active faults in the area. Each active fault is evaluated to establish its maximum credible earthquake magnitude based on fault characteristics and the historic seismic record (Slemmons, 1977). Ground motion parameters can be estimated by comparing the magnitude, location, focal depth, and focal mechanism of the maximum credible earthquake with existing strong motion data. Ground motion design criteria can be described as a time history, spectra response, or peak parameters involving ground displacement, velocity, and acceleration.

Types of ground failure that commonly occur during earthquakes include landslides, rockfalls, differential compaction, local subsidence, liquefaction, lurching, and cracking. Several of these phenomena often naturally occur or are man-induced without any earthquake influence. Strong ground shaking associated with earthquakes, however, may aggravate causative forces and increase the likelihood of failure. Areas favorable for ground failure can be readily identified during site specific studies. If the hazard is severe, avoidance may be the only valid alternative to prevent future ground-failure problems. If avoidance is unacceptable, structures should be designed using appropriate engineering technology.

Tsunamis, seiches, and other types of abnormal water-wave actions may also be generated by earthquakes. Tsunamis, large ocean waves created by rapid elevation changes of large earth masses during earthquakes, are not a problem in Colorado because of the great distance between the state and any ocean. Seiches are earthquake-induced standing waves in enclosed or restricted bodies of water such as lakes, reservoirs, bays, and rivers. Seiche waves usually have low amplitude (less than 0.3 m), but in shallow areas they may be as high as 6 to 9 m (McCulloch, 1966). Such high waves could cause severe impact to people and property along a lake or river. Dams and reservoirs can be overtopped by seiche waves and large volumes of water thus can be released. Damaging abnormal water-wave actions can also result from dam failure or large landsliding into bodies of water during an earthquake.

Regional subsidence or tilting may result from major, differential vertical and horizontal movements over broad areas during earthquakes. Over 180,000 km^2 of the sea floor and land in southern Alaska were warped during the 1964 Alaskan earthquake, with elevation changes locally exceeding 15 m (Hansen and others, 1966). Regional tilting and subsidence may seriously affect gradient sensitive facilities such as transportation routes and irrigation canals, and it may also cause permanent flooding of wide areas along coasts or lakes. Tectonic land changes over large areas are very hard to predict and the resulting complications are difficult to mitigate.

7. SUMMARY

Recent geological and geophysical data suggest the potential for damaging earthquakes in Colorado is somewhat higher than the historic earthquake record indicates. Several areas in the state have experienced repeated episodes of tectonic deformation, the most recent of which initiated near the beginning of the Miocene and has continued at least to a limited extent to the present. Faults that have been active during this period of Neogene tectonism are herein considered potentially active faults. Some of these designated potentially active faults may not have generated any damaging earthquakes during the Quaternary and thus may not need to be designed for. However, many show evidence of major Quaternary movement and several are documented to offset late Pleistocene and Holocene deposits. Such faults must carefully be evaluated for their potential to generate future earthquakes and may need to be accounted for in the design, construction, and maintenance of critical, high-risk structures.

Colorado can be divided into six principal seismotectonic provinces based on the distribution and characteristics of potentially active faults, historic earthquake record, major structural and physiographic regions, and our interpretation of earthquake potential. The six provinces include the Rio Grande rift, eastern mountain, plains, western mountain, Uinta-Elkhead, and Colorado Plateau provinces. Neogene tectonism in Colorado has been dominated by the Rio Grande rift, a major intracontinental rift zone that forms the easternmost prominent boundary of a large area in the western United States that has undergone tremendous regional extension during the Neogene. Within Colorado the Rio Grande rift can be subdivided into northern and southern subprovinces based on late Quaternary fault activity.

Seismic hazards in Colorado can be effectively mitigated. Construction over active faults should be avoided, or structures must be specially designed to withstand damage caused by fault rupture. Critical structures should be carefully sited, designed, and constructed to resist ground shaking induced by nearby earthquakes. Secondary hazards such as slope failures, liquefaction, ground deformation, and abnormal water-waves must also be recognized and dealt with during design and construction.

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Appendix 1
Modified Mercalli Intensity Scale
(from Richter, 1958)

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle, Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D* cracked. Small bells ring. Trees, bushes shaken visibly, or heard to rustle.

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, unbraced parapets, and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry ; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslide. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of light and level distorted. Objects thrown into the air.

* Note: Criteria for various grades of masonry construction described below.

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

Appendix 2. Summary of the characteristics of Neogene or potentially active faults in Colorado.

The following table summarizes the important characteristics of faults shown on Plate 1 and discussed in the text. Each fault or fault group is numbered on Plate 1. This number is used in column 1 to identify the faults. Fault name, if known, is given in column 2. Fault location is indicated in column 3 by specifying the townships in which the faults begin and end. A descriptive location is used where no township system is established.

Type of movement is indicated in column 4. The symbols used are N for normal faults, R for reverse faults, T for thrust faults, D for high-angle, dip-slip faults, and S-R or S-L for strike-slip faults with, respectively, right-lateral or left-lateral movement. The strike direction is shown in column 5 and is separated from dip direction by a slash. Column 6 lists fault length in kilometers.

Age of the most recent fault movement is given in column 7. The youngest deposit offset by the fault is indicated by the first symbol and the oldest deposit that covers the fault is indicated by the second symbol. If only one symbol is listed, it is for the youngest deposit displaced by the fault. Symbols used in this column represent the age and, where known, the name of the deposit. They are defined as follows:

H = Holocene
Qp = Pinedale glaciation
Qb = Bull Lake glaciation
Qw = Wisconsinan glaciation (undifferentiated)
Qpb = pre-Bull Lake glaciation
Qi = Illinoian glaciation or Sangamon interglacial period
Qk = Kansan glaciation or Yarmouth interglacial period
Qn = Nebraskan glaciation or Aftonian interglacial period
Q = Quaternary (undifferentiated)

Mt = Miocene Troublesome Formation
Mnp = Miocene North Park Formation
Mi = Miocene igneous rocks
Td = Miocene-Pliocene Dry Union Formation
Tsf = Miocene-Pliocene Santa Fe Formation
Tbp = Miocene-Pliocene Browns Park Formation
Ti = late Tertiary igneous rocks
Ts = late Tertiary sedimentary rocks
T - late Teriary (undifferentiated)

Comments about a fault are in column 8. A partial listing of references for each fault is in column 9. The numbers are keyed to the bibliography. Question marks are used to indicate uncertainty in the data.

Fault No. (1)	Name (2)	Location (3)	Movement (4)	Strike/dip (5)	Length(km) (6)	Age of Movement (7)	Comments (8)	Primary Sources (9)
1	Beaver Creek fault	T.11N.,R.104W.	N	N45W/SW	18	Tbp		81,108,167,267,273,323
2		T.10N.,R.100W.- T.11N.,R.102W.	N	N50W/SW	30	Tbp/Q	includes 5 faults	108,167,267,273,323
3		T.8N.,R.95W.- T.10N.,R.102W.	N	N50W/SW	70	Tbp/Q		53,108,164,167,267,273, 323
4		T.9N.,R.100W.- T.10N.,R.101W.	N	N55W/NE	24	Tbp/Q		108,167,267,273,323
5		T.6N.,R.104W.- T.7N.,R.103W.	N	N45E/SE	10	Tbp		108,167,267,273
6		T.6N.,R.104W.- T.6N.,R.103W.	N	N50W/NW	11	Tbp		108,167,267,273
7	Yampa fault	T.6N.,R.104W.- T.6N.,R.99W.	N	N85W/N	45	Tbp	includes 2 faults	108,164,167,267,273
8		T.7N.,R.101W.- T.7N.,R.99W.	D	N75E	19	Tbp	includes 2 faults	165,167,267,273
9		T.6N.,R.99W.- T.7N.,R.99W.	N	N45E/SE	2.5	Tbp		53,167,267,273
10	Cross Mountain fault	T.5N.,R.98W.- T.7N.,R.98W.	N	N20W/83°SW	19	Tbp/Q	includes 3 faults	53,108,164,167,267,273
11	East fault	T.6N.,R.98W.- T.7N.,R.98W.	R	N10W/85°SW	6	Tbp/Q		53,167,267,273
12		T.6N.,R.99W.- T.6N.,R.98W.	N		7	Tbp/Q	includes 12 faults	53,167,267,273
13		T.5N.,R.97W.	D	N50E	4	Tbp		167,267
14		T.5N.,R.96W.	N	N70W/SW	2	Tbp	includes 2 faults	167,267,273
15		T.6N.,R.94W.- T.7N.,R.93W.	N		14	Tbp	includes 8 faults	165,167,267,270
16		T.7N.,R.94W.- T.6N.,R.91W.	N	N50W/NE	15	Tbp/H	includes 6 faults	108,167,270,273,323
17		T.8N.,R.92W.- T.7N.,R.91W.	N	N30W/NE	20	Tbp/H	includes 4 faults	108,167,270,273,323
18		T.12N.,R.90W.- T.11N.,R.89W.	N	N45W/NE	24	Tbp		34,167,270,273,323
19		T.11N.,R.88W.	N	N45W/SE	4	Tbp		34,166,270,273

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
20	Willow Creek structural zone	T.12N.,R.88W.- T.11N.,R.86W.	N	N50W/NE	18	Tbp		34,270,273
21	King Solomon fault	T.11N.,R.86W.- T.10N.,R.84W	N	N75W/NE	22	Tbp		34,166,225,270,273,323
22	Silver City Creek fault	T.11N.,R.86W.- T.10N.,R.84W.	N	N70W/NE	13	Tbp		34,166,225,270,323
23		T.11N.,R.84W.- T.12N.,R.85W.	N	N5E/SE	13	Tbp	includes 2 faults	166,225,270,273
24		T.10N.,R.85W	N	N80W/NE	3	Tpb	includes 2 faults	34,166,225,270,273
25	Grouse Mountain fault	T.10N.,R.86W.- T.10N.,R.84W.	N	N80W/SW	21	Tbp/Qpb		34,166,225,270,273,323
26	Steamboat Lake fault	T.10N.,R.86W.- T.10N.,R.85W.	N	N85E/NW	9	Tbp/Q		34,166,225,270,273
27	Spillway fault	T.10N.,R.85W	N	N75W/NE	7	Tbp/Q		225
28		T.10N.,R.87W.	N	N55W/NE	7	Tbp/Q		34,166,270,273
29		T.9N.,R.84W.	N	N70E/NW	4	Tbp/Qpb		34,166,270,273
30	Sand Mountain fault	T.9N.,R.86W.- T.8N.,R.86W.	N	N10W/NE	16	Tbp		34,166,270,273
31		T.5N.,R.85W.- T.7N.,R.86W.	N	N45W/SW	44	Tbp/H	includes 2 faults	34,166,270,273
32		T.5N.,R.82W.- T.5N.,R.84W.	N	E-W/N&S	10	Ti/Qpb	includes 3 faults	270
33	Indepencence Mountain fault	T.12N.,R.81W.- T.12N.,R.82W	N	N40W/SW	6	Mnp		108,270,273
34		T.11N.,R.80W.- T.12N.,R.81W.	N	N30W/NE	13	Mnp		270,273
35		T.8N.,R.79W.- T.10N.,R.80W.	N	N20W/SW	23	Mnp/Qpb	includes 7 faults	127,128,270,273
36	Spring Creek fault	T.7N.,R.77W.- T.8N.,R.80W.	N	N70W/SW	37	Mnp/Qpb	includes 11 faults	16,108,123,128,270,273, 323
37		T.5N.,R.79W.	N	N40E/NW	6	Ti	includes 4 faults	270,273
38		T.5N.,R.79W.- T.5N.,R.80W	N	N30W/SW	6	Ti/Q	includes 4 faults	270,273
39		T.2N.,R.79W.- T.3N.,R.79W	N	N20W/NE	8	Mt/Q		108,270,273,323
40	Antelope Pass fault	T.1N.,R.80W- T.3N.,R.80W.	N	N10E/SE	16	Mt	includes 3 faults	108,270,273,323

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
41		T.2N.,R.76W.- T.3N.,R.77W.	N	N30W/SW	8	Mt	includes 4 faults	108, 323
42	Laramie River fault	T.4N.,R.75W.- T.11N.,R.76W.	N	N5W/NE	69	Ts/Q		108,273,323
43	Steamboat Springs fault zone	T.7N.,R.84W.- T.1N.,R.84W.	N	N-S/E	63	Tbp/Q	includes 13 faults	34,138,166,270,273,323
44		T.1N.,R.82W.- T.5N.,R.84W.	D	N35W/SW	30	Tbp/Q	includes 11 faults	34,166,270,273,323
45		T.1N.,R.85W.- T.2N.,R.87W.	D	N50W/NE	19	Ti/Q	includes 2 faults	166,270,273
46	Red Mountain fault	T.1N.,R.80W.	T			Mt	not shown on Plate 1	108,270
47		T.1S.,R.82W.- T.1N.,R.81W.	D	N45E	8	T/Q	2 faults	270,273,280,323
48		T.1S.,R.81W.- T.1N.,R.81W.	D	N20W	9	Tbp/Q		270,273,280,323
49	Gore fault	T.1S.,R.81W.- T.7S.,R.78W.	N	N25W/SW	70	Tt/Qpb	complex fault zone	28,263,272,273,277,278, 280,323
50	Frontal fault (Blue River fault)	T.2S.,R.81W.- T.6S.,R.78W.	N	N35W/NE	73	Q(?)/Qw	complex fault zone	262,263,273,278,280,315 323
51		T.3S.,R.79W	N			Tt/Qpb	includes 3 faults	273,280,282
52		T.4S.,R.78W.- T.5S.,R.78W.	D	N30W/NE	12	Tt/Qpb		273,280
53		T.1S.,R.80W.- T.3S.,R.77W.	N	N45W/NE	41	Tt/Qb	includes 3 faults	273,280,282,323
54		T.2S.,R.77W.- T.1N.,R.78W.	N	N30W/SW	22	Tt/Qb	includes 3 faults	273,280,282,323
55		T.2S.,R.78W.- T.1S.,R.79W.	N	N20E	7	Qpb/Qb	includes 8 roughly parallel faults	273,280,282
56	Mosquito fault	T.11S.,R.80W.- T.5S.,R.78W.	N	N20E/NW	62	Qw/H	includes 7 faults	262,264,265,272,273, 277,280,304,315,323
57		T.2S.,R.86W.- T.2S.,R.84W	N		10	Qpb	includes 7 faults	153
58		T.3S.,R.85W.- T.4S.,R.84W.	N	N45W/NE	21	Q	includes 2 faults	273,280
59		T.4S.,R.86W.- T.5S.,R.84W.	N		25	Ti/Q(?)	includes 7 faults	273,280

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
60		T.5S.,R.86W.	N	N30E	5	Q	includes 3 faults shown on Plate 1	131
61		T.6S.,R.89W.- T.7S.,R.89W.	N	N25W/SW	7	Qpb	includes 5 faults shown on Plate 1	175,273,280
62		T.7N.,R.87W.- T.7N.,R.88W.	D	N75E	5	Ti	includes 2 faults	273,280
63		T.12N.,R.87W.	D	N45/NE	4	Ti/Q		280
64		T.2N.,R.102W.- T.1N.,R.103W.	S-R	N50E	9	H	defined by seismological study at Rangely oil field.	26,51,55,72,173,174, 184,190,192-196
65	Redlands fault complex	T.1N.,R.3W.- T.1S.,R.1W	N&R	N30W/NE	16	Q	includes 3 faults and 2 monoclines	38,149,273,323
66	Glade Park fault	T.12S.,R.102W.- T.12S.,R.101W.	N	N80W/SW	16	Q/H		38,149,273,319,323
67	Ladder Creek fault	T.12S.,R.100W.	D	N80W	6	Q/H	"scissors" fault	149,273,319,323
68	Bangs Canyon fault	T.12S.,R.100W.- T.13S.,R.100W.	N	N35W/NE	9	Q		149,319,323
69		T.12S.,R.99W.- T.12S.,R.100W.	N	N45W/NE	4	Q		319
70	Cactus Park fault	T.14S.,R.99W.- T.13S.,R.100W.	N	N65W/NE	~5	Q/H		149,273,319
71		T.14S.,R.98W.- T.14S.,R.99W.	N	N70W/NE	10	Q/H		273,319
72		T.14S.,R.99W.	N	N55W/SW	4	Q/H		319,323
73		T.15S.,R.99W.	N	N55W/SW	13	Q		273,319,323
74		T.4S.,R.3E	N	N81W/49°SW	?	Qpb	observed only in roadcut	38,273,323
75	Little Dolores River Fault	T.12S.,R.104W.- T.20S.,R.25E.	N	N50W/NE	15	Q/H		38,273,323
76	Ryan Creek fault zone	T.14S.,R.103W.- T.22S.,R.24E	N	N60W/SW	36	Q		38,273,323
77		T.14S.,R.104W.- T.22S.,R.26E.	N	N35W/NE	10	Q		273,319

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
78		T.15S.,R.104E.- T.23S.,R.25E	N	N40W/NE	49	.Q/H		319
79		T.51N.,R.17W.- T.14S.,R.103W	N	N45W/SW	20	Q		39,40,273,319,323
80		T.50N.,R.16W.- T.15S.,R.103W.	N	N45W/NE	33	Q		39,40,273,319,323
81		T.48N.,R.13W.- T.49N.,R.16W.	N	N60W/SW	40	Q		273,319,323
82		T.48N.,R.12W.- T.48N.,R.13W.	N	N60W/NE	9	Q		319
83		T.47N.,R.14W.- T.48N.,R.15W.	N	N45W/SW	19	Q		273,319,323
84		T.46N.,R.11W.- T.47N.,R.13W.	N	N70W/SW	24	Q		273,319,323
85		T.46N.,R.13W.- T.47N.,R.14W.	N	N50W/SW	9	Q	includes 2 faults	273,319,323
86		T.46N.,R.12W.	N	N75W/SW	10	Q		319
87		T.46N.,R.12W.	N	N50W/SW	4	Q		273,319
88		T.45N.,R.11W.- T.46N.,R.12W.	N	N40W/SW	22	Q		273,319,323
89		T.46N.,R.10W.- T.46N.,R.11W.	N	N75E/SE	7	Q		273,319,323
90		T.48N.,R.19W.- T.45N.,R.16W.	N	N50W	62	H(?)	includes 12 faults which flank Paradox Valley	40,273
91		T.48N.,R.16W.- T.48N.,R.15W.	N	N20E/SE	6	H(?)	includes 4 cross faults in Paradox Valley	40
92		T.46N.,R.19W.- T.43N.,R.16W.	N	N60W	40	H(?)	includes 12 faults flanking Big Gypsum Valley	40,273
93		T.43N.,R.18W.- T.44N.,R.18W.	N	N70W	12	H(?)	includes 4 faults	273,279
94	Cimarron fault	T.47N.,R.3W.- T.48N.,R.4W.	N	N65W/NE	13	M(?)	only a part of the entire fault is suspected of Neogene activity	244,273,279

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
95		T.43N.,R.4W.- T.42N.,R.6W	C		45	Mi/P	includes 8 faults related to collapse of Lake City caldera	244,273,279
96		T.45N.,R.3W.- T.43N.,R.2W.	N	N25/SW	18	Mi/H		244,273,279
97		T.43N.,R.4E.- T.44N.,R.3E.	N	N20W	13	Mi/Qb	includes 4 faults	244,273,279
98		T.46N.,R.5E.- T.43N.,R.4E.	N	N20E	25	Mi/Qb	includes 3 faults	273,279
99		T.44N.,R.5E.- T.44N.,R.6E.	N	E-W/N	13	Mi/Qw	includes 2 faults	273,279
100		T.38N.,R.7E.- T.39N.,R.6E.	N	N35W	16	Mi/Q	includes 8 faults	144,244,273
101		T.40N.,R.4E.- T.38N.,R.3E.	N	N15W	28	Mi/Q	includes 5 faults	146,244,273
102		T.37N.,R.4E.- T.37N.,R.3E	N	N50W/SW	16	Mi/Q	includes 2 faults	142,244,273
103		T.37N.,R.5E.- T.34N.,R.6E.	N	N20W/SW	22	Mi/Q	includes 6 faults	143,244,273
104		T.34N.,R.6E.- T.32N.,R.5E.	N	N20E	25	Mi/Q	includes 5 faults	143,244,273
105		T.33N.,R.6E.- T.32N.,R.7E.	N	N15W	10	Mi/Q	includes 7 faults	143,244,273
106		T.35N.,R.7E.- T.33N.,R.6E.	N	N20E	20	Mi/Q	includes 9 faults	143,244,273
107	Manassa fault	T.33N.,R.9E.- T.28S.,R.73W.	N	N45E/NW	56	Q(?)/H	inferred from gravity data and geomorphology	15,35,123,272,273, 323
108	Mesita fault	Costilla County near Mesita	N	N-S/W	44	Qpb/H(?)	includes 2 faults	43,273,323
109	Sangre de Cristo fault zone	Costilla County, west of San Pedro Mesa	D	N-S/W	26(?)	Ti/H		273
110	Sangre de Cristo fault zone	Costilla County east of San Pedro Mesa	D	N-S/E	20	Ti/H		43

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
111		Costilla County, southwest of San Luis	N	N15W	18	Ti/H	includes 12 faults on Plate 1, many more observed in field	43
112	Sangre de Cristo fault zone	Costilla County, between Fort Garland and San Luis	N	N40W	19	Qw	includes 9 faults on Plate 1, many more observed in field	43
113	Sangre de Cristo fault zone	Costilla County, west flank of Culebra Range	N	N5W/SW	51	H	includes 16 fault scarps on Plate 1, many more observed in field	273,323
114	Sangre de Cristo fault zone	Costilla County, NE of Fort Graland	D	N75W/NE	12	H		43
115	Sangre de Cristo fault zone	Costilla County, north of Blanca	N	N-S/W	13	H		43
116	Sangre de Cristo fault zone	Costilla County, then N to T.48N.,R.8E.	N	N35W/SW	130	H	includes many scarps	104,134,135,212,219, 251,254,272,273,323, 328
117	Sangre de Cristo fault zone	Costilla County, east flank of Culebra Range	N	N10W/SE	60	Tsf	includes 13 faults on Plate 1 that flank the west side of the Culebra range	113,271,273
118	Villa Grove fault zone	T.45N.,R.10E.- T.47N.,R.9E.	N	N55W	29	Qp/H(?)	includes 14 faults on Plate 1; many more scarps exist	134,135,219,251,273, 323,328
119	Western Boundary fault	T.48N.,R.7E.- T.46N.,R.8E.	N	N-S/E	28	Q(?)		104,134,135,158,273, 279
120	Lucky Boy fault	T.47N.,R.7E.- T.46N.,R.8E.	N	N30W/NE	13	Q(?)		104,134,158,273,279
121		T.48N.,R.7E.- T.49N.,R.8E.	N			Td/Q	includes 14 faults that bound the Poncha Pass block	134,135,218,251,273, 279,297,323
122	Alvarado fault	T.27S.,R.72W.- T.47N.,R.11E.	D	N35W/NE	83	Tsf/Q	includes several subsidiary faults	219,220,251,273,323
123	Westcliffe fault	T.26S.,R.68W.- T.47N.,R.11E.	N	N50W/SW	95	Tsf/Q	includes 2 faults	219,220,251,253,273, 323
124		T.27S.,R.69W.- T.25S.,R.69W.	D		17	T/Q	includes 3 faults	251,273
125		T.25S.,R.69W.- T.25S.,R.65W.	N	E-W/N	42	T/Q		251,273

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
126	Wet Mountain fault	T.19S.,R.71W.- T.24S.,R.67W.	D	N30W/NE	75	T/H	includes 6 faults	144,157,219,220,255, 272,273,323
127		T.23S.,R.67W	N	N35W/NE	5	Qi		219,220,251,273,323
128		T.24S.,R.70W.- T.24S.,R.69W	D	N80E/NW	11	T/Q		251,273
129	Rosita fault	T.23S.,R.71W.- T.22S.,R.72W	N	N45W/SW	11	Ti/Qk		219,251,273
130		T.21S.,R.72W.-	N	N65W/SW	8	Ti/Q		219,251,253,273
131	Dead Mule Gulch fault	T.19S.,R.73W.- T.21S.,R.70W.	N	N60W/SW	40	T/Q		219,251,253,273
132		T.19S.,R.72W.- T.20S.,R.71W.	D	N75W	14	T/Q		219,251,273,
133		T.20S.,R.71W.- T.20S.,R.70W.	D	E-W	6	T/Q		219,251,273
134	Ilse fault	T26S.,R.68W.- T.17S.,R.72W	N	N30W/NE&SW	110	T/Q		219,237,250,251,255, 273,323
135	Texas Creek fault	T.46N.,R.12E.- T.50N.,R.12E.	N	N-S/W	35	Tsf/Qk		212,219,251,253,273, 323
136	Parkdale fault	T.18S.,R.72W.- T.18S.,R.71W.	D		7	T/Q	includes 2 faults	219,273,323
137	Rice Mountain fault	T.17S.,R.72W.- T.17S.,R.70W.	N	E-W/S	13	T/Q	includes 2 faults	219,251,273
138		T.17S.,R.71W.- T.18S.,R.71W.	D	N-S	9	T/Q		251,273
139	High Park fault zone & Bare Hills fault	T.16S.,R.71N.- T.15S.,R.72W.	N	N40E/SE	16	T/Q	includes 4 faults	219,251,273
140	Fourmile Creek fault	T.14S.,R.70W.- T.16S.,R.70W.	N	N20W/SW	20	T/Q		219,251,273,324,325
141		T.14S.,R.70W.- T.13S.,R.69W.	D	N20E	12	T(?)/Q		219,251,273
142		T.13S.,R.69W.- T.13S.,R.68W.	N	N65E/NW	11	T(?)/Q		219,251,273,373

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
143	Oil Creek fault	T.16S.,R.68W.- T.10S.,R.70W.	D	N10W/SW	58	T(?)/Qb		219,251,273,325
144	Ute Pass fault zone	T.16S.,R.67W.- T.9S.,R.69W.	D	N25W/NE	70	Qk(?)/Qi	includes 5 faults within fault zone	83,219,223,251,273, 323,326
145	Rampart Range fault	T.14S.,R.67W.- T.9S.,R.68N	R	N10W/NE	47	Qk/H		83,212,219,223,251, 273,300,323,326
146	Current Creek fault	T.12S.,R.75W.- T.17S.,R.72W	N	N35W/NE&SW	60	T/Q	includes 3 faults	59,219,251,272,273,323
147		T.13S.,R.72W.- T.13S.,R.73W.	D		7	T/Q	includes 2 faults	219,251,273,324
148		T.14S.,R.74W.- T.17S.,R.73W.	N	N20W/SW	32	T/Q		219,251,273
149	Pleasant Valley fault	T.51N.,R.10E.- T.48N.,R.11E.	N	N20W/SW	33	T/Q		219,254,273,323
150	Kaufman Ridge fault	T.14S.,R.76W.- T.15S.,R.75W.	N	N35W/NE	20	T/Q		219,273,323
151		T.48N.,R.11E.- T.49N.,R.10E.	N	N50W/NE	18	T/Qk		134,251,254,273
152		T.47N.,R.10E.- T.49N.,R.8E.	N	N50W/NE	32	T/Qi		134,251,277
153	Box Canyon and Quarry faults	T.49N.,R.10E.- T.49N.,R.9E.	D	N60W	7	Ti/Q	includes 2 faults	219,254,273
154	Dead Goat fault	T.49N.,R.9E.- T.50N.,R.8E.	N	N40W/SW	10	Ti/Q	includes 2 faults	134,135,219,273
155		T.50N.,R.8E.- T.51N.,R.8E.	N	N35W/NE&SW	11	Td/Qw	includes 2 faults	135,218,251,273,279, 295,297
156		T.50N.,R.8E.- T.51N.,R.8E.	N	N10W/SW	28	Td/Q		135,218,273,279,
157		T.51N.,R.8E.- T.13S.,R.78W.	N	N5W/SW	28	Td/Q	includes 4 faults	134,135,216,218,251, 273,279,295
158		T.50N.,R.8E.- T.49N.,R.8E.	N	N60W/SW	4	Qb/H		218,323
159	Sawatch fault	T.50N.,R.7E.- T.13S.,R.79W.	N	N-S/E	45	Qp/H	includes 8 distinct fault scarps	15,134,141,216,218, 251,272,273,323

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
160		T.12S.,R.80W.- T.11S.,R.80W.	N	N15W/NE	8	T/Qpb		273,277,280,282,323
161		T.12S.,R.79W.- T.10S.,R.80W.	N	N30W/SW	42	Td/Qpb	includes 7 faults	272,273,277,280,283
162		T.10S.,R.80W.- T.9S.,R.79W.	N	N-S/E	9	Td/Qpb	includes 4 faults	272,273,277,280
163		T.10S.,R.81W.- T.9S.,R.80W.	N	N40E/NW	19	Td/Qw	includes 2 faults	266,272,277,280,323
164		T.11S.,R.81W.- T.10S.,R.81W.	N	N5W/NE	24	Td/Qpb	includes 2 faults	277,280,323
165		T.10S.,R.81W.- T.8S.,R.80W.	N	N25E/SE	16	Qpb/Qb		266,277,280,323
166	Golden fault	T.5S.,R.69W.- T.2S.,R.70W.	R	N25W/NE	32	Qk/Qi(?)		31,129,168,212,213,272, 298,299,323
167	Valmont fault	T.1N.,R.69W.- T.1N.,R.70W.	N	N50E(?)/SE	?	Qi/H(?)		212,258,323
168	Rocky Mountain Arsenal fault	T.3S.,R.67W.- T.1S.,R.68W.	S-R	N30W(?)	16(?)	H	defined by earthquake epicenters	14,37,55,63,64,65,67, 87-97,153,155,206
169	Floyd Hill fault	T.6S.,R.69W.- T.3S.,R.72W.	N(?)	N40W/NE	41	Ts/Qw	movement may be largely left-lateral oblique slip	31,215,229,252,273
170	Kennedy Gulch fault	T.8S.,R.69W.- T.5S.,R.71W.	D	N40W	34	Ts/H		31,215
171		T.9N.,R.74W.- T.10W.,R.70W.	D	E-W/N	26	Ts/H		23,273
172	Fowler fault	T.22S.,R.59W.- T.21S.,R.60W.	N	N60W/SW	13	Qn/H		212,219,272,323
173	Cheraw fault	T.22S.,R.55W.- T.18S.,R.52W.	N	N45E/NW	48	Qn/H		212,227,272,323
174		T.12S.,R.76W.	N	N30W/SW	3	Td		59,219,272
175		T.13S.,R.73W.- T.14S.,R.72W.	N	N50W/NE	14	T/Q	includes 2 faults	219,251,272,324
176	Eleven Mile fault	T.13S.,R.73W.	N	N14W/NE	5	Qp/H		226
177	Chase Gulch fault-- East-Side fault	T.11S.,R.74W.- T.13S.,R.73W.	N	N35W/NE	29	Qp/H		31,219,226

Fault No.	Name	Location	Movement	Strike/dip	Length(km)	Age of Movement	Comments	Primary Sources
178	Chase Gulch fault-- West-Side fault	T.12S.,R.74W.	R	N20W/NE	1.5	Qp/H		226
179	Ridgway fault	T.45N.,R.10W.- T.45N.,R.8W.	N	N85E/SE	15	Q		248,272,279
180		Costilla County San Luis Hills	N	N50E/SE	25	Ti/H		271,273
181	LaSauses fault	Costilla County San Luis Hills	N	N5E/NW	32	Ti/H		271,273
182		T.38N.,R.10E.- T.45N.,R.8E.	N	N20W/SW	56	Q/H		271,272,273
183		T.37N.,R.12E.- T.40N.,R.11E	N	N20W/NE	35	Q/H		271,272,273
184		T.39N.,R12E.- T.46N.,R.9E	N	N20W/NE	71	Qw/H		104,134,271,272,273
185		Costilla County West of LaVeta Pass	N	N-S/W	14	T	includes 5 faults	271,273
186		T.3S.,R.80W.	N	N35E/NW	8	T/Qpb	includes 2 faults	271,273,280
187		T.1S.,R.81W.- T.2S.,R.81W.	N	-	7	T	includes 3 faults	271,273,280
188		T.1N.,R.78W. T.2N.,R.79W.	N	N60W/SW	14	T		270,271,273
189		T.1N.,R.79W.	N	N70W/SW	4	M+		270,271,273
190		T.10S,,R.72W.- T.9S.,R.74W.	N	N50W/SW	18	T		31,271,273
191		T.11S.,R.74W.- T.10S.,R.74W.	N	N20W/SW	11	T		31,271,273
192		T.13S.,R.71W- T.10S.,R.75W.	N	N55W/SW	39	T		31,219,271,273
193		T.15S.,R.71W.- T.13S.,R.70W.	N	N20E/NW	18	T		219,271,273
194	Jarre Creek fault	T.10S.,R.68W.- T.7S.,R.68W	D	N10W/NE	31	Ts		31,271,273

Appendix 3

List of the larger Earthquakes in or near Colorado from 1870 through 1979. (modified from Hadsell, 1968; Major and Simon, 1968; N.O.A.A., 1980)

Year	Date	Time (UTM)	Location	Latitude N.	Longitude W.	Max. M.M. Intensity*	Magnitude**	Focal Depth (km)
1870	Dec 4	12:00	Pueblo	38.5	104	VI		
1871	Nov 9	17:15	Georgetown	39.7	105.7	IV		
1880	Sep 17	06:00	Aspen	39.3	106.7	VI		
1882	Nov 8	01:30	Denver?	40?	105?	VII		
1882	Nov 10	a.m.	Gunnison	38.6	107.0	IV		
1882	Nov 23		Silverton	37.7	107.7	IV		
1886	July		Lake City	38.2	107.3	?		
1888	Oct 23	18:40		38.1	105.2	IV		
1889	Jan 15		Glenwood Spgs.	39.5	107.3	V		
1891	Dec		Axial Basin	40.5	108	VI		
1894	Jan 1	10:00	Telluride	37.9	107.8	IV		
1894	Aug 4	23:00	Georgetown	39.7	105.7	V		
1895	Mar 22		Steamboat Spgs.	40.5	107.1	V		
1901	Nov 15	10:00	Buena Vista	38.8	106.2	VII(VI)		
1910	Jul 26	01:30		41.5	109.3	V		
1913	Nov 11	21:55	Ouray	38.2	107.2	V		
1913	Nov 11	22:18	Ouray	38.2	107.2	V		
1913	Nov 11	23:45	Ouray	38.2	107.2	V		
1916	Oct 12	05:41	Boulder	40.0	105.0	III		
1928	Apr 20	09:40	Creede	37.8	107.0	V		
1928	Apr 24	10:00	Creede	37.8	107.0	V		
1928	Apr 29	10:00	Creede	37.8	107.0	V		
1928	Apr 30	15:50	Creede	37.8	107.0	V		
1928	Mar 1	09:22	Creede	37.8	107.0	V		
1928	Mar 3	19:40	Creede	37.8	107.0	V		
1928	Mar 4	10:00	Creede	37.8	107.0	V		
1928	Mar 10	10:10	Creede	37.8	107.0	V		
1928	Mar 29	07:17		38.1	102.1	V		
1930	Jul 28	09:35		41.5	109.3			
1941	Feb 13	11:32:30	Aspen?	38.9	106.8	IV		
1941	Feb 28	06:19:48		37.8	108.5			
1941	Aug 29		Durango	37.3	107.7	V		
1944	Sep 9	04:12:18	Mt. Gunnison	39.0	107.5	VI		
1952	Oct 7	09:20	Conejos Co.	37.0	106.0	V		
1954	Jan 20	20:50:01		41.5	105.5	V		
1954	Feb 21	20:20:46		40.0	109.0	IV		
1954	Feb 21	20:20:51		40.0	108.8	IV		
1955	Feb 10	17:30	Steamboat Spgs.	40.4	106.9	V		
1955	Aug 3	05:40	Lake City	38.0	107.3	VI		
1955	Nov 28	03:25	Rocky Ford	38.2	103.7	IV		
1956	Jan 14	18:43	Lamar	37.9	102.6	V		
1956	Jan 14	18:49	Lamar	37.9	102.6	V		
1958	Aug 7	00:46:43		41.1	106.0	IV		
1960	Oct 11	08:05:31	Montrose	38.3	107.6	VI	5.5 †	
1960	Oct 17	16:00	Aspen	39.2	106.9	V		
1961	Nov 27	00:55:46	South Park	39.0	106.1	IV		33
1962	Jan 13	13:33	Ridgway	38.4	107.8	IV	(4.4)	
1962	Feb 5	14:45:51	Cimarron	38.4	107.6	V	(4.7)	
1962	Jun 18	00:46	Derby	39.8	104.9	V	(3.1)	
1962	Dec 4	17:50:06	Derby	39.8	104.7	VI(V)	3.5+(3.2)	33
1962	Dec 5	13:48:00	Derby	39.9	104.6	V	4.0+(3.8)	33
1963	Jan 30	23:05:10	Derby	39.8	104.6	IV	(3.2)	33
1963	Apr 8	00:04:06	Derby	39.9	104.8	V	(3.4)	20

* Modified Mercalli Intensity - see Appendix 1; parentheses indicate intensity is from Hadsell (1968).
** Body wave magnitude except where designated by "+"; parentheses indicate magnitude is from Hadsell (1968) or Major and Simon (1968).
*** "E" indicates explosion.

Year	Date	Time (UTM)	Location	Latitude N.	Longitude W.	Max. M.M. Intensity*	Magnitude**	Focal (kr
1963	Apr 24	22:29:43	Derby	39.8	104.7	IV	4.1(3.8)	
1963	May 25	10:44:46	Derby	39.8	104.7	V(IV)	(3.5)	
1963	Jun 5	00:13:51		39.3	104.0		4.4(3.0)	
1963	Jun 6	08:05:36		36.5	104.3		3.8	
1963	Jul 2	08:02:56	Derby	39.8	104.6	V	4.6(4.0)	
1963	Jul 28	12:19	Derby	39.8	104.9	II	(3.1)	
1963	Aug 1	05:00:17		39.3	109.1		3.7	
1963	Nov 13	21:34	Pueblo	38.3	104.6	IV	(2.8)	
1964	Jan 5	13:57:21		41.0	109.5		3.9	
1964	Aug 4	11:13:25		39.7	106.0		4.0	
1965	Jan 5	23:26	Rocky Flats	39.9	105.3	III	(2)	
1965	Feb 16	20:17:54	Derby	39.9	105.1	IV	4.6(3.1)	
1965	Feb 16	22:21:44	Derby	39.9	105.0	VI(V)	4.9(3.0)	
1965	Mar 25	20:23:56	Derby	39.8	104.9	II	3.1(2.6)	
1965	Apr 16	17:24:48	Derby	39.8	104.9	V	3.4(2.7)	
1965	May 30	17:31:04		39.4	106.3		4.3	3
1965	Jun 14	09:24:44	Derby	39.8	104.9	IV	(3.0)	
1965	Jul 18	21:40:45	Derby	39.8	104.8	V(III)	4.6(3.1)	
1965	Jul 31	13:41:43	Derby	39.7	104.9	V	4.6	
1965	Sep 13	09:58:18	Derby	39.8	104.8	V	4.5(3.5)	
1965	Sep 14	16:36:47	Derby	39.8	104.8		4.7(2.8)	
1965	Sep 14	22:46:24	Derby	39.9	104.6	VI(V)	4.7(3.6)	
1965	Sep 14	23:16:10	Derby	39.5	104.9		4.8(3.0)	
1965	Sep 27	10:34:16	Derby	39.8	104.9	IV	(3.1)	
1965	Sep 29	18:59:57	Derby	39.8	105.1	VI	4.7(3.5)	
1965	Sep 29	19:20:41	Derby	39.8	104.8	V	4.6	
1965	Sep 29	23:22:58	Derby	39.8	104.8		4.6	
1965	Nov 21	03:59:59	Derby	39.8	104.8	IV	4.6(3.5)	
1965	Nov 21	04:02:29	Derby	39.8	104.8	VI(V)	4.5(3.8)	
1965	Nov 21	04:24:49	Derby	39.9	104.7		4.4	
1965	Nov 21	05:00:27	Derby	39.8	104.9	V	4.7(3.2)	
1966	Jan 2	00:13:42	Derby	39.9	104.8	III	2.1†	
1966	Jan 5	00:37:18	Derby	39.8	104.7	V	5.0(3.4)	
1966	Jan 23	01:56:39	Dulce	37.0	107.0	VII	5.5	1
1966	Jan 23	06:14:16	Dulce	36.9	107.2		4.2	
1966	Jan 23	11:01:07	Dulce	36.9	107.2		4.3	
1966	Jan 23	19:43:20	Dulce	36.9	107.1		4.5	
1966	Jan 23	23:48:08	Dulce	36.9	107.0	V	4.6	
1966	Jan 25	10:38:05	Dulce	36.8	107.1		4.0	
1966	Jan 27	07:48:29	Dulce	36.9	106.9	IV		
1966	Jan 27	09:29:01	Dulce	36.9	107.2	IV		
1966	Jan 31	15:43:52	Dulce	37.0	106.9	IV		
1966	Apr 3	16:21:34	South Park	39.36	106.46		4.7(3+)	E
1966	May 4	05:40:38	Dulce	36.8	107.1		4.1	
1966	May 8	17:23:38	Dulce	36.9	107.0		4.4(4.2)	
1966	May 8	17:50:37	Dulce	37.0	107.0		3.9	
1966	May 9	02:08:54	Dulce	36.9	107.0		4.2	
1966	May 9	02:57:24	Dulce	37.0	106.9		4.4	
1966	May 19	00:26:42	Dulce	36.9	107.0		4.6	
1966	Jun 2	21:59:12	Dulce	36.9	107.0		4.9	
1966	Jun 4	10:29:40	Dulce	36.9	107.0		4.0	
1966	Jun 21	05:24:38	Dulce	36.9	107.1		4.2	
1966	Jul 5	18:26:13	Rangely	40.2	109.0		3.7	
1966	Jul 5	20:02:41	Rangely	40.2	109.0		3.5	
1966	Jul 6	05:47:08	Rangely	40.1	108.9		4.1	
1966	Jul 24	02:48:50	Dulce	36.9	107.0		3.4	
1966	Sep 4	09:52:36		38.3	107.6		4.2	
1966	Sep 24	07:33:46		36.5	105.0		4.1	
1966	Sep 24	08:27:10		36.5	105.0		3.4	
1966	Sep 25	12:22:40		36.5	105.1		3.6	
1966	Oct 3	02:26:02	Trinidad	37.4	104.1	VI	4.5(4.6)	
1966	Oct 13	00:33	Castle Rock	39.3	104.6		(3.0)	
1966	Nov 1	07:40:28		40.2	106.9		4.0	

Year	Date	Time (UTM)	Location	Latitude N.	Longitude W.	Max. M.M. Intensity*	Magnitude**	Focal Depth (km)
1966	Nov 13	15:17:01	Derby	39.8	104.9	III	(3.1)	
1966	Nov 14	20:02:36	Derby	39.9	104.7	VI	4.1(3.5)	5
1966	Dec 16	02:00:44	Dulce	37.0	107.0		4.2	33
1966	Dec 19	20:52:33	Aspen	39.0	106.5	III	4.6(3.3)	5
1967	Jan 6	15:41:16	Dulce	36.93	106.97		4.3	33
1967	Jan 12	03:52:06		38.98	107.51		4.4	33
1967	Jan 16	09:22:46	Silverton	37.67	107.86		4.1	33
1967	Jan 18	06:12:01		40.05	107.05		3.8	33
1967	Feb 3	05:27:58	Derby	39.87	104.79	III	4.3(3.3)	11
1967	Feb 16	03:28:04	Rangely	40.10	109.07		4.5(4.4)	5
1967	Apr 4	22:53:40	Montrose	38.32	107.75		4.5(3.0)	33
1967	Apr 10	19:00:26	Derby	39.94	104.76	VI	4.9(5.0)	5
1967	Apr 10	19:35:53	Derby	39.9	104.8		(3.1)	
1967	Apr 10	19:36:38	Derby	39.89	104.77	III	4.4(3.5)	5
1967	Apr 10	20:11:23	Derby	39.86	104.91		(4.8)	
1967	Apr 10	23:58:41	Derby	39.92	104.79		4.3(3.0)	5
1967	Apr 27	17:24:42	Derby	39.91	104.77	VI	4.5(3.8)	5
1967	Apr 27	17:25	Derby	39.8	104.9		(3.3)	
1967	Jun 19	15:39:22	Derby	39.9	104.8	IV	2.9†	5
1967	Aug 9	13:25:15	Derby	39.8	104.9		(4.3)	
1967	Aug 9	13:25:06	Derby	39.9	104.7	VII	5.3	5
1967	Nov 15	07:10:12	Derby	39.9	104.6	V	3.7	5
1967	Nov 27	05:09:23	Derby	40.0	104.7	VI	5.2	5
1967	Nov 27	05:35:01	Derby	39.9	104.7		4.4	
1967	Dec 10	19:30:00	Project Gasbuggy	36.68	107.21		5.1	E
1968	Apr 21	07:08:07		37.8	102.1		3.8	33
1968	Jun 23	20:16:13		39.31	107.41		3.8	33
1968	Jul 15	18:33:12	Derby	39.9	104.8	V	3.4	33
1969	May 26	01:30:09		40.4	104.4	IV	4.2(3.5)	33
1969	Sep 10	21:00:00	Project Rulison	39.41	107.95		5.3	E
1970	Feb 3	05:59:36		37.92	108.31		4.0	33
1970	Apr 21	08:53:52	Rangely	40.1	108.9	V	4.3	4
1970	Apr 21	15:05:48	Rangely	40.09	108.90		4.6	5
1970	May 23	08:55:09		39.9	105.1	V	4.1(3.2)	5
1971	Jan 7	20:39:52		39.49	107.31	V	4.3	33
1971	Mar 18	09:09:00		40.71	106.97	V	4.4	10
1971	Aug 8	05:22:44	Derby	39.89	104.76	IV	4.4(3.8)	5
1971	Nov 12	09:30:45		38.91	108.68		4.0	5
1973	May 17	16:00:00	Project Rio Blanco	39.79	108.37		5.4	E
1973	Sep 23	03:58:55		37.1	104.57		4.2	5
1974	Mar 31	11:58:47		40.70	107.05	II	3.5	5
1975	Jan 30	14:48:40		39.27	108.65	V	4.4	5
1977	Sep 24	11:16:48		39.31	107.31		4.0	5
1978	May 29	16:45:18		39.28	107.32		3.0+	5
1978	Jun 10	20:57:54	Derby	39.79	104.87	IV	2.9	20
1978	Nov 30	18:50:16		40.47	107.61		2.8	5
1979	Jan 6	01:58:55	Divide	38.96	105.16	VI	2.9	5
1979	Jan 20	06:59:08		40.82	107.86		3.3	5
1979	Mar 19	14:59:30	Rangely	40.18	108.90	IV	3.3	2
1979	Mar 29	22:07:13	Rangely	40.27	108.81	V	2.6	2

Colorado Geological Survey
Department of Natural Resources
John W. Rold, Director

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Potentially Active Faults, Neogene Igneous Rocks, and Thermal Springs of Colorado

by
Robert M. Kirkham and William P. Rogers

Colorado Geological Survey
Department of Natural Resources
John W. Rold, Director

Bulletin 43
Plate 2
1981

Potentially Active Faults, Microearthquake Locations, and Local Geology of a Part of the Upper Arkansas River Valley, Colorado

by
Robert M. Kirkham and William P. Rogers

EXPLANATION

Qf, Qls, Qa	Holocene	Holocene	Quaternary	Cenozoic
Qf, Qls, Qpo (Qpoy, Qpoo), Qpt	Pinedale Glaciation	Pleistocene	Quaternary	Cenozoic
Qf, Qls, Qboy, Qbty, Qboo, Qbto	Bull Lake Glaciation	Pleistocene	Quaternary	Cenozoic
Qls, Qi, Qpbt	Illinoian Glaciation	Pleistocene	Quaternary	Cenozoic
Qls, Qk, Qpbt	Kansan Glaciation	Pleistocene	Quaternary	Cenozoic
Qls, Qn, Qpbt	Nebraskan Glaciation	Pleistocene	Quaternary	Cenozoic
Td	Miocene and Pliocene		Tertiary	Cenozoic
Ti	Eocene or Oligocene		Tertiary	Cenozoic
p€				Precambrian

Qa Holocene stream alluvium
Qf Holocene to Pleistocene fan alluvium
Qls Holocene to Pleistocene landslide deposits
Qpo Pinedale outwash, undifferentiated
Qpt Pinedale till, undifferentiated
Qpoy late Pinedale outwash
Qpoo early Pinedale outwash
Qboy late Bull Lake outwash
Qboo early Bull Lake outwash
Qbty late Bull Lake till
Qbto early Bull Lake till
Qpbt pre-Bull Lake till
Qi Illinoian alluvium
Qk Kansan alluvium
Qn Nebraskan alluvium
Td Miocene and Pliocene Dry Union Formation
Ti Eocene or Oligocene Mount Princeton Quartz Monzonite
p€ Precambrian metamorphic and igneous rocks

2.8m Potentially Active Fault--displaces rocks of Miocene or younger age; dashed where approximately located; dotted where concealed; ball on downthrown side; height of fault scarp in meters indicated by number.

? Lineament of possible tectonic origin (numerous additional photolineaments are shown by Scott, Van Alstine, and Sharp, 1975).

X③ Epicentral location of microearthquake.
Subscript indicates source of information:

1. a ten-day microearthquake survey conducted by AMAX Exploration, Inc. during March, 1974 (courtesy of Arthur Lange, AMAX Exploration, Inc).
2. a ten-day ground noise survey conducted by AMAX Exploration, Inc. during March, 1974 (courtesy of Arthur Lange, AMAX Exploration, Inc.).
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Drafted by Cheryl Brchan

INDEX MAP

SCALE 1:62 500
½ 0 1 2 3 4 MILES
1 .5 0 1 2 3 4 KILOMETERS
CONTOUR INTERVAL 80 FEET
DATUM IS MEAN SEA LEVEL

R6E R7E | R7E R8E | R8E R9E | 106°00'W | 106°15'W

Base from U.S.G.S.

Colorado Geological Survey
Department of Natural Resources
John W. Rold, Director

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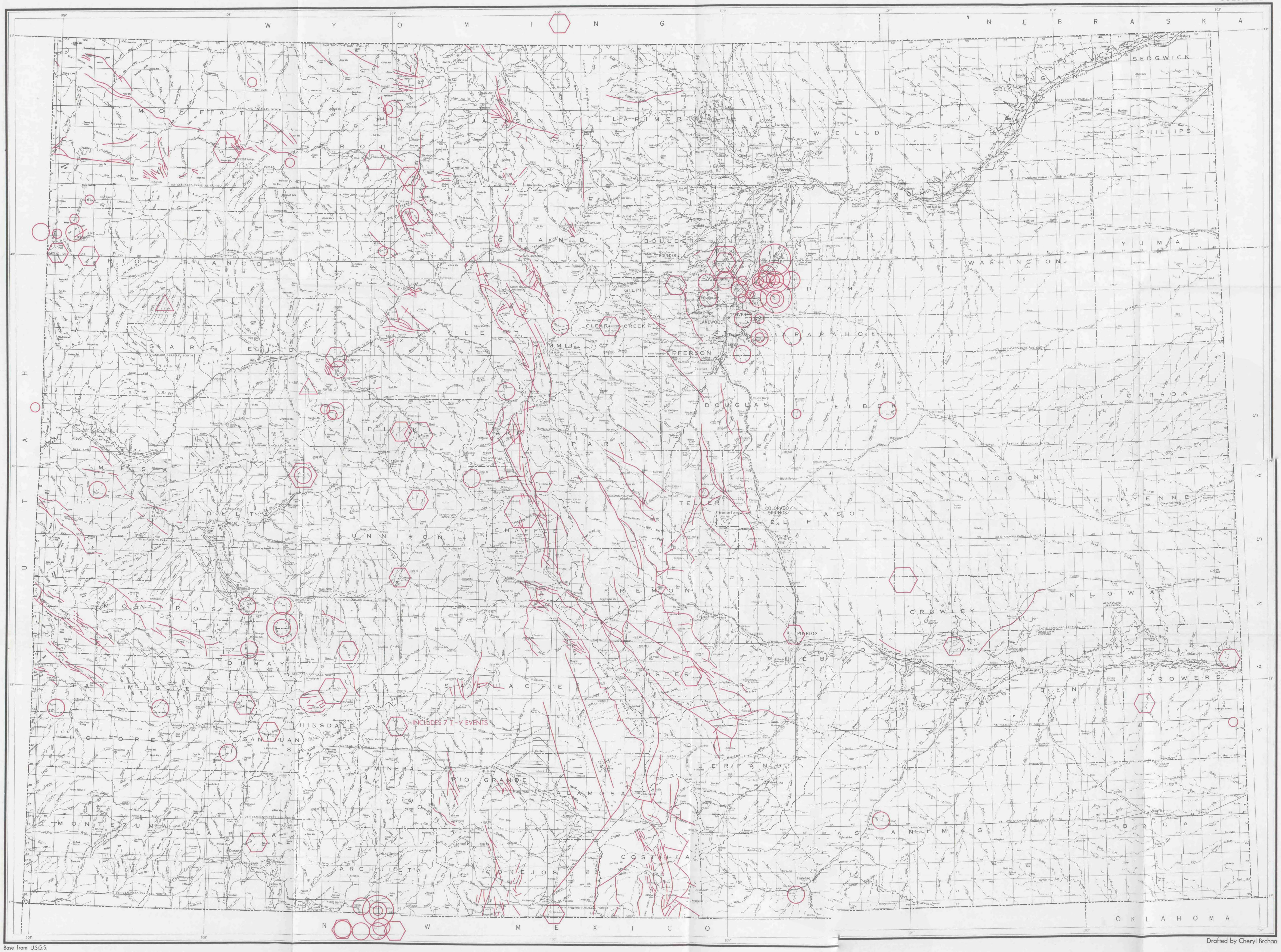
Plate 3
1981

Earthquakes from 1870 through 1979 and Potentially Active Faults in Colorado

by
Robert M. Kirkham and William P. Rogers



Base from U.S.G.S.

Drafted by Cheryl Brchan

EXPLANATION

- Epicentral location of an earthquake of magnitude 2.5 to 3.9; only selected earthquakes of this magnitude range are plotted near the Rocky Mountain Arsenal
- Epicentral location of an earthquake of magnitude 4.0 to 4.9
- Epicentral location of an earthquake of magnitude 5.0 to 5.9
- Location and intensity of a felt earthquake of Modified Mercalli Intensity III to V; only selected earthquakes of intensity III are plotted
- Location and intensity of a felt earthquake of Modified Mercalli Intensity VI
- Location and intensity of a felt earthquake of Modified Mercalli Intensity VII
- Nuclear explosions detonated as part of the Plowshare Program; magnitude 5.0 to 5.5
- Potentially active fault (from Plate 1)

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SCALE 1:1,000,000

25 0 25 50 MILES

25 0 25 50 KILOMETERS