Special Publication 19

COLORADO TECTONICS, SEISMICITY AND EARTHQUAKE HAZARDS:

Proceedings and Field Trip Guide of a Symposium Held in Denver, Colorado, June 4-6, 1981

EDITED BY W. RAHE JUNGE

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO / 1981

Cover: Seismotectonic provinces in Colorado proposed by Mr. R. M. Kirkham and Mr. W. P. Rogers in Colorado Geological Survey Bulletin 43. Explanation of map symbols:

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**

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sponsored by
Association of Engineering Geologists, Denver Section

edited by
W. Rahe Junge

Colorado Geological Survey
Department of Natural Resources
State of Colorado
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FOREWORD

As Colorado's population and attendant construction activities increase, the potential for damage caused by earthquakes increases. This earthquake risk probably has been underestimated in the past but must be carefully considered in the future to help minimize potential damage and, perhaps, loss of life. The Association of Engineering Geologists, Denver Section on June 4-6, 1981 conducted a symposium that addressed such a risk. The symposium discussed Colorado's tectonics, seismicity, and earthquake hazards and, thus, better defined Colorado's earthquake potential. This symposium offered the unique opportunity to learn of recent developments in the field of earthquake assessment, to discuss recent studies in Colorado, and to exchange ideas on Colorado's tectonics and seismicity. The Association of Engineering Geologists, Denver Section must be commended on conducting an excellent symposium on a timely and critical topic.

Persons involved in the organization of the symposium were Mike West and Gerald Burk (Program), Bob Kirkham (Field Trip), Bill Smith (Registration), Jerry Dodd (Meeting Arrangements), Ed Church (Refreshments), Ralph Mock (Treasurer), and Rahe Junge (Publications). Special recognition must go to Mike West for initiating the symposium and preparing the basic program. Additionally, Bob Kirkham prepared the field trip guide and conducted an excellent field trip. Finally, a special thanks to all of the speakers whose papers are included in this document.

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VARIATIONS OF EARTHQUAKE GROUND MOTIONS OVER SHORT DISTANCES

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ABSTRACT

It has long been a problem in seismology to predict variability of earthquake intensity over short distances, particularly in the near field of an earthquake source. One approach has been to micro-zone a region using microtremor seismograms obtained using ambient microseisms or signals from distant, underground explosions or natural earthquakes. The significance of the results has been questioned because of the problem of scaling from small ground motion amplitudes to the large amplitudes associated with ground shaking in major earthquakes.

An alternative procedure is to use arrays of strong-motion accelerograms near to the earthquake source and to correlate the ground motions between the elements. Such methods require common time base on all seismograms. Recently, some progress has been made with observations from arrays of strong-motion instruments. Two cases are discussed from California. First, the Coyote Lake earthquake of 1979 and, second, the Imperial Valley earthquake of 1980. Examples are given of the variability of ground acceleration, velocity, and displacement near to the rupturing faults and explanations are given in terms of source mechanism, directivity focussing, and local geological conditions.

For engineering design purposes, allowance should be made for the coherency of strong ground motion over distances equal to the dimensions of large structures (the "tau effect"). The application to the whole foundation of in-phase ground motion obtained from a single instrument is unrealistic, but little observational material on spacial phasing has been available. The gap is now being filled by observations from specially designed small arrays of strong-motion instruments being located in highly seismic areas around the world. The first of these special arrays to record earthquakes is SMART 1, located in the northeast corner of Taiwan. The configuration of the array is three rings of radii 250 meters, 1 km, and 2 km, respectively. Several earthquakes have been recorded in the first six months of operation. The earthquake of January 19, 1981 (local magnitude 6.9), was centered 30 km from the array. Fourier spectra from array elements and correlation diagrams in wave-number space indicate significant variability over distances of a few hundred meters and show the history of the seismic waves as the dislocation moves along the causative fault.

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ACTIVE FAULT ASSESSMENT OF EARTHQUAKE POTENTIAL OF FAULTS

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During the last decade there have been major advances in knowledge and methodology for evaluating active faults and predicting the nature of future activity. These studies are of direct value to siting and design of vital engineering structures, and to microzonation of areas for planning purposes.

Current practice involves the detection, delineation and determination of the character of active or capable faults. Empirical methods have been developed for correlating the size or magnitude of past surface faulting events, by use of fault rupture length, maximum displacement, and fault slip or displacement rates. These studies involve combinations of methods of evaluation, including geologic, stratigraphic, soil stratigraphic, geomorphic, and geophysical and seismological methods.

Examples of the application of some of these methods are given to illustrate some of the more recent investigations.

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ESTIMATION OF MAXIMUM EARTHQUAKE CAPABILITY FOR SOME CALIFORNIA FAULTS - A GEOLOGICAL APPROACH

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Efforts to appraise the earthquake-generating capability of California's faults have burgeoned spectacularly during the past two decades. Prompted in part by a deepened interest in improving estimates of seismic risk, these efforts have been focused mainly on assessments of late Quaternary activity along specific faults, and on characterizations of fault behavior and associated earthquake events. Long-term objectives include better understanding of regional tectonics and earthquake-generating mechanisms, reduction of seismic hazards, and capability for earthquake prediction.

The historic record of seismicity, though limited in California to little more than two centuries, is nonetheless a useful base for guarded extrapolations into the future. It also has provided valuable calibration points in recent detailed investigations of prehistoric late Quaternary activity along several major faults. As the record is thereby extended farther back through recent geologic time, it aids in the sharpening of empirical correlations that involve various earthquake parameters and factors such as fault length and style, rupture length and surface displacement for a given event, average slip rate, and average recurrence interval for slip events over a given period of time. Controlled sharpening is highly desirable, given the generous spreads of data points in most empirical plots; all too often these plots can only yield, for purposes of land-use planning and engineering design, projections that either are uncertain or may be extermely conservative.

The interplay of major movements along California faults also can be considered in terms of strain accumulation and relief in the framework of regional tectonics. Assuming broadly consistent motions of the pertinent crustal plates since mid-Pliocene time, the right-lateral San Andreas fault can be regarded as a first-order expression of plate-boundary activities, and the Hayward, Calaveras, San Gregorio, San Jacinto, and other major branches as important second-order features. Faults such as the Rinconada, Elsinore, and Newport-Inglewood, also with north-westerly San Andreas trend and histories of right slip but in positions more distant from the plate boundary, appear to be features of lesser order, even though most of them are capable of generating significant earthquakes.

The San Andreas stress-strain system is complicated in southern California by structural elements of the Transverse Ranges province, which at present is characterized by an east-west grain and numerous expressions of north-south crustal shortening. The Big Pine, Santa Ynez, Santa Susana-San Fernando-Sierra Madre, Banning, and other major faults in this province are thrusts with various contributions of lateral slip, chiefly left-hand. Relative to the San Andreas fault, some of them appear to qualify as stong second-order features and others as active or potentially active breaks of lesser implied capability.

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The Garlock fault, with a movement history dominated by left slip, is a near-vertical boundary between regions of quite unlike structure east of the San Andreas fault. South of the Garlock, which could be reckoned as a first-order feature, are lesser faults with San Andreas trend and movement sense, as well as oblique-slip faults in the easternmost part of the Transverse Ranges province farther south. North of the Garlock are northerly trending normal faults, some of them with significant components of strike slip, that reflect present east-west crustal extension and thinning in the southern Great Basin region. Chief among these is the Sierra Nevada, a first-order intraplate feature. Major faults to the east, including the Panamint and Death Valley, might be considered as strong second-order elements of the region.

The style of strain relief along California faults ranges from essentially aseismic creep to high-energy slip events that are widely spaced in time. It evidently can differ markedly from one region to another, from one fault or fault type to another, and even from one reach to another along the same fault. The differences in style may well reflect various combinations of large-scale fault geometry and lithologic contrasts among the crustal materials traversed by the faults, with the added influence of conflicting stress regimes in some regions. The differences are not yet well understood, but at least they can be estimated or reasonably inferred from the results of recent geologic studies that have ranged in scope from regional to site-specific.

During Quaternary time, the span of greatest interest for characterizing fault behavior in the context of engineering applications, most of the motion between the Pacific and North American crustal plates evidently has been accommodated by slip along the San Andreas fault and its principle branches. These breaks of the San Andreas system are prime candidates for future large earthquakes at relatively short intervals of 300 years or less, with the greatest events to be anticipated along "locked" reaches of the main fault zone in the Big Bend region north of Los Angeles and in the region extending north-northwestward from Monterey Bay. Such events could well be in the range M 8.0 to a maximum expectable of M 8.3, with M 8.5 for the maximum credible earthquake. A corresponding range of M 6.7 - M 7.0 (ME), M 7.5 (MC) seems appropriate for other reaches of the San Andreas, with average recurrence intervals of 200 years or less for the main fault and principal branches considered together at a given latitude. A lower range of M 6.5 - M 6.8 (ME), M 7.3 (MC) is tentatively assigned to the Rinconada and other Coast Ranges faults southwest of the San Andreas, and a range of M 6.5 - M 6.8 (ME), M 7.0 (MC) to the Newport-Inglewood and Elsinore faults in similar positions farther southeast. Average recurrence intervals could be 500 years or less.

On the basis of tectonic setting and the recent geologic record, a range of M 8.0 - M 8.3 (ME), M 8.5 (MC) can be assigned to the Sierra Nevada fault, but with an average recurrence interval for great events probably 500 years or more. A lower range of M 6.7 - M 7.0 (ME), M 7.5 (MC) is suggested for major intraplate faults in the region immediately to the east, with a similar or greater average recurrence interval. The Garlock fault, even with no record of historic rupture, should be regarded as a highly capable generator of large earthquakes. The range M 7.0 - M 7.5 (ME), M 7.8 (MC) is suggested for its easterly reach, with an average recurrence interval greater than 500 years; a higher range, perhaps M 7.8 - M 8.3 (ME), M 8.5 (MC) would not be inconsistent with data now available for its westerly reach, terminating in the Big Bend region of the San Andreas fault. Considerable lower values of M 6.5 - M 7.0

(ME), M 7.5 (MC) can be assigned to faults with San Andreas trend in the Mojave region south of the Garlock; average recurrence intervals could well be 500 years or more.

The Malibu Coast, Santa Susana, Sierra Madre, and other active faults along and near the southerly margin of the Transverse Ranges province evidently generate earthquakes that are widely spaced in time, with estimated average recurrence intervals of 500 to 2000 years or more. For the relatively large events, a range of M 6.5 - M 6.8 (ME), M 7.0 (MC) appears to be indicated. In contrast, distinctly higher ranges of magnitude and, in some instances, markedly shorter recurrence intervals are implied for major faults in the northwesterly part of the Transverse Ranges province and in the Big Bend region north of the San Andreas and Garlock faults. Estimated ranges for large earthquakes are M 6.8 - M 7.3 (ME), M 7.5 (MC) on the Santa Ynez fault, M 7.0 - M 7.5 (ME), M 7.7 (MC) on the Big Pine fault, and M 7.5 - M 7.7 (ME), M 8.0 (MC) on the White Wolf fault.

In summary, maximum earthquake-generating capability along California faults appears to be concentrated in (1) a narrow belt extending along the easterly base of the southern Sierra Nevada (Sierra Nevada fault); (2) a coastal belt extending north-northwestward from Montery Bay (San Andreas fault system); and (3) two interior belts that form a great X centered in the Big Bend region of the San Andreas fault (San Andreas falt system and Garlock-White Wolf-Big Pine-Santa Ynez systems). Other parts of the state include domains where strong earthquake activity is known or can be expected, but in general at lower levels of energy release.

HAZARD ESTIMATES FROM SEISMICITY PATTERNS: GAPS AND QUIESCENCE

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Seismic hazard estimates are often based on statistical analysis of small to medium magnitude seismicity. Extrapolating the known frequency magnitude relation, it is estimated what the recurrence time of a large earthquake may be. Two assumptions on which this method is based are that the seismicity rate is constant as a function of time, and that the cumulative number of earthquakes between successive main-shocks (at the same location) is constant in all tectonic areas that have the same b-value. Recent analysis of seismicity patterns have shown that these assumptions may not be valid in many parts of the world. In some areas observations of seismicity quiescence and seismic gaps may lead to useful seismic hazard assessments.

Seismic gaps are defined as segments of plate boundaries which have not ruptured recently by large earthquakes, while the neighboring segments have ruptured. McCann et al. (1979) have identified the seismic gaps of the Circum-Pacific, and they have classified these gaps according to their present potential for a large earthquake. The seismic gap concept works best along plate boundaries of simple tectonic structure. In areas where the recurrence time can be estimated approximately, the seismic gap technique can lead to a more refined estimate of seismic hazard than the estimate based on the frequency magnitude relation alone.

Seismic quiescence is defined as a substantial decrease in seismicity rate (about 50%) in a given area. This phenomenon was observed to have lasted for several years before several main-shocks (e.g.; Habermann, 1981a; Wyss et al., 1981), and it was shown to have been unique and highly significant in space and time (Habermann, 1981b). However, some false alarms (quiescence terminated without being followed by a main-shock) were also discovered (Habermann, 1981b). Since quiescence can last for more than a decade, and since 80% seismicity rate reductions can occur, it follows that the frequency-magnitude method of estimating seismic hazard may produce misleading results. On the other hand the identification of quiescence within a seismic gap can lead to the prediction of large earthquakes as in the case of the 1978 Oaxaca event (Ohtake et al., 1977).

The Hellenic island arc may serve as an example of the combined use of the gap and quiescence techniques to assess the seismic hazard. From historic felt reports the segments of the island arc which ruptured were identified approximately (Wyss and Baer, 1981a, b). It was found that most of the Hellenic arc must be considered to be a seismic gap of high earthquake potential. In addition a decrease of seismicity ($M \geqq 5.0$) of 80% has existed for more than 15 years in the western part of the Hellenic arc. We conclude that in this part of the arc a large earthquake must be expected within the lifetime of any new structure in Crete. In contrast, based on the magnitude-frequency relation of earthquakes since 1960 one would not expect the seismic hazard to be high in this area.

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References

Habermann, R.E., 1981a, The quantitative recognition and evaluation of seismic quiescence: Application to earthquake prediction and subduction zone tectonics: Univ. of Colorado Ph.D. thesis, Boulder.

______1981b, Seismicity rates in the central Aleutians: A quantitative study of precursors to moderate earthquakes: submitted, J. Geophys. Res.

McCann, W., Nishenko, S., Sykes, L. R., and Krause, J., 1979, Seismic gaps and plate tectonics. Seismic potential for major boundaries: Pure and Appl. Geophys., v. 117, p. 1082-1147.

Ohtake, M., Matumoto, T., and Latham, G. V., 1977, Seismicity gap near Oaxaca, southern Mexico as a probable presursor to a large earthquake: Pure Appl. Geophys., v. 115, p. 375.

Wyss, M., Johnston, A. C., and Klein, F. W., 1981, Multiple asperity model for earthquake prediction, Nature: v. 289, p. 231-234.

Wyss, M. and Baer, M., 1981a, Seismic quiescence in the western Hellenic arc suggests large earthquakes are imminent: Nature, v. 289, p. 785-787.

______1981b, Earthquake hazard in the Hellenic arc: Ewing Series AGU, Earthquake Prediction, May.

SOME GEOLOGIC DATA USED IN SEISMIC HAZARD EVALUATION IN THE GREAT BASIN

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A major element in the current goal of revising the national probabilistic ground motion map produced in 1976 by Algermissen and Perkins is improved definition of the seismic source zones used in the calculations for the map. This paper describes some of the information used in developing a seismotectonic framework for the delineation of source zones in the Great Basin region of the western United States and their extension to defining zones in much of the western United States.

We have used regional mapping of late-Quaternary surface faulting to characterize large seismic source regions that are distinctive on the basis of predominant ages of most recent movements on the faults within the region and the frequency of movement in late-Quaternary time. Development of a general geomorphic dating method to provide approximate ages for fault scarps has provided a means of assigning ages to most fault scarps rather than only at isolated sites where radiometric ages may be available.

We have focused our detailed mapping on western Utah, systematically scanning 1:60,000-scale aerial photos for all possible fault-related offsets of geomorphic surfaces developed on surficial materials. Features were then studied in the field to eliminate those not resulting from surface faulting. Those confirmed as fault scarps and suitable for quantitative geomorphology were studied by profiling according to the procedures described in Bucknam and Anderson (1979).

The measurements of the scarp have provided data both on the ages of the scarps and on the surface displacement at the scarp. An important assumption in our study is that fault scarps provide a useful estimate of the number of earthquakes of a given magnitude range that have occurred in a given span of time. Combined with surface displacement data from historic earthquakes, our studies indicate that within the Great Basin the fault scarps that we have mapped represent a nearly complete record of earthquakes in the magnitude range 7-7 1/2 that have occurred there during Holocene time. To the extent that the record is incomplete, rates of seismicity determined from Holocene fault scarp data would be expected to underestimate the frequency of large earthquakes.

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APPLICATION OF GEOMORPHIC AND SOIL-STRATIGRAPHIC TECHNIQUES TO ASSESS SEISMIC HAZARDS

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An important aspect of seismic hazard assessment relates to possible future fault displacement at or near a "critical" facility (e.g., nuclear plant, large dam, liquified natural gas terminal). Such a hazard is often assessed by reconstructing the late Quaternary history of the site, particularly to determine the timing and amount of tectonic offset. This assessment, however, is often difficult, owing to the usual death of unequivocal radiometric dates. However, as exemplified by recent geotechnical studies in California, geomorphic and soil-stratigraphic (pedological) techniques can be well employed to reconstruct fault history, especially by determining the approximate age of geomorphic surfaces, underlying sediments, and related relict and buried paleosols.

The age of the alluvial, nested fan deposits in a 10,000 sq km area of the Mojave Desert was ascertained as part of geotechnical investigations for proposed nuclear power plants (Vidal and Sundesert). Local absolute and relative dating "calibration" was provided by U-series assay of bone and calcrete, paleomagnetic stratigraphy, and association of episodic landscape stability (soil formation) with regional climatic change as recorded by the marine isotope stage chronology. Holocene deposits are typified by undeveloped (A-C) profiles, active channels, and lack of desert pavement. Latest Pleistocene fans (<u>ca</u>. 20,000 yrs.) are usually undissected and characterized by incipient desert pavement and varnish (patina), and local bar and channel topography. Surface soils are slightly-developed, often with cambic or weak argillic horizons and stage I and II multiple carbonate horizons (Bca, Cca). Late Pleistocene fluvial terraces and fans (<u>ca</u>. 125,000 yrs.) have well-preserved divides; desert pavement and varnish are moderate, particularly if clasts are derived from metamorphic and volcanic terrane; and soil profiles are moderately- to strongly developed with vesicular (Av), calcareous argillic (Btca), and multiple caclic (Cca) horizons. Middle Pleistocene deposits (<u>ca</u>. 720,000 yrs.) may have only narrow divides, strong desert pavement, and bear relict paleosols (Paleargids), the latter locally giving rise to laminar calcrete (K) horizons.

Last displacement and recurrent movement of faults near proposed nuclear plants (San Onofre) and a liquified natural gas facility (Pt. Conception) on the southern California coast were likewise assessed by geomorphic and soil-stratigraphic techniques. Local age calibration is provided by U-series and amino-acid dating of fossil bone and corral, by faunal association, and by association to the marine isotope stage chronology. Marine platforms, both offshore and onshore, were cut mainly during glacio-eustatically rising sea levels (isotope stages 3, 5a, 5e, 7, 9, etc.). Gravel-filled channels underlying modern coastal streams, some 30 m below sea level at the present shoreline, graded to a stage 2 lowstand, about 15,000 to 20,000 years ago. Continental mudflow and debris-flow deposits overlying stage 5a (<u>ca</u>. 40,000 yrs.) or 5e (<u>ca</u>. 125,000 yrs.) platforms contain intercalated, moderately-developed buried paleosols (Haplic Natrixeralfs). These paleosols,

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from sedimentation rates and bracketing radiocarbon dates, form in about 3,000 to 6,000 years, an order of magnitude faster than comparably-developed soils in central California or in the Mojave Desert. The buried soils are laterally-traceable in sea cliffs and in coastal arroyos; and are therefore useful stratigraphic markers to assess the amount and timing of tectonic displacement in late Quaternary time.

METHODOLOGIES FOR EARTHQUAKE HAZARD EVALUATION IN COLORADO

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The probabilistic analysis of seismic ground motion hazard is generally made using the total probability theorem: The annual probability of exceeding a specified level of ground motion at a site is calculated as that probability for an earthquake with specific source parameters at a given location, times the probability of that event at that location, integrated over all possible source parameters and locations. When only historical seismicity data are available, it has been shown through comparisons using the very long Chinese earthquake history that a short historical record provides generally accurate estimates of seismic hazard. When additional data are available, such as on recurrence intervals for faults of specific tectonic character, these data can be incorporated through more sophisticated probability techniques. Among these are renewal process models and models with both temporal and spatial memory (e.g., the semi-Markov model). The use of such methods generally requires the identification of seismotectonic zones, where the tectonic regime causing the occurrence of earthquakes is understood.

In areas such as Colorado where the causes of earthquakes are not well understood, seismogenic zones must be used to delineate seismic hazard. These are zones within which earthquakes are assumed to be homogeneous in their size and location distributions. Such zones have been delineated in Colorado for regional studies, but no detailed investigation of seismogenic zones in the state has been accomplished. Nevertheless, large earthquakes have occurred in Colorado: recent evidence indicates that the November 7, 1882 event was approximately magnitude (M_L) 6-1/2.

In areas where no or few empirical strong motion records are available, the quantitative estimation of ground motion amplitudes is controversial. Theoretical methods are always uncertain until verified with empirical data; combinations of regional specific intensity data with ground motion-intensity correlations from California (or other seismic areas) have inherent physical drawbacks; and extrapolation of low-level motion studies to strong ground motion amplitudes involves considerable uncertainty. The best hazard analyses use and compare several methods of ground motion estimation, and draw conclusions based on the perceived applicability of each method.

A preliminary estimate of average seismic hazard can be made using the western two-thirds of Colorado (the portion comprising the Rocky Mountains) as a single seismogenic zone, with a maximum possible earthquake size of M_L = 6-1/2. Application of basic seismic hazard methods using this zone and historical seismicity indicates a return period of about 500 years for Modified Mercalli (MMI) VI, and about 2,000 years for MMI VII, at any specific site located in the Colorado mountain area. These are average return periods; under a more specific set of seismogenic or seismotectonic zones, a given site might have longer or shorter return periods for these values of MMI than those indicated.

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GEOMETRIC MODELS OF SIMPLE AND COMPLEX FAULT SCARPS

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Geometry of surface fault scarps depends on deformation style in the near-surface environment. Such deformation creates fault scarps whose height often differs from vertical fault displacement on the underlying fault. As the scarp broadens with time, scarp height usually increases over its original value. Thus at any given time, fault scarp height may bear no relation to original fault displacement. Where fault displacements are inferred from scarp heights, as in earthquake hazard studies, an understanding of scarp geometry is critical. Models presented herein quantitatively relate fault displacement to geometric parameters of simple and complex fault scarps.

A simple fault scarp is created by a simple translational offset along a single fault plane. As the scarp declines, scarp height increases, but surface offset remains constant. Equations relating to two scarp size parameters (scarp height, h2; surface offset, so) to the two fault parameters (vertical displacement, hl; net dip slip, ns) are:

$$\text{(1)}\quad so = hl(1 - \cot\beta \tan\alpha)$$

$$\text{(2)}\quad h2 = hl\left\{\frac{\sin\Theta \sin(\beta-\alpha)}{\sin\beta \sin(\Theta-\alpha)}\right\}$$

$$\text{(3)}\quad ns = \frac{hl}{\sin\beta}$$

where: α = fan surface slope
β = fault dip
Θ = maximum scarp slope angle

Steepening of fault dip near the surface can result in formation of open fissures. Collapse of the upthrown or downthrown block into such fissure leads to three complications characteristic of complex fault scarps: (1) downthrown surface rotation toward the fault, (2) graben formation, and (3) failure of the upthrown block by step-faulting. In (1) and (2), height of the resulting scarp exaggerates displacement on the underlying fault. Exact amount of exaggeration depends on width of the affected zone, size of the rotation angle, displacement on antithetic faults, and fan surface slope. For step-faults (3), cumulative scarp heights exceed fault displacement if rotation toward the fault occurs, but falls short of displacement if rotation is away from the fault.

Sedimentation below the scarp and/or erosion above the scarp can also cause underestimates of fault displacement. Magnitude of both effects increases with scarp age. The vertical component of material eroded or deposited, if known, can be added to apparent displacement to approximate true displacement.

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MICROEARTHQUAKE SURVEYS: USES AND ABUSES

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When a client requests a microearthquake survey several questions should be asked: Is a location or a detection network indicated? Is a quick and dirty answer sought or does the client require a deterministic answer for facility design? The number of clients who have satisfactory answers to these philosophical questions is small.

Once the objectives of a survey are clear and the expected results can be estimated from a recurrence curve, a detection threshold curve, and the assumption of stationarity of the earthquake sequence. Each assumption is subject to challenge and must have an engineering evaluation.

Detection threshold curves (subject to several significant assumptions) are reproduced as Figure 1. The following assumptions are used in the construction of these curves:

1. The curves are based on observations in southern California, a high-attenuation area.

2. A 2mm trace deflection can be detected despite the ambient noise level.

3. Frequency response extends to 20 Hz.

Once a crew is fielded, there are several pitfalls that can be avoided. Detection networks peaked in the wrong frequency band, seismometers not emplaced properly, lack of time information, one instrument networks, and networks which do not control for manmade artifacts are mistakes often made.

Pitfalls commonly encountered in the operation of location networks are all of the above plus an optimistic view of the accuracy and precision of the network and an inadequte number of stations. The accuracy of the locations is dependent on the correspondence of the mathematical velocity model and the actual physical geology. The precision of the hypocenter locations can be quantitatively estimated by uncertainty analysis.

Popular computer programs, including the HYPO series, often flunk both accuracy and precision tests for microearthquake location problems. Interpretation and geologic insight are more important in the location of local events than raw computer power.

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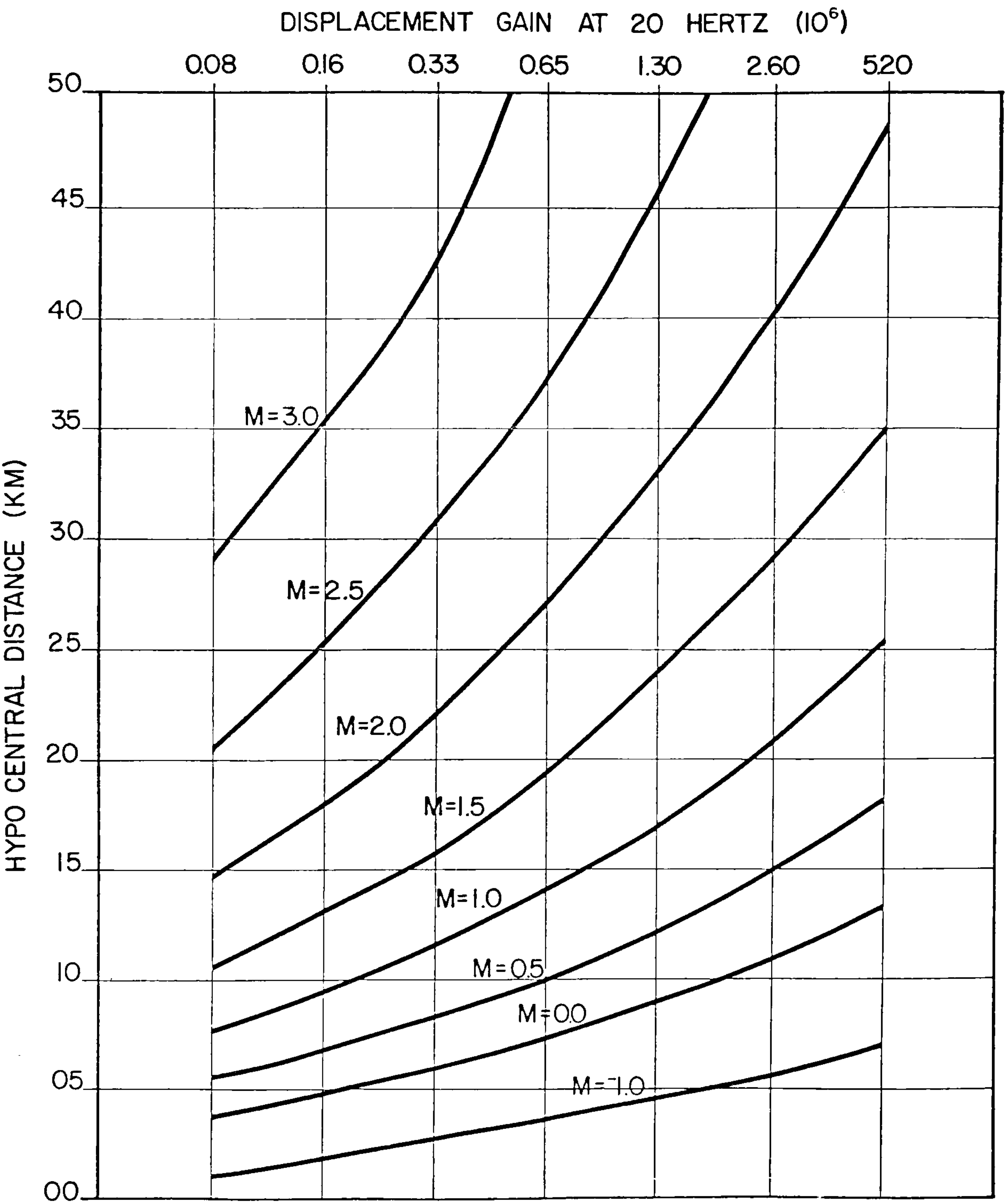

Figure 1: Detection Threshold Curves: Based on Richter with corrections for near field in Southern California by Brune and Allen, these curves denote the conditions of gain, magnitude and distance, for a 2mm pen displacement.

PUBLIC INFORMATION ASPECTS OF EARTHQUAKE HAZARDS

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The USGS NEIS in Golden, Colorado is the center for disseminating rapid preliminary hazard information on damaging or significant earthquakes both world-wide and in the United States on a 24-hour basis. This is accomplished through a system known as the Earthquake Early Reporting Service.

The Early Reporting Service determines earthquake epicenters and magnitudes rapidly and accurately for release to disaster emergency services, scientific groups, groups planning aftershock studies, other government agencies, and to public information channels.

The service is activated by the sounding of an alarm triggered by the recording of ground motion at four seismograph stations in the western United States which are telemetered to the NEIS in Golden, Colorado. The service can also be activated by visual observation of an incoming seismic signal or by a telephone or felt damage report. The service also collaborates with the Pacific and Alaska Tsunami Warning Service.

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AN OVERVIEW OF THE TECTONIC HISTORY OF COLORADO, WITH EMPHASIS ON THE CENOZOIC

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The basic structural framework of Colorado was created in the Precambrian during several periods of regional folding, batholithic intrusion, and extensive faulting. Four general fault trends were established: 1) a dominant north-northwest trend along which much of the Phanerozoic tectonism was later concentrated, 2) a northeast trend consisting of wide crushed and sheared zones, possibly associated with major strike-slip movement, 3) a west-northwest trend in the southern part of the State, and 4) an east trend of apparent limited extent in north-central Colorado.

Tectonic activity in the early and middle Paleozoic was limited to repeated epeirogeny, local minor fault movement, and igneous intrusion in the Cambrian and Devonian(?). Major vertical block faulting occurred during the late Paleozoic when the ancestral Rocky Mountains and related basins were formed. Three large uplifts, the Front Range highland, Apishapa highland, and Uncompahgre-San Luis highland, developed at this time. Each uplift appears to be bounded on one side by major faults and primarily upwarped along folds on the other. Cumulative fault displacements were as great as 3,000 m during the late Paleozoic. Major fault activity diminished in the Permian, but minor recurrent movement associated with this period of tectonism occurred on some faults in the Triassic and may have locally continued into the Late Jurassic.

By the end of the Cretaceous, a thick, relatively undisturbed sequence of sediments, dominantly marine, blanketed Colorado and buried the ancestral Rockies. Minor fault activity during deposition locally affected sedimentation patterns, but it was not until near the close of the Cretaceous that major orogenic uplift occurred. The Laramide orogeny created broad uplifts and deep adjacent structural basins. Laramide orogenic activity continued into the Eocene. Most of the buried ranges were re-elevated along preexisting faults at this time, but new uplifts rose from within the central Colorado trough. These new uplifts include the Uinta Mountains, Axial anticline, White River uplift, Elk Mountains, Sawatch anticline, and Sangre de Cristo Mountains. The Needle Mountains were uplifted from the site of a late Paleozoic basin on the southwest side of the Uncompahgre-San Luis uplift.

Large structural basins formed simultaneously with the uplifts, and thick sequences of orogenic sediments were deposited within them. Major Laramide basins include the Denver, Piceance, Sand Wash, San Juan, and Raton basins. North, Middle, and South Parks formed as structural sags within or adjacent to the Front Range. Igneous intrusions along the trend of the Colorado Mineral Belt fed Laramide volcanoes that shed andesitic materials into adjacent sedimentary basins.

Considerable controversy surrounds the nature of the stress field responsible for the Laramide orogeny. Large thrust faults border many of the

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Laramide uplifts. Some workers interpret these as near-surface manifestations of high-angle faults that are the product of vertical up-arching. Other workers believe the thrusts dip gently and are the result of horizontal compression, which may be related to subduction of the Farallon Plate beneath the North American Plate.

Erosion of the uplifted areas occurred during and after the Laramide orogeny. In some places erosion kept pace with uplift, and the raised areas were never topographically prominent. By the end of the Eocene, a widespread erosion surface had developed across many of the uplifted areas. This erosion surface may correlate with a thick paleosol found in Eocene rocks on the High Plains. For the most part, the erosion surface was a broad, undulating plain, but local relief of a few hundred meters along channels and monadnocks was common.

A widespread, intermediate-composition volcanic field that covered much of central Colorado formed on the late Eocene erosion surface during the Oligocene. Lava flows and ash-flow tuffs that were erupted from these volcanoes on the Eocene surface provide valuable time lines to document later Neogene faulting. The largest preserved volcanic area is in the San Juan Mountains. Other centers are found near Thirtynine-Mile Mountain and in the Elk and West Elk Mountains, Cripple Creek area, Sawatch Range, Wet Mountains, Spanish Peaks, Rabbit Ears Range, and Never Summer Mountains. Tectonically, the Oligocene was fairly quiet. Most structures active during this period were of a volcanic origin.

Near the beginning of the Miocene, the igneous activity changed from dominantly intermediate composition to a bimodal basaltic-rhyolitic composition. This change was accompanied by initiation of block faulting associated with development of the Rio Grande rift. Block faulting began about 28 m.y. ago in Colorado, somewhat prior to the extensional tectonism that created the Basin and Range province in the Western United States. Uplift has continued since this time, but the rate of uplift appears to have accelerated in many parts of Colorado during the late Miocene and Pliocene. Activity on a number of Neogene faults continued into the Pleistocene, and Holocene movement has been documented on several of these faults.

Large-magnitude Neogene faulting in Colorado has been demonstrated on several faults within the Rio Grande rift, a Neogene structure that cuts across Laramide structural highs. Appreciable Neogene offset is also present on other faults adjacent to the rift. San Luis Valley and the upper Arkansas Valley are prominent topographic basins within the Rio Grande rift in Colorado. San Luis Valley consists of two distinct structural areas. The northern area is a generally eastward tilted block that has a buried intra-basin horst structure within it. The Sangre de Cristo fault, a major Neogene fault with as much as 7,000 m of post-Oligocene displacement, bounds the east side of the basin. Repeated late Quaternary movements are well documented on this fault. Thick sequences of Cenozoic valley fill are found in the northern area. The southern part of the graben is upthrown relative to the northern part along the northeast-trending Manassa fault.

The upper Arkansas Valley consists of a northern and southern graben separated by a structural high south of Twin Lakes. Both grabens are bounded by step faults on the east, but their western border appears to be controlled by a single fault. A number of Oligocene paleovalleys formerly crossed the upper Arkansas Valley. These paleovalleys provide limiting dates for initiation of rifting and can be used to evaluate the style and amount of structural deformation in the valley. Evidence of recurrent late Quaternary faulting has been demonstrated on one major fault in the upper Arkansas Valley, the Sawatch fault.

Most Neogene faults outside of the Rio Grande rift are nearly parallel to the trend of the rift. Exceptions are faults associated with the Uncompahgre Plateau and the Uinta-Elkhead trend. Total Neogene displacement on faults outside of the Rio Grande rift is usually a thousand meters or less. Certain Neogene faults in Colorado appear to be the result of non-tectonic processes. Included in this category are faults related to evaporite flowage or solution, and to caldera collapse.

Neogene tectonism in Colorado may be related to extension resulting from interaction of the North American and Pacific Plates. Colorado also appears to have undergone considerable epeirogenic uplift during the late Cenozoic. Most Neogene structures in Colorado are interpreted to be extensional features, but a few folds and faults in the northern part of the State may be the result of compression.

References

Epis, R. C., and Chapin, C. E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains, in Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 45-74.

Grose, L. T., 1972, Tectonics, in Geologic atlas of the Rocky Mountain region: Rocky Mtn. Assoc. Geologists, p. 35-44.

Izett, G. A., 1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, in Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 179-209.

Kirkham, R. M., and Rogers, W. P., 1981, Earthquake potential in Colorado--A preliminary evaluation: Colo. Geol. Survey Bull. 43, p. 171.

Knepper, D. H., Jr., 1974, Tectonic analysis of the Rio Grande rift zone, central Colorado: Colorado School Mines Ph.D. Thesis T-1593, 237 p.

Scott, G. R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, in Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 227-248.

Taylor, R. B., 1975, Neogene tectonism in south-central Colorado, in Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 179-226.

Tweto, Ogden, 1975, Laramide (Late Cretaceous-Early Tertiary) orogeny in the southern Rocky Mountains, in Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 1-44.

______1980, Tectonic history of Colorado, in Kent, H. C., and Porter, K. W., eds., Colorado geology: Rocky Mtn. Assoc. Geologists, p. 5-9.

RECORDED SEISMICITY OF COLORADO

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The principle sources of instrumental information on the seismicity of Colorado are the numerous maps prepared by Ruth Simon and the CSM theses of Bruce Presgrave and Linda Hadley. The purpose of this paper is to put their excellent work in perspective for a person evaluating seismic risk in Colorado. Additionally, several detailed microearthquake networks have been operated in the state and their contribution to the recorded seismicity will be discussed.

The massive compilation of Simon was obtained by careful analysis of the GOL (Bergen Park) records. Presented in map form, this data set is a good guide to the probability of events in a specific area. Presgrave corrected the data set for blasts to the extent possible and corrected for the detection threshold of the single station. He presented the data as contour maps for intensity and magnitude with specified return periods.

The work of Hadley is more germane to a site investigation in Colorado. Simon's maps attribute many events to a location called Cabin Creek very near the pumped storage project of that name. The events have some time correspondence with the beginning of operation of that project. Very careful analysis by Hadley showed that the locations and time sequences of the data correlated far better with I-70 Georgetown - Silver Plume construction than they do with activities at Cabin Creek. The analysis included a set of off-working hours events which corresponded, upon investigation, with the work orders of the construction blasting crew.

Networks operated along the Front Range were sponsered by Army Corps of Engineers, the Denver Water Board and the Department of Energy. The bulk of the findings of these networks are still undergoing analysis but some general ideas about network operations can be discussed. Signal to noise ratios are very bad unless the instruments are placed on the crystallines of the Front Range. Numerous man-made events dominate the records. Very few, if any, events occur outside the known Derby fault zone.

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AN OVERVIEW OF EARTHQUAKE HAZARDS IN COLORADO

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An analysis of potentially active faults and earthquake history suggests that the potential for damaging earthquakes in Colorado is even higher than the historic record indicates and that a potential exists for large damaging earthquakes. The hazard from such earthquakes has often been underestimated in the past and should be carefully considered in the future to adequately design vulnerable structures. Potentially active faults and seismotectonic provinces both should be considered in the determination of the design event.

In 1974, the Colorado Geological Survey prepared initial guidelines and criteria that included the recognition and mitigation of earthquake hazards in the State of Colorado. These guidelines and criteria, to be used by State and local planning agencies, concluded that Colorado's seismic records are too short to serve as the only basis for evaluating future seismicity and that the seismic risk classification (Zone 1) was probably too low and not sufficiently detailed for general State-wide use. Additional information and analysis on potentially active faults was needed to evaluate seismic risk. Coincident with the start up of a project by the Colorado Geological Survey, Irving Witkind of the U.S. Geological Survey released an open file map in 1976. This map was essentially an office compilation of known and suspected active faults in Colorado. Bob Kirkham and Pat Rogers of the Colorado Geological Survey used Witkind's work as a basis in extending their evaluation of Colorado's earthquake potential.

Kirkham and Rogers, in reports released in 1978 and 1981, described potentially active faults and summarized the historic and instrumental events in Colorado. Potentially active faults are defined as faults that have moved during the Neogene (Miocene and younger age) and may have some potential for future movement. Selection of this definition was based on known regional and State-wide patterns of Neogene deformation and the lack of knowledge on the Quaternary history of faults in Colorado. Neogene faults have a potential for movement during the Quaternary, but not all potentially active faults have moved in this time period. All potentially active faults will not necessarily meet the U.S. Nuclear Regulatory Commission's definition of a capable fault and, therefore, may not be active faults from a design standpoint. In contrast, faults not currently mapped or recognized as being active will almost certainly be identified in the future and prove to be capable with detailed field investigations. Any potentially active fault, or faults should be carefully evaluated for specific projects and should be considered in the design of vulnerable facilities.

Earthquake history of an area is valuable in the evaluation of future seismicity because past earthquakes suggest both the location and magnitude of future earthquakes. There are, however, serious limitations to using the Colorado historic earthquake record by itself to predict future events.

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Historic events date back only 110 years and high-gain instrumental recordings are available for only about 20 years. Combined, the historic and instrumental events suggest that Colorado is an area of relatively low seismicity. Care must be taken with such a conclusion because of 1) the very short earthquake record in Colorado; 2) the historic distribution of population in Colorado; 3) widely varying construction practices throughout the State; 4) confusion between natural and man-made tremors; 5) bias of seismic rates due to detection threshold; and 6) complex geologic relationships that influence epicentral location accuracies. To adequately access the seismic rate and maximum magnitude of future events, the earthquake record must be used in conjuction with the analysis of potentially active faults.

Seismotectonic provinces can be delineated by the distribution and characteristics of Neogene faults and the past earthquake record, especially when this data is compared to major structural and physiographic regions. The Colorado Geological Survey defines six seismotectonic provinces in Colorado: Rio Grande rift, Eastern Mountain, Western Mountain, Plains, Uinta-Elkhead, and Colorado Plateau provinces. The Rio Grande rift is characterized by major Neogene faults, some of which have repeated Quaternary fault movement. Neogene fault offset is much greater along the Rio Grande rift than any other seismotectonic province in Colorado. The Rio Grande rift province is divided into two subprovinces based on the amount of late Quaternary faulting as well as total Neogene offset. The southern subprovince has major faults that have repeated late Quaternary movement. However, it is generally an area with low recorded seismicity although an intensity VII event occurred in the subprovince in 1901. The amount of known Quaternary offset is less in the northern subprovince; however, this subprovince has had a moderate number of recorded events. The Eastern Mountain province contains numerous faults with considerable Neogene movement, but Quaternary movement has been documented on only a few of the major faults. Historic seismic activity in the province has been low. The Western Mountain province has relatively few known Neogene faults and those present are of short length and part are related to caldera collapse or evaporite flowage. In contrast to the sparse Neogene faulting, numerous earthquakes have been felt or instrumentally recorded in the Western Mountain province. The Plains province contains no major Neogene faults but a few potentially active faults are present in the lower Arkansas River Valley. Earthquakes have generally occurred at relatively low rates historically and are widely dispersed in this province. An exception to this is the sequence of earthquakes triggered by fluid injection at the Rocky Mountain Arsenal and an intensity VII event (1882) which may have been located north of Denver. The Uinta-Elkhead province has west and northwest trending Neogene faults and associated short north-south cross faults. Seismic activity has been generally low in this province. The Colorado Plateau has few recognized Neogene faults except for those along the Uncompahgre uplift and collapsed salt anticlines. Seismicity is generally low; however, several moderate-sized events have occurred at specific areas within the province.

In summary, major, potentially active Neogene faults are present in many parts of Colorado. These faults must be carefully considered in the hazard assessment of vulnerable facilities in Colorado. These Neogene faults and the historic and instrumental seismicity define seismotectonic provinces within Colorado. These provinces are intended to serve as an aid in the design of vulnerable structures and to serve as a basis for eventual seismic zoning in the State of Colorado.

THE ROCKY MOUNTAIN ARSENAL WELL AND THE DENVER EARTHQUAKES

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At 10 minutes and 23 seconds after 4 o'clock on the morning of April 24, 1962, a small crack developed in the crystalline rocks about 15,000 feet below the town of Derby, Colorado. No person felt the surface motion.

The earthquake was the first of almost 2,000 "Denver Earthquakes" that have become internationally famous as the example of seismicity induced by fluid injection. Mr. David Evans, in November 1965, pointed out that the rate of injection into the RMA well, as much as 8 million gallons per month, correlated well with the number of earthquakes detected per month, as many as 120 in July of 1965. Injection into the well stopped in February 1966. The largest earthquake, three of $M \simeq 5.0$, did not occur until 1967. Between 1967 and 1981 there was a slow decline in activity, to a level of a few per year during the last decade.

The swarm has been the subject of much debate. The last paper, by P. A. Hsieh and J. D. Bredehoeft on "A Reservoir Analysis of...", being published in the J. G. R. as late as 10 February 1981. The swarm dominates estimates at the seismicity of the Front Range urban corridor. Estimates of risk to Denver depend directly on our confidence that the swarm was induced by the activity of man. There are three features of the Derby activity that detract, slightly, from this confidence:

1) In November 1882 there may have been an earthquake felt in the Derby area,

2) The magnitude distribution of these earthquakes is normal ($b \cong 0.84$), one might have hoped that induced earthquakes would show an abnormal "b" value,

3) The energy budgets of the pumping and the earthquakes do not correlate well in time.

Confidence in a low level of future activity in the area is not strengthened by the earthquake of 2 April 1981 whose magnitude was close to 4.0. Why so big, so late?

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APPARENT LATE PLEISTOCENE AND HOLOCENE SURFACE FAULTING ALONG THE EAST FLANK OF THE GORE RANGE SUMMIT COUNTY, COLORADO[1]

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Since 1962, potential earthquake hazards in Colorado have been the subject of increasing controversy. Reports of recent surface faulting in various parts of the state have added to the controversy and stimulated research. In 1970, the U.S. Geological Survey[2] described major Pleistocene and Holocene surface faulting along the Frontal (Blue River) fault bounding the east flank of the Gore Range in Summit County, Colorado.

The Gore Range forms a major segment of the north-south trending Laramide-age Park Range anticline. During Miocene-Pliocene time, the Gore Range was differentially uplifted along major bounding faults and thus was structurally isolated from the parent Laramide structure. Reports of surface rupture along the Frontal fault suggested that uplift continued into the Holocene. Moreover, an apparent similarity between the Frontal fault and other normal and high angle reverse faults in central Colorado implied a relationship to a postulated northern extension of the Rio Grande rift system.

The Frontal fault is a complex normal fault abutting Precambrian basement rocks on the west against a 2,130± meter (7,000± foot) sequence of Mesozoic and Tertiary(?) age sediments on the east. The east flank of the Gore Range including much of the trace of the Frontal fault is covered by deposits of two(?) major Pleistocene and two(?) minor Holocene glacial advances. In addition to the glacial debris, the Quaternary stratigraphic sequence includes deposits of alluvial and colluvial origin.

Evidence for surface faulting cited by the U.S. Geological Survey included:

1. unvegetated fault scarps in late Pleistocene moraines up to 18 meters (60 feet) in height;

2. fault displacement of Holocene avalanche deposits;

3. active extrusion of gouge boils 100 meters in diameter and up to 12 meters (40 feet) in height;

4. several large landslides apparently triggered by fault movement;

5. ridgetop springs along the fault zone; and

6. reports (circa 1920) of simultaneous landsliding, spring activity and scarp development over a linear distance of 6.4 kilometers (4 miles) along the fault zone.

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Field work performed by the writer disclosed additional circumstantial evidence for Pleistocene/Holocene movement along the Frontal fault including:

7. numerous air photo lineaments both with and without apparent geologic control and arranged in a left en echelon pattern to the fault zone;

8. alignment of stream drainages along the fault; and

9. the presence of anomalous troughs and scarp-like forms in and near the fault zone.

A small number of instrumentally recorded seismic events (1966 through 1973) in the Gore Range also supported the interpretation of geologically young faulting. Prior to detailed geologic study of the Frontal fault, a seismic gap and/or tectonic creep were believed reponsible for the relative quiescence of the study area.

The results of field mapping performed by the writer indicate that features attributed to recent tectonic surface faulting are related instead to normal alpine mass movement and other erosional processes. The relatively broad zone of shearing and brecciation associated with the Frontal fault localized major landsliding along the fault zone, particularly where it intersects major glaciated valleys. At several places along the range front, landslide features (scarps, pressure ridges) mimic tectonic landforms and can be easily mistaken for tectonic fault displacement. The landforms produced by mass gravitational movement are not related to recent tectonic movement and/or earthquake ground shaking as suggested by earlier workers.

Although Quaternary faulting cannot be entirely discounted along the east flank of the Gore Range, it is almost certainly older and more subdued than previously reported. In the writer's opinion, the minimum age of fault movement along the east flank of the Gore Range is Pliocene or early Quaternary. Moreover, a reanalysis of instrumental seismic data and times of occurrence indicates events located in the Gore Range are probably related to mining activity.

In conclusion, evidence reported for late Quaternary surface faulting along the east flank of the Gore Range can be readily explained by mass gravitational movement. The potential hazard posed by the Frontal fault in terms of both ground rupture and earthquake generation is believed to be comparable with other Miocene, Pliocene or early Quaternary faults in central Colorado.

1 Modified from: West, M. W., 1978, Quaternary geology and reported surface faulting along east flank of Gore Range, Summit County, Colorado: Colorado School of Mines Quaterly, Vol. 73, No. 2, 66 pp.

2 Tweto, O., Bryant, B., and Williams, F. E., 1970, Mineral resources of the Gore Range - Eagles Nest Primitive Area and vicinity, Summit, Eagle, and Grand Counties, Colorado: U.S. Geological Survey Bulletin 1319-C, 127 pp.

EARTHQUAKE HAZARD STUDIES FOR SPINNEY MOUNTAIN DAM PARK COUNTY, COLORADO

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The Spinney Mountain Project comprises an earth-fill dam, reservoir and diversion channel now under construction for the City of Aurora, Colorado. The dam will have a crest height of 90 feet and length of about 4,100 feet, providing active reservoir storage of 48,000 acre-feet. The project is located on the South Platte River near the lowest elevation of the South Park Basin.

Seismicity-related investigations inlcuded an epicenter compilation, seismogram analyses, fault studies, and tectonic analysis. Geologic exploration utilized low-sun-angle aerial photography, field mapping, drilling, trenching, and geophysical surveys. Fault movements were dated by a combination of radiometric, geomorphic, and pedologic methods. Displacement within the past 35,000 years was considered evidence of fault capability.

Three capable faults were delineated within ten miles of the project site. Two of these, the East-Side and West-Side Faults, are located on the flanks of Spinney Mountain between one and two miles from the dam site. The third, named Eleven Mile Fault, is located south of Eleven Mile Canyon Reservoir, between six and nine miles southeast of the project. The two capable faults situated nearest the site were localized by segments of the much older Elkhorn Thrust and Chase Gulch Normal Fault systems, that underwent major displacement tens of millions of years ago. Capable faults were not found to coincide with segments of any other major faults in the South Park basin.

A conservative estimate of seismic capability assumes the East-Side Fault connects with the Eleven Mile Fault about six miles southeast of the dam site. Such a coupling would imply a fault-rupture length of about ten miles, assuming continuity where the fault is masked by floodplain deposits of the South Platte River and by Eleven Mile Canyon Reservoir. This system is related to the Chase Gulch Fault and is believed to be the controlling structure with respect to potential earthquake shaking. The West-Side Fault is interpreted as a subsurface branch of the main (East-Side) capable fault. The predecessor plane of the West-Side Fault is structurally related to the Elkhorn Thrust and is effectively terminated by a cross-cutting fault north of the dam site.

A Richter magnitude of 6.2 is considered a reasonable estimate for the maximum earthquake associated with displacement of the East-Side Fault over the expected life of the project. Embankment design was based on a slope deformation analysis, utilizing a peak horizontal ground accleration of 0.6 g and duration of strong motion of 15 seconds. Although the likelihood of a capable fault passing through the dam foundation was considered very small, plans were formulated to accomodate up to a six-inch vertical or overthrust bedrock displacement. Excavation of the core trench indicated no capable faulting in the foundation, eliminating the need for those measures.

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EVIDENCE FOR RECURRENT LATE QUATERNARY FAULTING, SAWATCH FAULT, UPPER ARKANSAS VALLEY, COLORADO

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The upper Arkansas Valley, together with the San Luis Valley, are the best expressed elements of the Rio Grande Rift within Colorado. Range bounding scarps in Quaternary deposits demonstrate continuing fault activity in both valleys, in contrast with the low rates of historic seismicity. Structurally, the upper Arkansas Valley consists of two distinct, but coeval grabens. The south Arkansas graben extends about 55 km north-south from south of Salida to about 20 km north of Buena Vista. The north Arkansas graben extends about 30 km north-south from the Twin Lakes area to about 5 km north of Leadville. Both grabens have thick accumulations of Miocene and younger fill with numerous intergraben faults.

Water and Power Resources Service's seismic hazard studies for three damsites in the north Arkansas graben emphasized two tasks: 1) mapping, dating and correlation of late Quaternary deposits in the north and south grabens, and 2) detailed studies of faulted Quaternary deposits. A relative-age chronology for Quaternary deposits in the upper Arkansas Valley was developed through airphoto interpretation of the morphologic relationships of each unit to adjacent units (mainly moraine-terrace relationships) and by interpretation of quantitative relative-dating data collected in three key areas: Leadville, Twin Lakes, and Chalk Creek. Moraine surface weathering features and soil profile field and laboratory data (mainly B horizon characteristics) were used to develop local relative chronologies which were then tied to the alluvial terrace sequence in the main valley. The lack of materials suitable for absolute dating of late Quaternary deposits led to our use of relative-dating techniques for correlation of the Quaternary sequence of the upper Arkansas Valley. This local sequence was then correlated to other sequences in the Rocky Mountain region with some absolute dating control.

Our studies of known and suspected Quaternary faulting supplemented existing mapping with airphoto and field reconnaissance mapping and trenching. Work in the south Arkansas graben focused on examination of the amount, extent and uniformity of late Quaternary faulting in various approximately correlative units by detailed surface mapping and trenching of scarps at two sites along the Sawatch fault west and southwest of Buena Vista. Assessment of faulting in the north Arkansas graben was based on airphoto and surface mapping along known and suspected faults together with the development of structural and geomorphic assessment of the activity of the poorly located intrabasin faults. A lack of favorably located deposits in the main north graben limited subsurface exploration to examination of secondary features south of Twin Lakes in a subsidiary extension of the main graben.

In the south Arkansas graben, scarps are present in "Bull Lake" and younger deposits for approximately 29 km along the Sawatch fault. Major scarp groups are several kilometers in length and are composed of shorter more closely spaced scarps hundreds of meters in length. Lateral spacing of scarps varies roughly with scarp length and ranges up to a kilometer for major scarp

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groups. Scarp heights in deposits of "Bull Lake" age average 8 to 10 meters, while those in "Pinedale" age deposits average 2 meters. Scarp heights are relatively uniform along their lengths and decrease rapidly where scarps terminate.

Trenches in scarps near Cottonwood Creek (Cottonwood Trench Site) and south of Chalk Creek (Eddy Trench Site) in the south Arkansas graben revealed a displacement history of at least six surface faulting events on the Sawatch fault in the past 100,0000 to 150,000 years (Table 1). Displacement estimates for most events are estimated from thicknesses of scarp-derived colluvial wedges preserved on the downthrown side of the fault. Comparisons of relative soil profile development on the wedges with profile development on till, outwash, and colluvium exposed in the trenches and in nearby soil pits and elswhere in the upper Arkansas Valley provide a basis for estimating the age of displacements. The discrepancy between post - "Bull Lake" scarp height and cumulative displacement estimated from colluvial wedge thicknesses is inferred to result from events producing less than about 0.2 to 0.3 meters of surface displacement. Such displacements are believed to be too small to leave discernible colluvial wedges. The inferred long-term recurrence of these small displacement events is consistent with the occurrence of such an event tentatively dated at less than 4000 14C years ago.

In the north Arkansas graben, Quaternary surficial deposits along the southern half of the Sawatch fault consist mostly of hummocky "Pinedale" and post - "Pinedale" landslide deposits and till in heavily forested terrain. The geomorphic expression of the range front suggests late Quaternary displacement less than or comparable to that of the Sawatch fault in the south Arkansas graben. However, geomorphic relations along the north portion of the Sawatch fault in the north graben suggest a significantly different displacement history for that portion. Subdued range front morphology and unfaulted mid-Quaternary surfaces at and south of Turquoise Lake are suggestive of relative quiescence of the fault since the surfaces were formed. These relations suggest a maximum late Quaternary rupture length including no more than the southern half or two-thirds of the Sawatch fault in the north Arkansas graben.

Numerous Neogene intragraben and step faults bordering the east side of the north Arkansas graben (Tweto and Case, 1972; Tweto and Reed, 1973; Tweto, 1979; Water and Power Resources Service, in preparation) have been mapped and inferred based on: 1) parallelism of faults in early Cenozoic and pre-Cenozoic bedrock to late Cenozoic trends, and 2) poorly defined anomalies in valley fill thickness over bedrock. These faults are poorly located and displacement amounts and ages are equally indistinct. Reconnaissance mapping suggests a lack of post - "Bull Lake" movement on these faults and in some cases may preclude any late Quaternary displacement at all. This lack of geomorphic expression of young faulting on graben-related structures other than the Sawatch fault is consistent with reconnaissance observations in the south Arkansas graben. The resolution of these observations would probably enable detection of 0.6 - to 1-meter surface displacements in "Bull Lake" and younger deposits.

TABLE 1

Tentative Correlations and Estimated Ages of Surface Faulting Events at ETS and CTS, With Associated Magnitudes

ETS Eddy trench site		CTS Cottonwood trench site		M_L from displacement (M = 0.45)	Min. and max. avg. rupture length (from length-magnitude relation) (km)	M_L reflecting max. probable rupture length* and displacement
Age (10^3 yr)	Displacement (m)	Age (10^3 yr)	Displacement (m)			
>>100-150 100-150	>1 0.5	>100-150	0.9	6.9	22	6.9
50-100	1.5-2.6	50-100	0.3	6.7-7.25	16-50	7.0
12-25	1.1-1.8	12-25	1.4	6.7-7.1	16-31	7.0
<12-25	0.4-0.6	<12-25	1.2-1.7	6.6-7.1	15-31	7.0
<12-25	0.7-1.1	<12-25	0.3	6.5-7.0	11-30	7.0
<4	0.1-0.15	<4	0.15	6.25	6	6.25

* The maximum probable rupture length is defined by the scarp length of 29 km.

Note: All magnitude determinations are based on Slemmons (1977) and are reported in terms of Richter magnitude (M_L).

SEISMIC HAZARD STUDIES FOR RIDGEWAY DAMSITE, COLORADO

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The Uncompahgre uplift is a 160 km long, 50 km wide, northwest trending, uplifted fault block extending from north of the San Juan Mountains of southwestern Colorado into eastern Utah. Movement on the bounding faults of the Uncompahgre uplift was probably initiated during late Precambrian time with a major pulse of uplift of this part of the ancestral Rocky Mountains occurring during Pennsylvanian and Permian times. Vertical offset of Precambrian rocks of as much as 6100 m along the southwest margin of the uplift adjacent to the Paradox basin is supported by widely spaced well data. A zone of en echelon faulting forming the boundary of the uplift extends from the Paradox basin southwest through Gateway to east of Ridgway, Colorado.

The Ridgway fault together with other east-west trending faults to the south form a series of horsts and grabens with Late Paleozoic displacement along the southwestern margin of the Uncompahgre uplift. The Ridgeway fault is expressed as a 25 km long south-facing line escarpment with a maximum height of 300 m north of Ridgway, Colorado. The Cretaceous Dakota sandstone is the cap rock of the upthrown side of the fault and is offset about 460 m down to the south. This movement has been considered a result of Laramide deformation. Northwest of Ridgway, along the southwestern margin of the Uncompahgre uplift near Gateway, Colorado, published work indicates possible Pliocene and early Pleistocene movement on the bounding faults.

The Uncompahgre River heads in the San Juan Mountains and flows north, crossing the fault line escarpment 2 km north of Ridgway where it enters the 300 m deep canyon on the upthrown side of the fault. Terminal moraines of several relative ages are present immediately upstream of the fault line escarpment and other moraines are found further south up the Uncompahgre River canyon and its tributaries. North of the fault line escarpment remnants of outwash terraces at 275 m, 140 m, and 110 m above the river are preserved along the canyon. None of these deposits can be correlated with glacial deposits south of the fault. However, the youngest outwash terrace, about 15 m above the river and of probable "Pinedale" age, can be traced continuously from Montrose, Colorado, upstream across the fault to the youngest moraine south of the fault. From this we conclude that no major displacement has occurred on the Ridgway fault in at least the last 15,000 years. No assessment of the potential for major earthquakes with a recurrence interval greater than 15,000 years can be made based on available geologic evidence.

The historic record of earthquake occurrence in southwestern Colorado is very short and incomplete. The most notable earthquakes occurred within 15 km of the damsite and include two pre-instrumental MMI V events (Modified Mercalli intensity) and three instrumentally recorded earthquakes of Richter magnitude (M_L) 3.3, 3.8, and 5.5, the latter producing MMI VI ground shaking in the vicinity of the damsite. Although the location accuracies of the determined epicenters for these events are probably no better than 10 to 20 km, there appears to be a spatial relationship between these earthquakes and the Ridgway fault and associated north-trending branch faults.

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In an attempt to better define the seismicity of the damsite region, a 5-station network of high gain portable seismographs was installed within 17 km of the damsite. The microseismic survey was operated continuously for 87 days during the months of January, February, and March 1979. Sixty-six separate identifiable events with S-P times less than six seconds were recorded during the study with the majority of these earthquakes occurring in two distinct swarms. Only 11 of these 44 swarm type microearthquakes were located using computer program HYPO71.

The computed epicenters of these 11 microearthquakes plus two other events recorded during the study locate just south of the surface trace of the Ridgway fault at focal depths between 5 and 11 km. Limited station coverage precluded the determination of the focal mechanism of these events; however, their distribution with depth is consistent with a south dip on the Ridgway fault. The similar character, as observed on the seismograms, between the located and non-located events suggests 51 microearthquakes are associated with movement on the Ridgway fault.

Six microearthquakes located interior to the array within about 8 km of the damsite. The epicenters of four of these events are within 5 km of the north-trending branch faults and may be due to stress release on these structures. Five poorly located events appear to be originating outside of the array to the south and southeast in areas of known mining.

The magnitudes of all located microearthquakes ranged between -0.25 and 2.7 and were computed using the coda duration method and empirical constants derived for southern California. Therefore, they are only crude estimates of Richter magnitudes and only useful in representing the relative size of an event versus the other located microearthquakes recorded during this study.

GEOLOGIC INVESTIGATIONS OF THE SEISMIC HAZARDS ASSOCIATED WITH THE GOLDEN FAULT, COLORADO

Arthur C. Darrow and Alan P. Krusi
Dames & Moore*

The Golden Fault is a roughly N20°W trending, west dipping, high angle reverse fault, which is located to the east of and roughly parallel to the steep eastern flank of the Front Range of Colorado. The fault is approximately 32 km long, extending northward from the Turkey Creek area to near Coal Creek.

The Golden Fault is generally interpreted to have formed during the final stages of the Laramide orogeny when the eastern flank of the Front Range was extensively deformed, and most researchers have concluded that movement along the Golden Fault ceased during the Eocene. However, Colorado Geologic Survey open-file report 78-3 presents the inferrence that the Golden Fault should be considered a capable structure (USNRC criteria for capability). This inferrence was based upon the identification of a late Quaternary, graben-like structure near the mapped trace of the Golden Fault, just north of Clear Creek, and upon the assumption that the graben was probably structurally related to the Golden Fault. The activity on the "graben" has been inferred to imply activity on the Golden Fault.

To evaluate the possibility that the Golden Fault may be active and hence may present a seismic hazard to the region, a series of geologic, geodetic, and microseismic investigations were conducted. Reconnaissance and detailed field mapping programs were conducted to select appropriate trenching locations along the fault at three locations. Concurrent with these investigations, a six-month microseismic monitoring program was conducted along the fault, and available geodetic data were analyzed. In addition, the "graben" was further investigated and its potential relationship to the Golden Fault was theoretically and experimentally analyzed.

None of the investigations produced credible evidence that the Golden Fault has been active during the last 500,000 years. To the contrary, the exposures in the three trenches across the main trace of the fault exhibit unfaulted Verdos-age alluvium (600,000 ybp). Therefore it is concluded that the Golden Fault is not capable by USNRC criteria, and does not present a signficant seismic hazard to the region.

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NEOTECTONICS OF THE NORTHERN SANGRE DE CRISTO MOUNTAINS, SOUTH-CENTRAL COLORADO

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Well-preserved fault scarps offsetting Quaternary alluvium at the base of the northern Sangre de Cristo Mountains, Colorado, document recurrent pre-historic surface faulting associated with Rio Grande Rift tectonism. Detailed Quaternary geologic mapping supports correlation of glacial-alluvial deposits in and near the fault zone with the well-dated Pinedale-Bull Lake glacial chronology of the Rock Mountains. Fault scarps offsetting dated outwash fans and terraces present several geometries, each indicating a specific timing of faulting relative to deposition-erosion.

Two fault zones were mapped in detail. The Villa Grove Fault Zone is a 10 km-long intrabasin swarm of about 40 discontinous, low, parallel, basin-facing scarps. Scarps offsetting successively older alluviums are progressively higher and more degraded. Geomorphic evidence indicates that surface displacements of 0.8 to 1.4 m, representing magnitude 6.5 to 7.0 earthquakes, occur roughly every 100,000 years.

Prominent but discontinuous fault scarps at the range front mark the 120 km-long Sangre de Cristo Fault Zone. At five key locations, recurrent movement on a single strand of the fault has offset up to five Quaternary terraces. Measurements of scarp heights and trench exposures indicate that: (1) faulting recurrence averages 25,000 to 30,000 years, but can range from as little as 2500 to as much as 60,000± years, and (2) the two most recent events occurred between 15,000 and 10,100±110 years ago, and shortly before 7660±120 years ago.

Surface displacements from single events indicate paleoearthquakes of magnitude 6.8 to 7.4, similar to historic shocks on other Basin-Range faults. Both individual and cumulative displacements reach a maximum in the Crestone area, where present topograhic relief is highest. Deduced frequency and magnitude of large pre-historic earthquakes is compatible with the lack of instrumentally detected seismicity in the study area, but not with negligible activity over the 110-year historic record. Study area faults may resemble other Basin-Range faults, which have generated rare large shocks, but relatively few minor ones.

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MORPHOLOGY OF FAULT SCARPS IN THE RIO GRANDE RIFT, COLORADO, AS AN INDICATOR OF AGE OF FAULTING

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The Rio Grande Rift contains most of the well-defined fault scarps in Colorado. These scarps displace all but upper Holocene deposits and range in height from less than 1m to more than 30 m. Except for where these fault scarps cut late Pinedale or younger deposits, the scarps are the product of multiple fault movements.

Newly developed methods allow estimates of the ages of scarps from their morphology (Nash, 1980a, Bucknam and Anderson, 1979). The evolution of many scarps can be mathematically simulated by a diffusion equation, which predicts that the greatest topographic change will occur at the points of maximum profile curvature. Both empirical data (Bucknam and Anderson, 1979) and the theoretical model (Nash, 1980b) show that, for a given scarp age, lower scarps have gentler slope angles, and that, for a given scarp height, older scarps have lower slope angles. The rate of scarp degradation also depends on a variable that is a function of climate and lithology. Most previous morphometric studies have examined only scarps resulting from a single faulting episode or other geomorphic event.

Both the diffusion-equation expression and morphometric data from fault scarps in the Rio Grande Rift in Colorado indicate that the interrelations among height, slope, and age for single-event scarps are also valid for multiple-event scarps. However, the morphologies of single- and multiple-event scarps are not directly comparable. Multiple-event scarps have lower scarp angles than single-event scarps for similar heights and ages of last faulting.

To estimate scarp ages or the time since the last fault rupture of multiple-event scarps, measurements of maximum scarp angle are plotted against the log of the scarp heights (Figure 1). The relative positions of the resulting lines are indicative of age if climate and lithology are assumed to be equivalent between areas being compared. Such lines for the multiple-event fault scarps in the study area are remarkably parallel, suggesting that method is indeed valid for multiple-event scarps. The relative positions of the lines for scarps in the northern San Luis and Upper Arkansas Valleys are consistent with ages of faulting derived from radiocarbon dates and soil stratigraphy. Considering the theoretical difference between single- and multiple-event scarps, the positions of these lines are also consistent with published data for single-event scarps of similar age in Utah (Figure 1). However, the positions of the lines for scarps in the southern San Luis Valley are inconsistent with those for scarps in the northern San Luis Valley, upper Arkansas Valley, and Utah. Because of the differences between the geologic setting of the southern San Luis Valley and that of the other areas, these data suggest a strong influence of lithology on scarp morphology and a need for local time calibration of the method.

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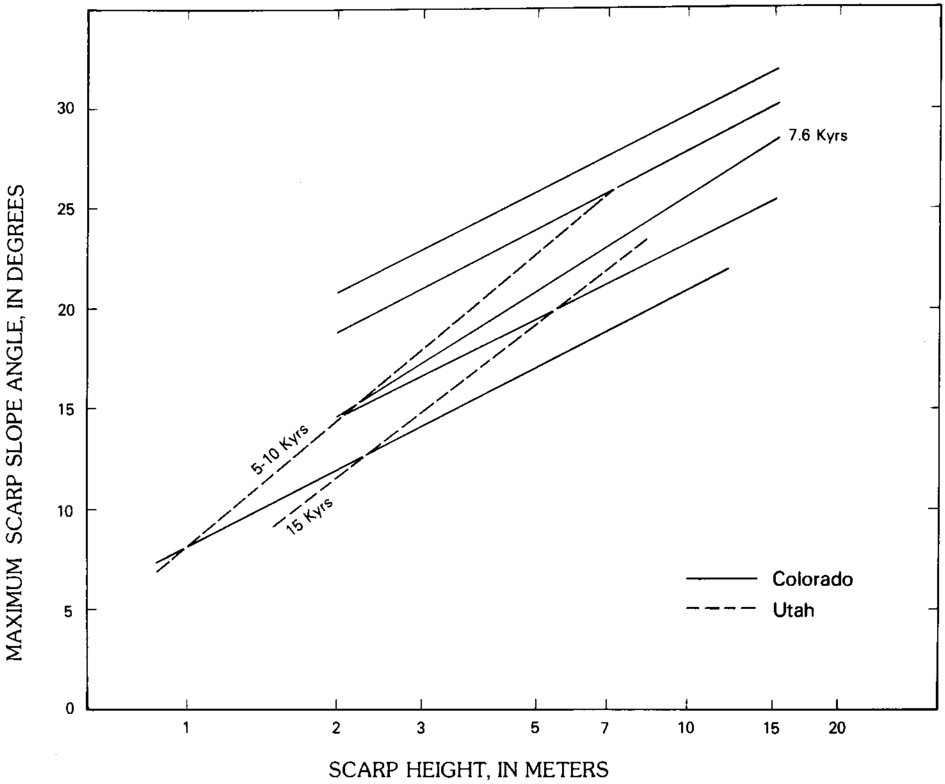

Figure 1.--Plots of maximum scarp angle against scarp height for selected scarps in Utah and in the Rio Grande Rift of Colorado. Utah data is from Bucknam and Anderson (1979). All scarps were formed or were last faulted between 5000 and 15000 years ago. More precise ages are given where known.

References

Bucknam, R. C., and Anderson, R. E., 1979, Estimation of fault-scarp ages from scarp-height--slope-angle relationship: Geology, v. 7, p. 11-14.

Nash, David, 1980a, Forms of bluffs degraded for different lengths of time in Emmet County, Michigan, U.S.A.: Earth Surface Processes, v. 5, p. 331-345.

______1980b, Morphologic dating of degraded normal fault scarps: Journal of Geology, v. 88, p. 353-360.

EARTHQUAKE HAZARD, RISK AND LAND-USE IMPLICATIONS IN COLORADO

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A better understanding of Post-Laramide tectonism and growing intensity of investigations of active faulting has caused reappraisal of seismic risks and zonation over the past twenty years throughout the Rocky Mountain region. In Colorado, general studies by the U.S. Geological Survey and Colorado Geological Survey (CGS), and project-oriented investigations by others have advanced our knowledge of earthquake potential. Papers to be presented at this conference will give the results of several such technical investigations. In this paper I will describe some of the background and problems that are inherent in formulating and implementing a new policy such as revised concepts of seismic risk, and accompanying constraints on land use.

The process followed in an effort to achieve more stringent and appropriate seismic safety requirements in Colorado can be broken down into three general areas: 1) policy formulation, 2) obtaining a specific legal basis for proceeding, and 3) strategies for accomplishig the intent of the policy. In the policy formulation area, a preliminary evaluation by the CGS in the early 1970s strongly convinced us that the generally accepted UBC designation was not adequate. Consequently, we elected to give seismicity equal billing with the many other better recognized geologic hazards that were in the public eye at that time. This enabled seismicity to be one of many geologic hazards to receive specific legal status in Colorado through HB-1041 of 1974. The CGS land-use manual for geologic hazards, mandated by HB-1041, gave wide distribution within the State of our perception of the seismic hazard. The strategies we devised for effecting the needed changes were threefold. In CGS reviews of major projects, we started raising the question of seismicity. This has generally resulted in more conservative designs and occasionally in detailed local studies that greatly improved our knowledge of specific areas. We also felt that there was a need for a readily available summary of what was known about seismicity and potentially active faults in Colorado. Otherwise, each governmental unit or consulting firm would have to go through the same time consuming exercise that we had. Funding assistance from the USGS, and our open-file report of 1978 resulted in the formal report just published. The third and most difficult effort--that of transmitting and transalting the body of technical information into workable governmental and institutional processes will be the most difficult of all. This will require careful analysis and revision of building codes, retrospective study of certain critical facilities that may have been built under earlier standards, and perhaps most of all it will require the confidence and concerted efforts of key professional and administrative people such as those attending this conference. It is the intent of the CGS to continue an active role in increasing our understanding of seismic risks and at the same time facilitating acceptance and implementation of new standards that will continue to emerge as science gradually overcomes bureaucratic inertia.

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EARTHQUAKE EMERGENCY PREPAREDNESS

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Emergency management planning must be based on risk analysis which identifies potentially hazardous events, geographical areas where they may occur, and their likely severity. A few hazards have been isolated as requiring State participation in response and management roles whenever they occur; e.g. accidents at the Rocky Flats Plant or the Fort St. Vrain Station, or a nuclear attack on the Nation. Otherwise, the State has a well-defined emergency preparedness system which emphasizes the management role of the local jurisdiction. The community is the primary actor in saving lives, assessing the extent of loss and damage, and then undertaking recovery. State resources, e.g. manpower, emergency air and ground vehicles, technical and financial assistance, are committed when local resources are inadequate to meet needs, or become depleted.

When a potentially disastrous event occurs local jurisdictions activate their own warning and response systems, notifying the State Division of Disaster Emergency Services (DODES) of the problem. If needed, lifesaving assistance can be provided at once. If local leadership adopts a disaster resolution, other forms of State assistance can be requested. DODES then acts to verify damages, and may activate the State Emergency Operations Center, assembling representatives from the appropriate mix of State and Federal agencies. This team will coordinate the provision of response assistance to be applied in most cases under local control. When conditions warrant, a disaster is declared by the Governor, and action can then be taken to provide relief and recovery assistance through disaster funds, legislative action, or a request that the President authorize Federal assistance.

Specific preparedness and response planning for the low-level seismic activity experienced in Colorado thus far has taken the form of dam safety planning. One of the primary concerns of DODES for several years has been the threat to Colorado residents who have settled downstream from some of Colorado's 2,800 dams. As threatened populations, potential inundation zones and water travel times are identified, communities are asked to develop population warning and evacuation plans.

As the dam safety program is only starting to evolve, so is the broader effort to be prepared to cope with a large scale seismic event. Population evacuation plans for Colorado's major cities are been developed as part of a "Crisis Relocation Program" for possible nuclear attack. These plans could be applicable to potential earthquake situations, as can the other response mechanisms discussed above, but a better understanding of the potential scale and impacts of seismic events on Colorado's developing settlement pattern is needed. A more detailed estimate of the seismic hazard would be particularly useful in stimulating preparedness at both the State and local levels.

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FIELD TRIP ROAD LOG GUIDE*

LATE TERTIARY AND QUATERNARY FAULTING IN CENTRAL COLORADO

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INTRODUCTION

On June 4, 5, and 6 of 1981, the Denver Section of the Association of Engineering Geologists conducted a symposium on seismic hazards in Colorado. The final day of the symposium was devoted to an optional field trip which viewed evidence of late Tertiary and Quaternary faulting in central Colorado. The main purpose of this field trip was to examine the Sawatch fault, a recently active fault within the Rio Grande rift that bounds the east flank of the southern Sawatch Range. Other Neogene faults along the trip route were also discussed.

The trip initiated and ended at the parking lot near the spectacular roadcut exposure through the Dakota hogback at the intersection of Interstate I-70 and Colo-26 (Figure 1). The first stop at this meeting place discussed the Golden fault. The bus then proceeded westward on I-70 over the uplifted Front Range block. The Rio Grande rift was entered near Dillon and the Blue River fault on the east flank of the Gore Range was discussed.

From Dillon, the south trending Rio Grande rift was followed. Near Leadville, the upper Arkansas Valley was entered and the northernmost prominent physiographic expression of the rift was viewed. Additional stops were made near Buena Vista to examine recent fault scarps along the Sawatch fault and to discuss the Quaternary history of the valley.

Just south of Buena Vista the field trip proceeded over the Mosquito Range on US-285, leaving the Rio Grande rift and entering South Park. Evidence of recent fault activity in South Park was discussed at a stop in this large intermontane valley. The route continued northeastward and returned to the origination point.

* Field Trip Speakers: Allan Krusi, Mike West, Dean Ostenaa, Alan Nelson, and Steve Losh

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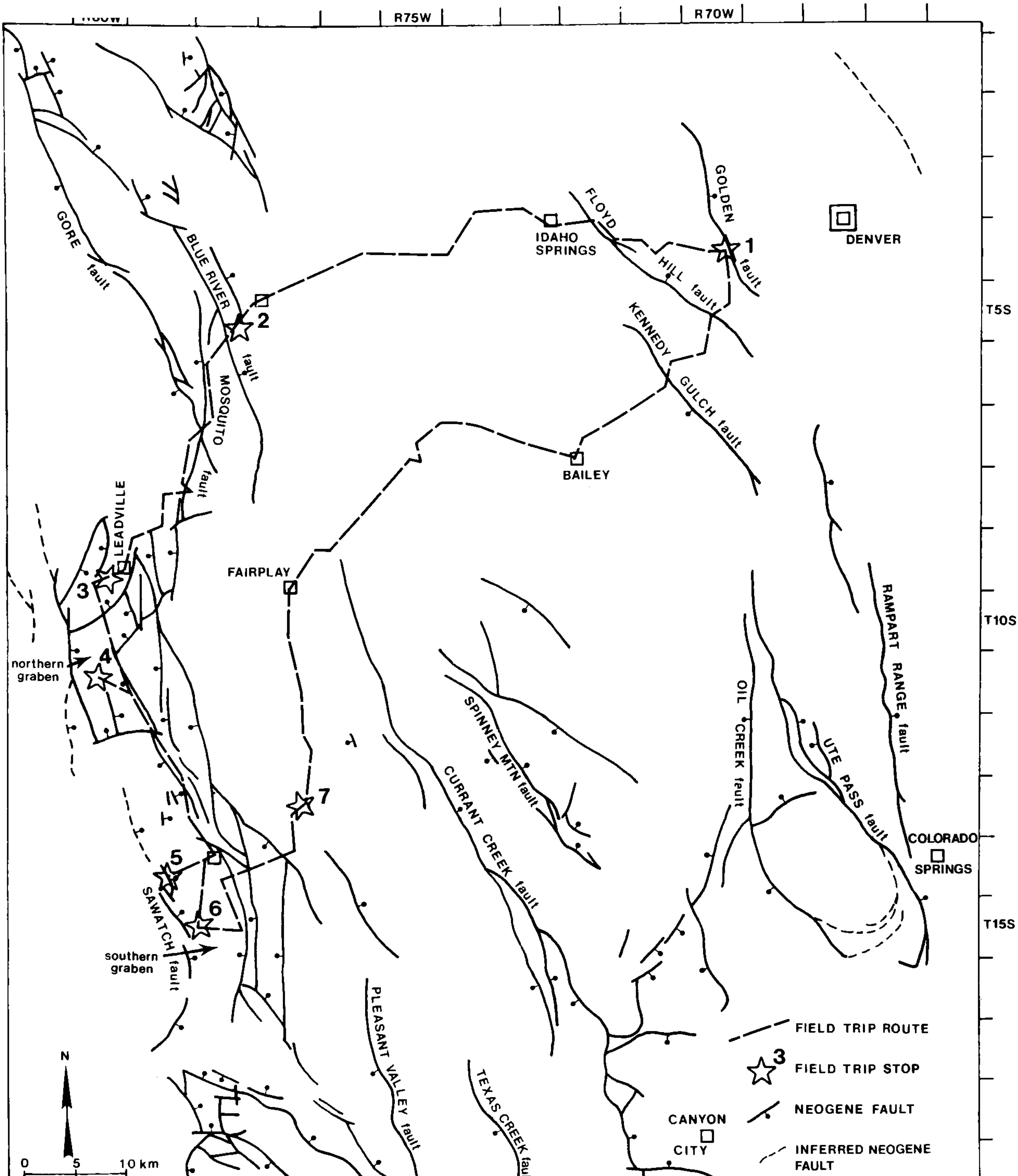

Figure 1. Late Cenozoic faults in central Colorado. (after Kirkham and Rogers, 1981).

FIELD TRIP ITINERARY

Mileage

0.0 Intersection of I-70 and Colo-26.
STOP 1. A discussion of the Front Range and the Golden fault.

The Front Range is a large, generally north-trending, up-arched block over 150 miles long and up to 43 miles wide. An ancestral Front Range was initially uplifted during the late Paleozoic and later eroded and buried by Mesozoic sediments. Up-arching during the Laramide orogeny re-elevated the Front Range in Late Cretaceous to Eocene time. By the end of the Eocene, erosion had lowered the Front Range to the same general elevation as the adjoining sedimentary basins of South Park and Denver Basin, and a widespread erosion surface extended eastward across this region. During the Oligocene, volcanic flows, tuffs, and associated rocks that in part originated in the Sawatch Range, were deposited in paleochannels on the erosion surface. These deposits are found as far east as Castle Rock. The paleochannels were disrupted by block faulting that probably initiated during the early Miocene. The present day topographic configuration of the area is largely the result of this Neogene differential up-faulting of the Front Range and accompanying erosion.

Differential uplift during the Neogene varies along the east flank of the Front Range. The southern part of the Front Range has been uplifted about 1,600 ft relative to the plains, whereas there is very little and possibly no differential faulting along the mountain front at the Colorado-Wyoming line. Near Golden, there appears to be only 200 to 500 ft of differential Neogene offset, based on rough projections of the preserved late Eocene erosion surface in the mountains onto the plains.

At Golden, the east flank of the Front Range is characterized as a locally faulted monocline. The primary fault along this part of the Front Range is the 30 km long Golden fault, a high-angle, west-dipping reverse fault. Maximum displacement on the Golden fault occurs near Clear Creek and is on the order of about 9,000 ft of combined Laramide and Neogene offset. There is no obvious surface expression of Quaternary activity on the Golden fault, but a clay exploration trench northwest of Golden, first described by Glenn Scott, contains evidence suggestive of Quaternary faulting along a possible branch fault. Additional trenching in this area by Bob Kirkham and Pat Rogers in 1976 revealed evidence of multiple movements on a small graben-like feature with a total of 18 ft of post-Kansan displacement.

Because of the potential seismic hazard posed by the existing evidence, the Rocky Flats nuclear processing plant was requested to conduct a thorough earthquake hazard evaluation of the Golden fault and associated faults. This detailed investigation was conducted by Dames and Moore, who recently released a draft report on their findings.

A number of trenches were excavated by Dames and Moore across the main trace of the Golden fault. No evidence of late Quaternary activity was found, but several anomalous features suggestive of fault activity affect the bedrock-Verdos alluvium contact. The upper part of the Verdos alluvium exposed in the trenches, however, was not faulted. Whether these anomalous features are of a tectonic origin is debatable, but not significant from an earthquake hazard standpoint.

The relationship between the Golden fault and the Quaternary deformation described by Scott, Kirkham, and Rogers is still poorly understood. No definitive evidence regarding the tectonic significance of these features has yet been discovered.

Get on I-70 westbound.

0.3 Approximate contact of the Pennsylvanian and Permian Fountain Formation with Precambrian rocks. For about the next 25 miles the Precambrian rocks are comprised of a variety of interlayered gneisses that were metamorphosed about 1.8 b.y. ago. These gneisses have been complexly folded and are cut by numerous faults ranging in age from Precambrian to late Tertiary. The highway begins its ascent to the general level of the late Eocene erosion surface at this point.

2.8 Crossing the Junction Ranch fault, a fault with no apparent Neogene movement. The shear zone is exposed in the road cut on the right. Note degree of weathering at the surface in these exposures. Such weathering is typical of areas where the late Eocene erosion surface is preserved.

4.0 Generally accordant topography and areas of deep weathering on the right mark the late Eocene surface. Intense shearing in the Blackhawk fault zone can be seen in the road cut above the quonset hut.

4.5 Highway follows the Blackhawk fault zone for about the next 1.5 miles. Upper Tertiary gravels that cap a hill to the northwest cover this fault.

4.9 Genessee exit.

6.1 View to right across canyon cut by Clear Creek during the Pliocene and Quaternary. Gently rolling area beyond canyon is a remnant of the late Eocene surface.

7.1 El Rancho-Evergreen exit.

8.6 Upper Tertiary gravel caps the hill on the north just past the powerline.

10.1 Upper Tertiary gravel that caps the hill to the left has been downthrown about 500 ft. by the Floyd Hill fault.

11.1 Highway generally parallels the Floyd Hill fault for several miles up this broad valley and then down to Clear Creek. The Floyd Hill fault is a northwest-trending Precambrian fault that has repeatedly been reactivated. About 2,000 ft. of Neogene movement has occurred on it, as is apparent from offsets of the late Eocene surface.

13.5 Prominent ridge directly in front of bus across Clear Creek is capped by upper Tertiary gravel.

14.1 Junction of I-70 with US-6 at Clear Creek. Stay on I-70.

17.5 At Idaho Springs the field trip route enters the Colorado Mineral Belt, a northeast-trending zone that is 10 to 15 miles wide characterized by richly mineralized areas and Laramide porphyry intrusives.

26.1 Junction of I-70 and US-40. Stay on I-70. For the next 17 miles we pass through Precambrian rock composed of intrusive bodies of the 1.4 b.y. old Silver Plume granite emplaced in 1.8 b.y. old gneiss. Numerous Precambrian faults cut across the field trip route, but none appear to have been reactivated during the Neogene.

30.5 Georgetown exit.

43.0 Approaching Eisenhower Tunnel. Loveland ski area is on the left. The tunnel runs beneath a low saddle in the Continental Divide. A wide faulted and fractured zone, the Loveland Pass-Berthoud Pass shear zone, passes through this general area. Shearing is especially intense in the saddle area. Considerable engineering problems were encountered during tunnel construction because of crushed and broken rock in the shear zone.

44.8 Leave tunnel. The highway descends along steep grade down Straight Creek. Numerous north to northwest-trending faults cross the valley and are exposed in Precambrian rock in the road cuts. Many of these faults originated in the Precambrian, but also have experienced later movement. To the north in Williams Fork valley, Neogene movement can be documented on this fault system. At this location the faults border a graben filled with Miocene sediments. There are some indications of pre-Bull Lake activity during the Quaternary on a few faults in Williams Fork Valley.

As we descend toward Dillon, the Gore Range and Tenmile Range come into view. Both ranges are bounded on the east by the Blue River or Frontal fault. This fault is part of an extensive Precambrian fault zone over 150 miles long that is known as the Ilse-Gore fault system. It was reactivated in late Paleozoic, Laramide, and Neogene times.

50.8 An exposure of the Laramide age Williams Range thrust fault, along which Precambrian rock is thrust over the Cretaceous Pierre Shale, is on the right. No evidence of Neogene activity has been discovered on this fault or on other major Laramide thrust faults in Colorado.

52.9 Exit from I-70 onto Colo-9. Turn right into parking lot of Village Inn Pancake House.
<u>STOP 2</u>. A discussion of the east flank of the Gore Range by Michael W. West, J. W. Patterson & Assoc., Inc.

The southern end of the Gore Range from the North Willow Creek drainage to Frisco and the Tenmile Range south to the Breckenridge/Hoosier Pass area are visible from this stop. The large rounded peak on the skyline to the west is Buffalo Mountain. The South Willow Creek valley north of Buffalo Mountain was the site of the proposed Red-Buffalo interstate alignment. This route, vigorously opposed by environmental groups, was abandoned in favor of the Vail Pass route constructed during the mid-1970's.

The Frontal (Blue River) fault juxtaposing Precambrian crystalline rocks of the Gore Range fault block against Mesozoic and Tertiary sediments of the Blue River fault block, lies at the base of the Gore Range, about 3 miles to the west. The fault intersects the Mosquito fault near the mouth of Tenmile Canyon and is believed to continue to the south along the east flank of the Tenmile Range, over Hoosier Pass and into South Park. To the north, the fault swings to the west across the crest of the Gore Range in the vicinity of the Colorado River, thirty miles to the north. The zone of maximum Quaternary displacement reported by Tweto, Bryant, and Williams (USGS Bulletin 1319-C, 1970) lies between Surprise Lake, 18 miles to the northwest and the town of Frisco at the mouth of Tenmile Canyon.

Movement along the Frontal fault has produced an impressive fault-line scarp more than 2,200 feet in height along the central, east flank of the range. As much as 4,000 feet of structural relief is believed to exist between the crest of the range and Precambrian rocks underlying Mesozoic sediments in the Blue River valley. The fault probably experienced displacement during Laramide time, perhaps along a pre-existing structure. Maximum displacement along the Frontal fault, however, probably occurred during the Neogene uplift of the Gore Range.

The Frontal fault along the central, east flank of the range consists of a series of short segments, striking north to northwest and arranged in a left en echelon pattern. These segments are connected by a second family of faults, striking northwest and connecting the first set of faults in a zig-zag pattern. In several areas, a number of parallel or sub-parallel faults separated by brecciated zones are present. Individual faults are vertical or dip at high angles to the east. The Frontal fault along with other major high-angle normal and reverse faults in north-central Colorado are believed to be part of the Rio Grande rift system, which extends from southern New Mexico to possibly as far north as the Colorado-Wyoming border.

Unfortunately, the Frontal fault and reported late Pleistocene/Holocene surface features associated with the fault, with one exception, are not visible from this stop. The base of the mountain front is obscured by a sloping piedmont surface averaging 2 to 5 miles in width and several hundred feet in height above the present level of the Blue River. This piedmont surface is extensively mantled by Pleistocene glacial deposits and landslide debris.

A large landslide complex believed by Tweto, Bryant, and Williams (USGS Bulletin 1319-C, 1970) to represent early glacial and post-glacial displacement along the Frontal fault is visible between North and South Willow Creeks. The most striking feature of this landslide complex is a crown scarp over 800 feet in height and almost 5,000 feet in width. The landslide mass itself extends over 6,000 feet from crown to toe. Part of the Frontal fault zone, comprising several individual fault strands separated by brecciated and hydrothermally altered rock, is present in the scarp. Holocene avalanche deposits and at least one periglacial rock stream are visible on or below the slide scarp.

During my work in the area, I concluded that two major episodes of landsliding were indeed represented by the landslide complex, although ages of landsliding could not be established with certainty. No evidence could be found to substantiate fault movement as a trigger for either episode of landsliding. Moreover, Holocene avalanche deposits lying across individual fault traces in the slide scarp were undisturbed. In my opinion, the landsliding occurred due to a combination of high shearing stresses associated with steep slopes in the area and severely weakened and perhaps saturated rock associated with the fault zone. These factors alone could result in landsliding of the magnitude observed without requiring tectonic fault displacement and/or earthquake ground shaking. This landslide as well as others in or near the Frontal fault zone are the result of topographic, compositional, hydrologic, and structural controls.

Please refer to the Symposium program and cited references for a more complete discussion of these features.

Return to I-70 west-bound.

56.7 Cross the Blue River fault.

57.4 Frisco exit.

62.6 Junction of I-70 and Colo-91. Turn south on Colo-91. The valley which the highway generally follows is in the Mosquito fault zone. The fault is a reactivated Laramide structure and borders the west side of the Tenmile Range in this area. To the south it is on the west flank of the Mosquito Range.

65.4 The Gore fault joins the Mosquito fault in this area, but the relationship is obscured by a Laramide intrusive and covered by extensive glacial cover.

73.9 Fremont Pass. Climax mine, the world's largest molybdenum mine is to the east. The ore body is on the upthrown side of the Mosquito fault, which is just in front of the caved hole. To the north the fault is at the break in the grassy slope above timberline. Southward across the valley, the fault is in the grassy saddle area to the right of the peak and is marked by a prominent scarp in bedrock, the result of differential erosion along the silicified, brecciated fault zone. Anomalous geomorphic features that suggest Quaternary activity are found along the fault where it crosses the south lateral moraine of the valley. Just west of the main trace in this area there are several unusual east-facing scarps in both morainal and landslide deposits. These scarps could be antithetic faults related to the Mosquito fault or they might be caused by slope instability.

Deep drilling indicates the ore body at Climax, which is younger than 30 m.y., is offset about 9,000 ft by the Mosquito fault. South of Climax, slivers of the upper Tertiary Dry Union Formation occur within the fault zone. Similar rocks are found over 2,000 feet lower to the west.

86.8 Enter downtown Leadville. Mountains to the west are the Sawatch Range. The upper Arkansas Valley is the northernmost prominent physiograhic expression of the Rio Grande rift. This area was the site of a huge north-trending anticlinal structure during the Laramide orogeny. The Sawatch Range formed the crestal and western parts of the anticline and the Mosquito Range was on the east flank. The upper Arkansas Valley is a Neogene structure consisting of two grabens that cut longitudinally through the Laramide anticline.

The west side of both grabens is essentially a single fault or fault zone at the base of the Sawatch Range. The east side is step-faulted along a series of north-trending normal faults. The Mosquito fault is the easternmost fault in this group. The upper Tertiary Dry Union Formation, which is locally covered by glacial deposits, fills the valley. Tweto (1961; 1978) and Tweto and Case (1972) suggest that several faults in the northern end of the valley offset pre-Wisconsin gravels.

87.7 Turn right towards County High School.

87.9 Turn right into the parking lot of the Lake County High School. STOP 3. An overview of the Neogene history of the upper Arkansas Valley by Dean Ostenaa, Allan Nelson, and Steve Losh, U.S. Water and Power Resources Service.

The main north Arkansas graben extends from just north of Turquoise Lake, across the valley to the west, and south to the Twin Lakes area. It is bordered on the west by the Sawatch fault, which consists of north-northeast to north-northwest trending segments along the valley-range margin. Excepting an area south of Turquoise Lake, Quaternary deposits at the surface along the fault trace are "Pinedale" and younger.

In the Turquoise Lake area, the Sawatch fault trends northeast. The rangefront is fairly linear, but not strongly faceted. Dry Union Formation (?) exposed in roadcuts along the front dips 13° to 16° SE. Geomorphic expression of faults mapped or inferred in bedrock is inconsistant along strike, more suggestive of erosional control than of young faulting. Precambrian rocks underlying remnants of erosional surfaces are deeply grusified and show no evidence of erosion by "Pinedale" outwash or of young faulting.

In contrast to the western graben boundary, the eastern boundary is apparently a several kilometer wide zone of north-trending step faults extending from west of Leadville to the Mosquito Range on the eastern skyline. Geomorphic expression of these faults on "Bull Lake" and pre-"Bull Lake" alluvial surfaces is lacking in the area east and south of Leadville. None of these surfaces extend across the Mosquito fault, the easternmost of the step faults.

Return to US-24.

88.1 Turn right on US-24.

90.7 Malta railroad junction. The lowest gravity low (-338 mgals) in the conterminous U.S. is in the northern graben to the right. An estimated 3,000 to 4,000 ft of Tertiary deposits fill the graben at this location.

90.9 Pre-Bull Lake gravel exposed in road cuts on left for next 1.5 miles.

92.2 Pediments ahead on left are primarily cut on Dry Union Formation.

94.2 Weston Pass road.

98.7 Prominent gullies on right cut into pre-Bull Lake outwash. Faults which offset the outwash are exposed in the gullies.

99.3 Enter small canyon cut into Precambrian rock in the south end of northern graben.

101.5 Junction of US-24 and Colo-82. Turn right on Colo-82. Cross Bull Lake moraine.

102.6 Early Pinedale terminal moraine at left.

103.0 Lower lake of Twin Lakes.

103.8 Turn left into picnic area.

104.3 STOP 4. A discussion of the Twin Lakes area by Dean Ostenaa, Allan Nelson, and Steve Losh, U.S. Water and Power Resources Service.

The Twin Lakes area is the southern end of the main north Arkansas graben. To the west, the Sawatch fault is along the lower slopes of Mt. Elbert where it is concealed beneath "Pinedale" till and landslide deposits. East to northeast trending cross faults are inferred in the area to account for 1) the 5-km east-west offset in the rangefront; 2) differences in lithologies in the Dry Union Formation north and south of the Twin Lakes area; and 3) the lack of surface and shallow subsurface outcrops of Precambrian bedrock north of the Twin Lakes area in the main graben. A 5 to 8-km wide extension of the main north graben extends south about 8-km to the Clear Creek area.

The high moraines around Twin Lakes are "Pinedale" in age as are the moraines in the damsite vicinity. A large "Pinedale" and younger landslide complex is present to the west on either side of the Mt. Elbert Powerplant. The Precambrian outcrop at this stop, together with outcrops along the Arkansas River canyon to the east, mark the northern limit of surface and shallow subsurface bedrock in the main north graben.

Return to US-24.

107.1 Junction Colo-82 and US-24. Turn right on US-24. Old gold placer workings in pre-Bull Lake outwash.

109.4 Enter Granite

116.4 Enter north end of southern graben.

116.7 Pre-Bull Lake terraces on right.

118.9 Tree covered surface to right underlain by pre-Bull Lake till. Fault scarps along the Sawatch fault are present in this unit about 1 mile west of the highway.

120.8 Road cut on right exposes Kansas alluvium.

122.0 High peaks at 8 o'clock are Buffalo Peaks, capped by Oligocene volcanic rocks. The andesitic flows and tuffs erupted from a volcano in the Sawatch Range and flowed eastward down a paleochannel that extended across the upper Arkansas Valley prior to graben formation during the Neogene.

123.0 View of the Sawatch Range on the right and the Mosquito Range on the left. The Sangre de Cristo Mountains are straight ahead. The Sawatch fault, represented by a series of en echelon scarps at the base of the Sawatch Range forms the west side of the southern graben. A series of step faults border the east flank of the graben. About 4,000 ft of Cenozoic deposits underlie the valley near Buena Vista.

125.3 Enter Buena Vista.

126.0 Junction of US-24 and Colo-306. Turn right on Colo-306.

130.6 Turn left into parking area at ranch.

STOP 5. Discussion of the Sawatch fault at South Cottonwood Creek by Dean Ostenaa, Allan Nelson, and Steve Losh, U.S. Water and Power Resources Service.

This stop will examine fault scarps in "Bull Lake" and "Pinedale" till and outwash. Three trenches and several soil pits were excavated in this area by the Water and Power Resources Service.

To the south, the Sawatch fault defines the contact between valley fill and Tertiary intrusive rocks and is marked by a pronounced slope break. About 300-m south of the highway, the fault enters a sequence of "Bull Lake" and "Pinedale" terraces and becomes strongly en echelon, stepping east about 150-m as it traverses the site. Along the western segment of the fault, a "Bull Lake" terrace/moraine sequence is offset 5 to 7-m along a zone of discontinuous en echelon scaprs which end at the "Pinedale" surface on which the road is built. A second, eastern scarp segment, itself composed of two right echelon portions, defines the eastern edge of the "Bull Lake" terrace and forms a 2-m scarp in the "Pinedale" surface. This scarp is visible as a rise in the road immediately west of the irrigation ditch adjacent to the ranch building south of the road. This eastern scarp continues northward across Cottonwood Creek, where 2 to 3-m scarps are present on a correlative "Pinedale" terrace.

Two trenches were excavated in "Bull Lake" till and outwash on the western fault segment, and a third trench was excavated across the eastern fault segment scarp in the "Pinedale" outwash adjacent to the road. The geomorphic expression of faults at the site suggests somewhat different displacement histories for the two segments. Combined data from the three trenches suggest at least six surface faulting events of the "Bull Lake" surfaces at the site.

These events are primarily delimited by scarp-derived colluvial wedges preserved on the downdropped block.

Return towards Buena Vista.

131.6 Buffalo Peaks paleovalley at 11 o'clock. The Trout Creek paleovalley is at 1 o'clock. It trends eastward near the crest of the ridge south of Trout Creek. We will travel up this valley as we return home.

134.3 Junction Colo-306 and Chaffee County Rd. 321. Turn right on Chaffee County Rd. 321.

140.9 Junction of Chaffee County Rds. 321 and 322. Turn right on Chaffee County Rd. 322.

141.1 STOP 6. An overview of the Quaternary geology at Chalk Creek by Dean Ostenaa, Allan Nelson, and Steve Losh, U.S. Water and Power Resources Service.

The Sawatch fault in the south Arkansas graben trends along the moderately faceted slopes of the Collegiate Range to the west. To the north and west it is marked by a steep bedrock scarp abutting mid- to late Quaternary alluvium, and is continuous with the scarps at Cottonwood Creek.

Immediately to our west, the surface on which we parked (Nebraskan of Scott and others, 1975) is in fault contact with Tertiary intrusive rock at the base of the slope break. The fault is either en echelon or offset by a cross fault across Chalk Creek. Across Chalk Creek to the south is a 38-m scarp in a "Bull Lake" moraine. Scarp heights in correlative outwash less than 1-km south of the moraine and elswhere in the valley along the fault average about 10-m. Trenches in the "Bull Lake" and "Pinedale" outwash immediately south of the moraine indicated a history of recurrent late Quaternary displacement similar to events described near Cottonwood Creek.

Similar to the north graben, the eastern boundary of the south Arkansas graben is not a single fault, but rather a series of step faults and tilted blocks. This structure is largely defined by offsets of Oligocene volcanic rocks atop the Eocene erosion surface.

Remnants of the Buffalo Peaks and Trout Creek paleovalleys can be seen on the east side of the valley. Eagle Rock consists of the early Oligocene Wall Mountain tuff. The long, flat-topped ridge to the right of Eagle Rock is composed of the Badger Creek Tuff and an overlying andesitic lava flow. Bald Mountain is the vent for the late Oligocene (28-29 m.y.) rhyolitic Nathrop Volcanics. Ruby Mountain and Sugarloaf Mountain, the two brownish hills in the foreground just beyond the Arkansas River, are steeply west dipping remnants of the Nathrop Volcanics that have been downfaulted during the Neogene.

Retrace route to Chaffee County Rd. 321.

141.3 Turn right on Chaffee County Rd. 321. Descend steep grade to valley of Chalk Creek.

142.4 Junction of Chaffee County Rd. 321 and Colo-162 at Mt. Princeton Hot Springs. Turn left on Colo-162.

144.8 Junction Colo-162 and US-285. Turn left on US-285.

145.2 Late Oligocene Nathrop Volcanics at Ruby Mountain (3 o'clock) and Sugarloaf Mountain (1 o'clock) dip steeply west. Vent at Bald Mountain (in distance at 2 o'clock) was the source of the volcanics.

150.6 Junction US-24 and US-285. Turn right on US-285. Highway generally parallels the Trout Creek paleovalley over Trout Creek Pass.

150.9 Enter Johnson Village.

152.2 Leave the upper Arkansas Valley. Route climbs up and over the Mosquito Range. A number of step faults along which the Arkansas graben has been downdropped are traversed by the highway during the next several miles. Note faulting and shearing in Precambrian rocks exposed along this part of the route.

154.3 Elongate ridge to the south that nearly parallels the highway consists of Oligocene Badger Creek Tuff capped by andesitic lava.

158.2 Prominent rocky landforms to right are remnants of Oligocene ash-flow tuffs, primarily the Wall Mountain Tuff.

160.4 Buffalo Peaks at 11 o'clock.

162.6 Trout Creek Pass

163.4 Turn left onto U.S.F.S. Rd. 202.
STOP 7. (optional) Discussion of Neogene faulting in South Park by Mark Shaffer.

South Park is a sedimentary basin created during the Laramide orogeny. The basin is floored by formerly more extensive sediments of Paleozoic and Mesozoic age, but the terrestrial South Park Formation of Paleocene age was deposited entirely within the confines of the basin. Major fault trends in South Park appear to have been established as early as the Paleozoic. Thrust or reverse faults dipping away from the basin form the western and eastern boundaries of the park, converging to the north. The physiographic basin is bounded on the south by Oligocene volcanic rocks that overlie and obscure older formations and structures. Faulting in the volcanics and accumulation of Miocene sediments in the Antero Syncline attest to later tectonic activity that has been correlated in part with formation of the Rio Grande rift. Earthquake activity in South Park is almost unknown historically and seismographically.

Probable Neogene structures in South Park include the generally northwest-striking Currant Creek and Chase Gulch fault systems and numerous relatively minor faults in the volcanic terrain of the southeast basin margin. These systems were studied by Converse Ward Davis Dixon in connection with the City of Aurora's Spinney Mountain Dam. The investigations revealed a rather complex fault system in the Spinney Mountain area interpreted to have been active through both Pinedale and Bull Lake glaciations. Slocum Alluvium was displaced by the same amount as Bull Lake deposits. Post- Pinedale soil profiles do not appear to have been cut, suggesting displacements on the faults occurred roughly between 13,000 and 150,000 years ago. The faults are thus classified as capable under most regulatory criteria. The controlling tectonic structure of the capable system is a segment of the Chase Gulch normal fault; however, Quaternary shear planes exposed in shallow excavations are distinct from earlier planes of movement. Quaternary displacement evidently resulted from tectonic subsidence east of the Chase Gulch fault.

Return to US-285.

164.2 Antero Junction. Continue north on US-285.

165.7 Hills at 10 o'clock and 1 o'clock capped by the Oligocene Buffalo Peaks Andesite and underlain by Wall Mountain Tuff. Hill at 3 o'clock formed by Wall Mountain Tuff. The hills mark the position of the Buffalo Peaks paleovalley where it entered South Park.

185.2 Enter Fairplay

188.7 Red Hill Pass

200.9 Enter Jefferson

205.4 Kenosa Pass. Entering drainage of the North Fork of the South Platte River

206.8 The South Platte River valley follows a fault zone for the next 17 miles to Bailey.

212.6 Entering Grant

223.8 Entering Bailey

224.1 Highway turns north to climb Crow Hill. For the next 25 miles we traverse a series of hills and valleys. Part of the hills are preserved remnants of the late Eocene surface, and the valleys have been cut along northwest-trending fault zones. Roadcut on left shows Quaternary gravels in vertical contact with Precambrian rocks. This is an erosional contact.

226.1 Crest of Crow Hill. Now we are on the late Eocene surface.

227.1 Crossing a broad northwest-trending fault zone that follows Deer Creek valley. Offset of the contact between Pikes Peak Granite of the Rosalie lobe and Precambrian gneiss indicate several thousand feet of right-slip movement.

229.2 Crossing another northwest-trending fault zone with right-slip movement.

230.3 Upper Tertiary stream gravels in road cut on left. Note the size of the larger clasts.

230.6 Enter Pine Junction. Crossing the Pine Gulch fault zone. About 0.5 miles to the northwest, the Pine Gulch fault is covered by the Tertiary gravel exposed in the last road cut.

232.4 Crossing another northwest-trending fault. This one shows left-lateral displacement. Note shear zones in road cuts on the left.

232.7 Cross Elk Creek at Shaffers Crossing

233.1 Crossing a northeast-trending fault. The valley to the right follows this fault to the Conifer post office and separates Silver Plume Granite on the left from gneisses on the right.

233.5 Valleys to left and right mark a fault zone with left-slip movement.

235.6 Conifer post office.

235.8 Excellent exposures of Silver Plume Granite on left.

236.7 Entering the Kennedy Gulch fault zone. For the next 0.6 miles the highway crosses this wide shear zone. Several exposures of this fault can be seen in road cuts in this area. The Kennedy Gulch fault offsets the late Eocene surface about 1,000 ft.

237.7 Evergreen turn-off. Kennedy Gulch fault continues northwestward up the valley to the left.

238.6 Enter Aspen Park.

243.5 Cross yet another unnamed northwest-trending fault.

245.4 Enter the Floyd Hill fault zone. Highway generally follows the fault for the next 1.5 miles. The Floyd Hill fault offsets the late Eocene surface about 2,000 ft.

245.7 Cross North Turkey Creek.

245.8 Road cut in the Floyd Hill fault zone. Note slope stability problems caused by the broken and crushed rock.

247.3 Enter Turkey Creek canyon.

249.7 Leave Turkey Creek canyon. Precambrian-Paleozoic contact on left.

249.8 Junction US-285 and Colo-8. Exit north on Colo-8.

252.1 Enter Morrison. Prominent exposure of Lyons Sandstone in front of bus. Junction of Colo-8 and Colo-74. Turn right on Colo-74.

252.3 Turn left at the Tabor Bar. Follow strike valley in Morrison Formation to parking lot.

254.2 Merge with Colo-26.

255.7 Return to parking lot at Colo-26 and I-70.

REFERENCES

Bryant, Bruce, McGrew, L. W., and Wobus, R. A., 1978, Preliminary geologic map of the Denver 1° x 2° quadrangle, north-central Colorado: U.S. Geol. Survey open-file rept. 78-397.

Kirkham, R. M., and Rogers, W. P., 1981, Earthquake hazards in Colorado--A preliminary report: Colo. Geol. Survey Bull. 43, 171 p.

Ostenaa, D. A., Losh, S. L., and Nelson, A. R., 1980, Recurrent late Quaternary faulting in the upper Arkansas valley near Buena Vista, Colorado: Geol. Soc. America Abstracts with Programs, v. 12, no. 6, p. 300.

Scott, G. R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, in Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 227-248.

Scott, G. R., Taylor, R. B., Epis, R. C., and Wobus, R. A., 1978, Geologic map of the Pueblo 1° x 2° quadrangle, south-central Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-1022.

Shaffer, M. E., 1980, Seismic hazard evaluation, Spinney Mountain project, Park County, Colorado: Converse Ward Davis Dixon, Inc., rept. 78-5129, prepared for R. W. Beck and Associates, 77 p.

Tweto, Ogden, 1961, Late Cenozoic events of the Leadville district and upper Arkansas valley, Colorado: U.S. Geol. Survey Prof. Paper 424-B, p. 133-135.

Tweto, Ogden, Bryant, B., and Williams, F. E., 1970, Mineral resources of the Gore Range - Eagles Nest primitive area and vicinity, Summit and Eagle Counties, Colorado: U.S. Geol. Survey Bull. 1319-C, 127 p.

Tweto, Ogden, 1978, Northern rift guide 1, Denver-Alamosa, Colorado, in Hawley, J. W., ed., Guidebook to the Rio Grande Rift in New Mexico and Colorado: New Mexico Bur. Mines & Mineral Res. Circ. 163, p. 13-27.

Tweto, Ogden, and Case, J. E., 1972, Gravity and magnetic features as related to geology in the Leadville 30-minute quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 726-C, 31 p.

Tweto, Ogden, Moench, R. H., and Reed, J. C., Jr., 1978, Geologic map of the Leadville 1° x 2° quadrangle, northeastern Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-999.

Tweto, Ogden, Steven, T. A., Hail, W. J., Jr., and Moench, R. H., 1976, Preliminary geologic map of the Montrose 1° x 2° quadrangle, southwestern Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-761.

West, M. W., 1977, A preliminary evaluation of the Quaternary geology, reported surface faulting, and seismicity along the east flank of the Gore Range, Summit County, Colorado: Colorado School Mines M.S. Thesis T-1828, 209 p.

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BULLETIN 40 -- Radioactive Mineral Occurrences of Colorado and Bibliography, J. L. Nelson-Moore, D. B. Collins, and A. L. Hornbaker, 1978, 1054 p. Fiche text and plates $4.00, Fiche text and original plates $12.00.

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GEOLOGIC MAP OF COLORADO -- U.S. Geological Survey, Ogden Tweto, 1979, 2 sheets, revised colored state geologic map, scale 1:500,000, $10.00 ($10.50 rolled and mailed).

MAP SERIES 13 -- State Lands Status Map, Lands and Minerals Administered by Agencies of the Colorado Department of Natural Resources, 1979, scale 1:500,000, $3.00.

BULLETIN 37 -- Bibliography and Index of Colorado Geology 1875-1975, compiled by Americal Geological Institute, 1976, $7.50 (soft cover); $10.00 (hard cover) (mail orders add $1.00 for each copy, postage and mailer).

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RESOURCE SERIES 5 -- Coal Resources of the Denver & Cheyenne Basins, Colorado, R. M. Kirkham & L. R. Ladwig, 1979, 70 p., 5 pls., over-the-counter $7.00.

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RESOURCE SERIES 10 -- Proceedings of the Fourth Symposium on the Geology of Rocky Mountain Coal, 1980, L. M. Carter, ed., 1980, 131 p., $5.00.

SPECIAL PUBLICATION 13 -- 1979 SUMMARY OF COAL RESOURCES IN COLORADO, D. K. Murray, 1980, 24 p., 28 figs., 14 tables, $2.00.

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