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Contributions to Colorado Seismicity and Tectonics — A 1986 Update

William P. Rogers
Robert M. Kirkham
Editors

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INTRODUCTION

This collection of papers and reports consists of recent work on seismicity and tectonics of Colorado. Contributions were invited from numerous individuals and organizations known by us to be engaged in relevant project or research work pertaining to Colorado. It is intended as an update and supplement to the Colorado Geological Survey Special Publication 19 (1981). The editors have made or suggested no changes in texts submitted by the authors. Some minor changes in organization and format were made in the interest of uniformity. The data and interpretation presented herein are solely those of the individual authors.

REASSESSMENT OF POST-LARAMIDE UPLIFT AND TECTONIC HISTORY OF THE FRONT RANGE, COLORADO

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INTRODUCTION

The Front Range of the southern Rocky Mountains occupies an area of Colorado that has seen several episodes of mountain building during Phanerozoic time (Figure 1). The modern Front Range is a result of uplift and erosion since the early Oligocene (35 Ma) with major uplift since the latest Miocene (Epis and others, 1976, 1980; Trimble, 1980), while the earlier orogenic events took place during the latest Cretaceous-Early Tertiary (67.5-50 Ma) Laramide orogeny (Tweto, 1975) and the Middle Pennsylvanian-Early Permian (305-270 Ma) Ancestral Rocky Mountain orogeny (Kluth and Coney, 1981). Many articles and publications mistakenly consider the present-day Front Range as a Laramide uplift because they completely ignore the Late Cenozoic history of this part of Colorado. It is true that the present-day Front Range is basically the core of the older Laramide mountain range, but the present topographic relief is due to regional uplift and differential erosion that has exhumed the buried core of the older structure.

The Front Range, the easternmost uplift of the southern Rocky Mountains, extends about 300 km (186 mi) southward from the Colorado-Wyoming state line to the Arkansas River near Canon City and is 40-72 km (25-45 mi) wide (Figure 1). It is flanked on the east by the Denver Basin, a structural basin formed during the Laramide orogeny and on the west by an enechelon series of smaller, intermontane basins called the North Park, Middle Park and South Park basins, also of Laramide age, although their structure has been modified by Neogene normal faulting (Figures 1 and 2A). Most of the Front Range is exposed Precambrian igneous and metamorphic rock intruded by a few younger, Laramide age plutons and incompletely veneered with Quaternary surficial deposits including glacial till, talus, colluvium, and alluvium. Many of the Laramide plutons were intruded along a northeast-trending zone called the Colorado Mineral Belt, a zone that contains most of the major mining districts of Colorado and whose location is thought to be controlled by Precambrian shear zones (Tweto and Sims, 1963). These shear zones are also part of the Colorado lineament of Warner (1978, 1980), a set of northeast-trending faults and shear zones that extend from Arizona to Minnesota. Warner has suggested that this feature originated as a Precambrian age, large-scale strike-slip or transform fault like the San Andreas fault in California, though many of the actual faults and shear zones he has included as parts of the lineament are now known to be parts of unrelated, independent structures (Keweenawan Rift in Minnesota and Nash Fork-Mullen Creek suture zone in southern Wyoming/northern Colorado). The Precambrian origin of the Colorado lineament is thus still unknown and may contain elements of diverse origin, although it had a profound influence on the later Phanerozoic geologic history of the Front Range and northern Denver Basin area (Warner, 1980).

The Precambrian core of the Front Range is cut by a network of faults and shear zones of many ages, but some major trends stand out that have had

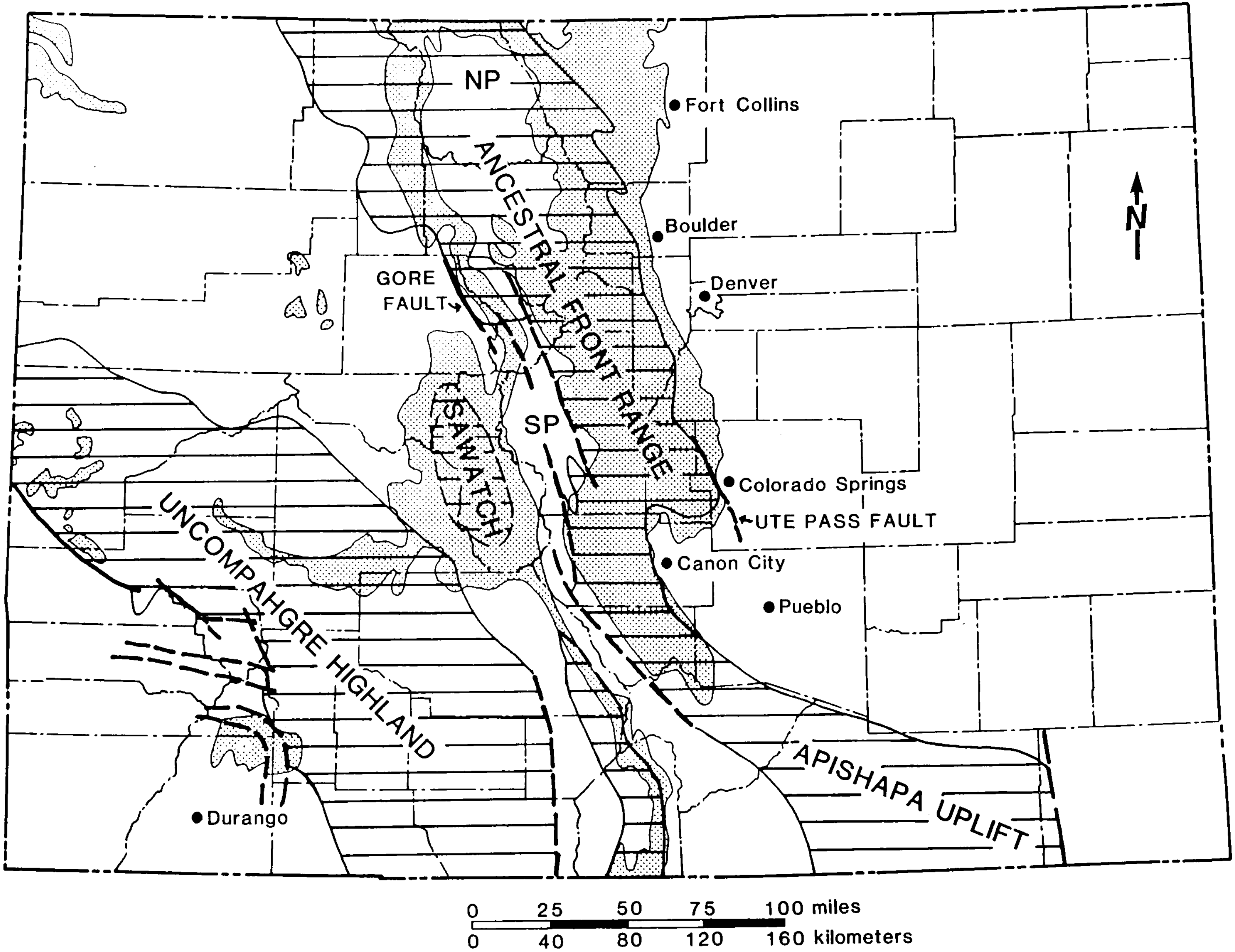

Figure 1. Map of Colorado showing area of Precambrian exposure (shaded) and principal Ancestral Rocky Mountains uplifts (horizontal lines). NP-North Park, SP-South Park. Modified from DeVoto (1980).

recurrent movement since the Precambrian. According to Tweto (1980a, 1980b) four major systems of Precambrian age faults and shear zones can be delineated in the state of Colorado. Three of these, the north-northwest-trending faults, the northeast-trending faults and shear zones, and the faults with generally east trends are prevalent in the Front Range. Many of these structures are thought to have been repeatedly reactivated and thus to control the location and orientation of the various Front Range uplifts. Recurrent movement on Precambrian basement structures of these trends may also have influenced sedimentation patterns and development of structures in the Denver Basin and other areas of Colorado (Weimer, 1980; Sonnenberg and Weimer, 1981; Maughan, 1983).

Along the east flank of the Front Range, from the vicinity of Boulder to the Wyoming state line, the Paleozoic and Mesozoic strata of the western edge of the Denver Basin are faulted and folded into a variety of structures, including monoclines, symmetrical and asymmetrical folds, domes, and basins (Matthews and Work, 1978). From the vicinity of Boulder to the south, the Front Range is bounded by a series of long, enechelon reverse to thrust faults that dip to the west (Harms, 1965; Bieber, 1983; Jacob, 1983; Jacob and Albertus, 1985).

ANCESTRAL FRONT RANGE

The Ancestral Rocky Mountains were a series of northwest-trending basement block uplifts that formed in the Colorado region well away from any deforming plate margins during Pennsylvanian time. Their formation was related to the differential stress generated in the craton from the continent-continent collision that was in progress to the southeast. This collision, called the Ouachita-Marathon orogeny, was between North America and the joint land mass of South America-Africa (Kluth and Coney, 1981). The ancestral Frontrange (single word usage after Mallory, 1975), was the block uplift that shed the coarse arkosic conglomerates and red beds of the Fountain Formation on its east side and the Minturn and Maroon Formations on its west side in central Colorado (Mallory, 1972, 1975; DeVoto, 1980). The Frontrange uplift was a northwest-trending tilted fault block with the major faulting on the west side and no faulting or only minor faulting along its east side (Figure 2D).

A possible candidate for Late Paleozoic faulting on the east side of the Front Range is the ancestral Ute Pass fault near Manitou Springs, a place where the Fountain Formation is coarsest (boulder conglomerate) and thickest (Suttner and others, 1985). One of the major bounding faults on the west side was the Gore Fault which has tremendous structural relief across it of pre-Jurassic age. Upper Jurassic Morrison Formation rests on Precambrian rocks on the east side of the fault while on the west side, 3000 m (10,000 ft) of Paleozoic and Lower Mesozoic strata separate the Morrison from Precambrian rocks (Tweto, 1980a). The trend of this mountain range was much more to the northwest than the north-south trend of the present-day Front Range (Figure 1).

Although the late Paleozoic Ancestral Rocky Mountain orogeny is usually considered to be the first Phanerozoic deformation event to affect the Front Range area, there is evidence for an Ordovician tectonic event. The major fault zones along the east side of the Front Range, especially the Ute Pass and Rampart Range faults, have sandstone dikes intimately associated with them (Harms, 1965). These dikes, which only cut Precambrian crystalline basement, were originally considered by Harms (1965) to be Laramide (Late Cretaceous-Early Tertiary) in age, but are now considered to be Ordovician

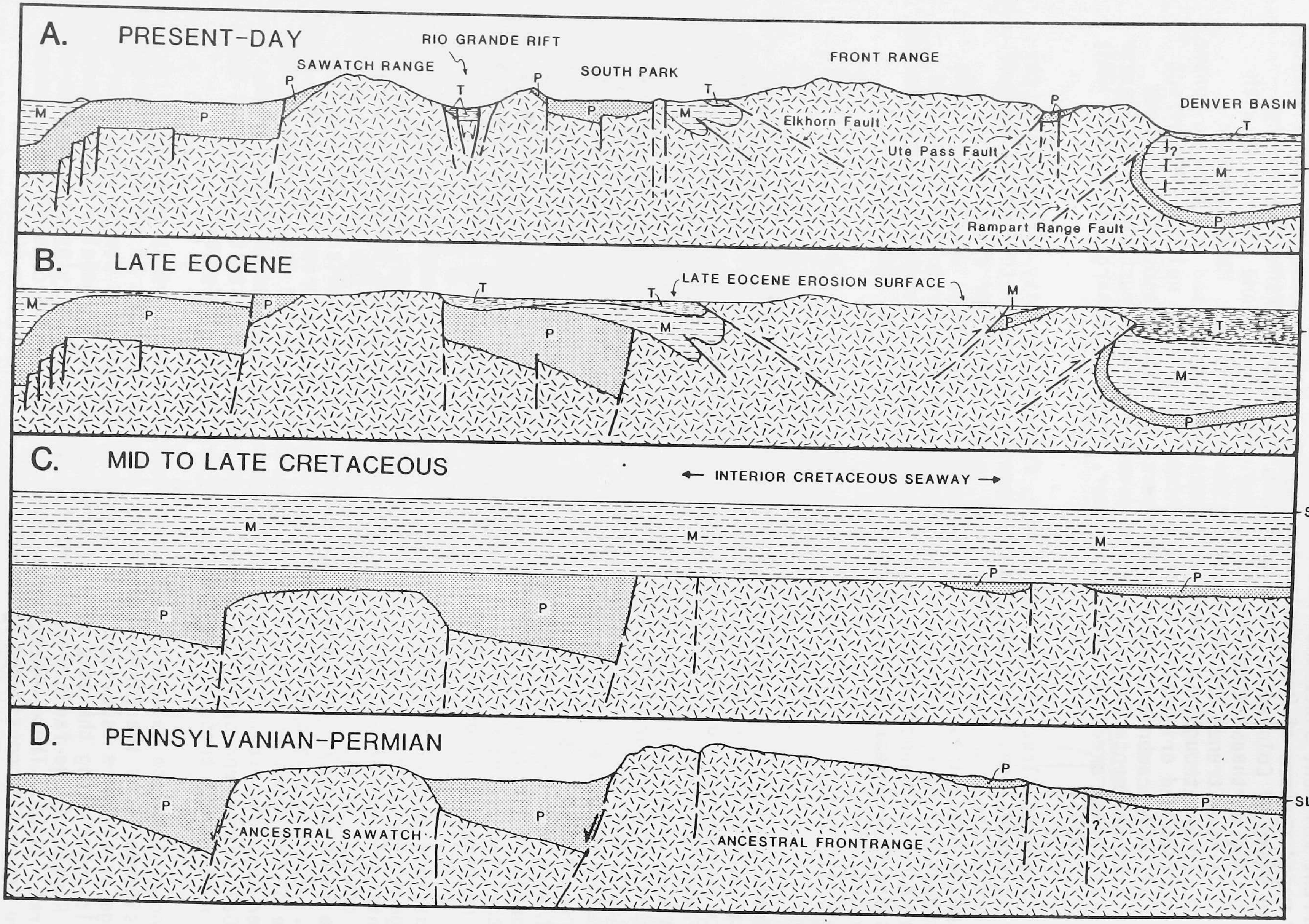

Figure 2. Schematic, west-east cross sections across central Colorado at different geologic times. P-Paleozoic strata, M-Mesozoic strata, T-Tertiary strata, SL-sea level.

based on geological relationships (Kupfer and others, 1968) and paleomagnetic evidence (Kost, 1984). This tectonism did not create any mountains in Colorado but may have caused low fault scarps to form on the Ordovician sea floor (Kupfer and others, 1968) and the opening of fissures in the vicinity of the major faults into which wet sand from the Cambrian Sawatch Sandstone was injected from above (Harms, 1965; Kupfer and others, 1968). There is also evidence for plutonism and igneous dike intrusion of this age in southern Colorado, though no rocks of this age have been dated in the Front Range (Larson and others, 1985).

LARAMIDE FRONT RANGE

After the Ancestral Rockies were eroded flat and tectonic quiescence became established in the Triassic, Colorado began to slowly subside though low hills may have remained in the Front Range area until Morrison (late Jurassic) time. In the Early Cretaceous the entire region began to subside more rapidly due to crustal loading to the west in the developing backarc Sevier fold-and-thrust belt (Jordan, 1981). A continental margin magmatic arc and subduction zone had become established along the western margin of the North American plate in the Triassic (Dickinson, 1981). Backarc compression, beginning in the Late Jurassic to Early Cretaceous and related to westward continental underthrusting of the North American craton beneath the Cordilleran miogeocline, created the Sevier fold-and-thrust belt (Figure 3A) (Scholten, 1982; Lowell, 1977). A major marine transgression into the subsiding foreland basin developed along the eastern margin of the fold-and-thrust belt, produced the intracontinental Cretaceous Interior Seaway (Kauffman, 1977). Both the Ancestral Frontrange and the Denver Basin area became buried under about 3000 m (9842 ft) of marine and marginal marine sedimentary rocks of Cretaceous age (Figure 2C).

At the end of the Cretaceous, this large retroarc foreland basin began to break up with the formation of basement-cored, reverse and thrust fault-bounded uplifts and smaller intermontane basins (Figures 2B and 3B). This Late Cretaceous-Early Tertiary compressional tectonic episode is called the Laramide orogeny and was the result of an eastward migration of the locus of regional deformation associated with the Sevier fold-and-thrust belt out of the miogeocline and onto the craton. The thrusting in the Sevier belt was mainly confined to the miogeoclinal sedimentary prism but as the locus of compression shifted eastward onto the craton, the deformation was no longer limited to the sedimentary section. The craton only had a relatively thin veneer of sedimentary rocks on it and the stresses reactivated pre-existing basement faults and shear zones (Lowell, 1983).

Thrusting in the Sevier belt continued into the Tertiary, possibly as late as Eocene. The eastward migration of deformation has been attributed to a decrease in dip of the east-dipping subducting oceanic (Farallon) plate (Figures 3A and 3B) (Dickinson and Snyder, 1978) caused by subduction of a buoyant aseismic oceanic ridge or plateau (thicker, less dense oceanic crust) (Livaccari and others, 1981; Henderson and others, 1984), by an increase in convergent rates (Jurdy, 1984) or both. The direction of covergence also changed during the Laramide orogeny resulting in a systematic change in the development of specific ranges and basins in the central and southern Rocky Mountains (Gries, 1983). The early Laramide (Late Cretaceous) and preceeding Sevier orogeny were the result of west-east compressional stresses while the later Laramide (Paleocene-Eocene) deformation reflects a rotation of compressional stresses in an anticlockwise direction, so that the axis of

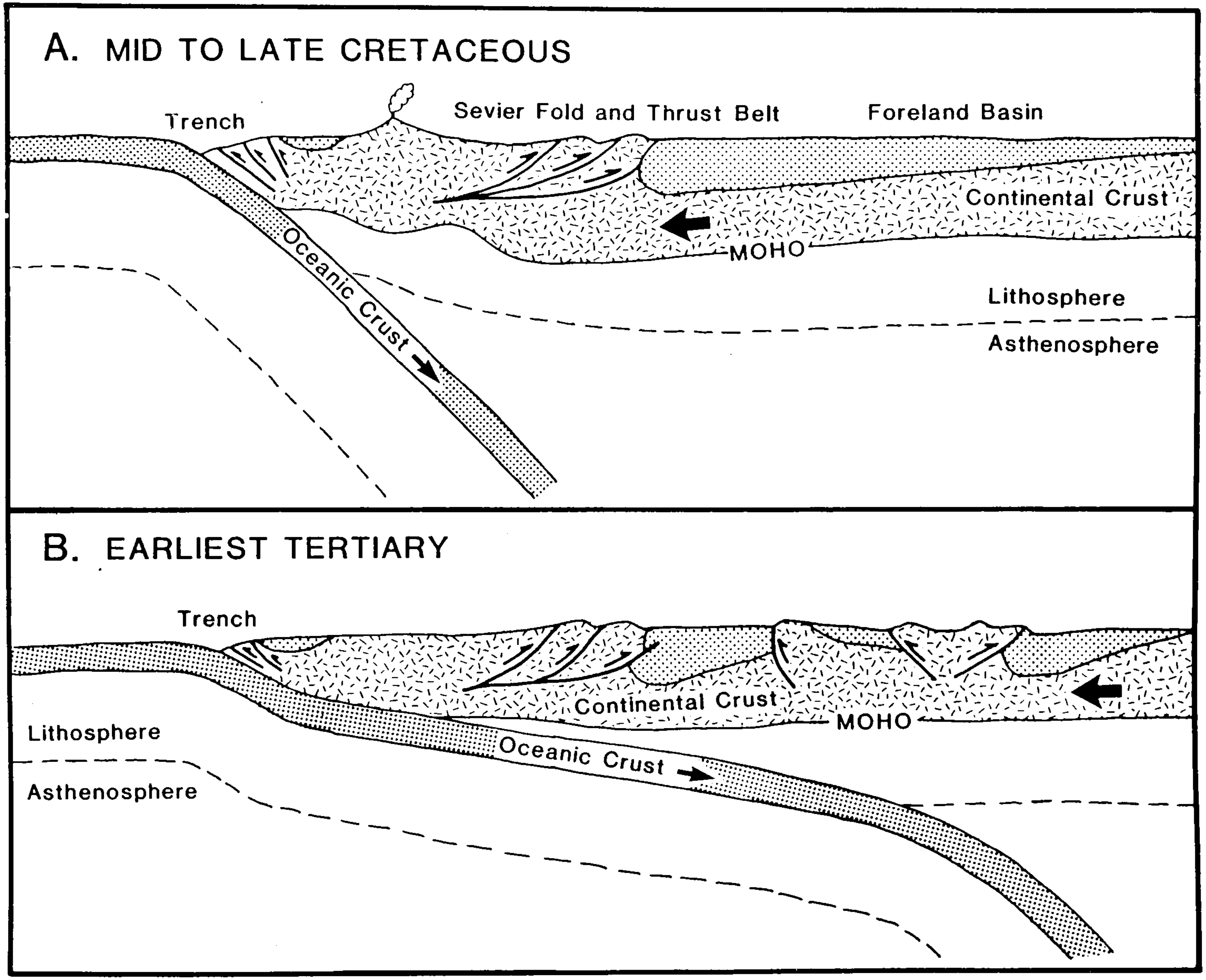

Figure 3. Lithospheric, west-east cross sections for the western half of North America during the (A) Sevier orogeny and (B) Laramide orogeny. The oceanic plate being subducted is the Farallon plate.

compression became more southwest-northeast (Chapin and Cather, 1981) or even very late stage north-south compression (Gries, 1983). This change in compression direction was due to a change in the direction of convergence between the oceanic Farallon plate and the North American plate which was ultimately due to changes in the "absolute" motion (relative to the hot spot frame of reference) of the North American plate (Engebretson and others, 1984).

The uplift of mountain ranges during the Laramide orogeny in Colorado did not begin at the same time in all places. The earliest major uplifts began in the period 72-70 Ma while the uplift of the Gore, Park and Front Ranges began during the interval 70-65 Ma (Tweto, 1980c). The original Laramide Front Range was not as broad as the modern one and had a more north-northwest trend similar to the Ancestral Frontrange of Pennsylvanian age. The northeastern part of the range and its extension into Wyoming as the Laramie Range were uplifted in the Paleocene, about 65-58 Ma (Tweto, 1980c). The Laramide Front Range, with much the same configuration as the range has today, continued its intermittent uplift until sometime in the Eocene. The uplift of the Front Range and other mountain blocks of the Laramide Rocky Mountains are considered by most to be the result of horizontal compression (Brown, 1981; Gries, 1981, 1983; Jacob, 1983; Lowell, 1983), though others have suggested essentially vertical tectonic origins (Prucha and others, 1965; Stearns, 1978; Matthews and Work, 1978), or wrench tectonics (Sales, 1968; Stone, 1969). Chapin (1983) and Chapin and Cather (1981) have proposed a wrench fault mechanism for late Laramide deformation in the southern Rocky Mountains, suggesting the existence of early Eocene, north-trending, major right-slip faults along the western flank of the Front Range. This wrench faulting is thought to have created the en-echelon basins (North, Middle, South and Echo Park basins) that form the western margin of the Front Range. The en-echelon thrust faults that bound the western margin of the Front Range (Elkhorn, Williams Range, and Never Summer thrusts) are considered to be downward steepening splays of complex "flower structures" above the major wrench faults (Chapin, 1983). Earlier, early Laramide east-west compression is thought to have produced the major structures on the east flank of the range. The existence of thrust faults bounding the east and west margins of the southern part of the Front Range (Rampart and Ute Pass thrust faults on the east and the Elkhorn Fault on the west in South Park), has led to the expression "mushroom tectonics" (Jacob, 1983), to characterize the cross-sectional structure of the range (Figure 2A).

Erosion of the earlier Mesozoic, mainly marine sedimentary strata off the rising Laramide Front Range kept pace with the rate of uplift and deposition in adjacent basins so that the actual topographic relief of the mountains was never great, much less than that of the present-day Rocky Mountains. Great thicknesses of these sediments are preserved in the North Park/Middle Park basin (Coalmont and Middle Park Formations), with lesser amounts in the Denver Basin (Denver, Arapahoe and Dawson Formations). Most of the faulting, folding and eastward tilting of the sedimentary strata along the western margin of the Denver Basin happened during the Laramide orogeny. By the late Eocene, uplift had ceased and a regional, low-relief erosion surface was developed across the area of both the uplifts and the basins (Epis and Chapin, 1975; Scott, 1975; Epis and others, 1976, 1980; Trimble, 1980; Colman, 1985).

PRESENT-DAY FRONT RANGE

During development of the late Eocene erosion surface, tectonic quiescence was again established and this quiet period extended through the Oligocene (Figure 2B). During the Oligocene, the regional topography is thought to have been very similar to the present-day eastern plains of Colorado but with a maximum elevation of about 900 m (2920 ft) based on the flora and fauna found in deposits such as the Florissant Lake Beds (Epis and others, 1980). It is important to realize that this erosion surface has been recognized at varying elevations throughout the Front Range, from Rocky Mountain National Park in the north to the Arkansas River in the south, as well as elsewhere in Colorado; it is truly a regional surface (Colman, 1985). Thus, the Front Range, as we know it today, did not exist in the middle Tertiary. This setting probably existed well into the Miocene when major thermal uplift and east-west extension began in central New Mexico and propagated northward into south-central Colorado forming the Rio Grande Rift, a major Neogene extensional feature of crustal dimensions (Tweto, 1979; Cordell, 1982; Colman and others, 1985).

Late Miocene/Pliocene (5 Ma) to present uplift involving both regional uplift of the Great Plains and the Front Range (Trimble, 1980) and differential vertical movement on north-trending normal faults has broken up and uplifted the late Eocene erosion surface. This uplift and its accompanying erosion, has exhumed the structural core of the Laramide Front Range and produced the elevation and relief of the present-day Front Range (Epis and others, 1976, 1980; Scott, 1975; Izett, 1975; Taylor, 1975). Recent studies of various faults along the eastern flank of the Front Range, particularly the Golden Fault, the Front Range is still actively rising (Kirkham and Rogers, 1981) though other studies suggest that these major range-bounding faults are thrust faults with little significant movement since the Laramide (Bieber, 1983; Jacob, 1983; Jacob and Albertus, 1985).

Published works depicting the structural boundary along the southeastern margin of the Front Range, particularly the Rampart Range and Ute Pass faults, show distinctly different interpretations. On the recent compilation map of the Front Range Urban Corridor, Colorado Springs-Castle Rock area by Trimble and Machette (1979), the Denver 1° x 2° quadrangle map by Bryant and others (1981), and the Pueblo 1° x 2° quadrangle map by Scott and others (1978) these range-bounding faults are depicted as high-angle, nearly vertical faults. This interpretation relies heavily on the mapping and interpretation of late Cenozoic (Neogene) alluviums and estimates of late Cenozoic differential uplift within the Front Range (Scott, 1975; Taylor, 1975; Epis and others, 1976, 1980; Trimble, 1980). Trimble (1980) actually shows these range-bounding faults as normal faults on his figures. This differs greatly from studies that suggest very different geometries for the range-bounding faults. Harms (1965), Bieber (1983), Jacob (1983), and Jacob and Albertus (1985) depict these major faults as west-dipping reverse or thrust faults, in places having nearly horizontal dip (Figure 2A). The data presently available do not significantly favor either theory. Both interpretations have conflicting data sets that cannot yet be adequately explained by the other theory and more detailed work must be done along this mountain front to provide new answers.

During the fall of 1985, Target Surveys, Geco Geophysical Co., and GeoQuest Exploration Inc. completed a seismic reflection survey of the structure of the Front Range between Denver and Colorado Springs with 7 east-west seismic lines layed out across the mountain front to test the thrust fault hypothesis (Keener, 1985). Jacob and Albertus (1985) reported surface hydrocarbon (soil gas) anomalies along fracture zones in Pikes Peak Granite up to 8 km (5 mi) west of the Rampart Range mountain front. This has led to increased interest by a variety of oil companies and geophysical companies as outlined above and should provide adequate additional data to resolve the question of mountain front structure.

AMOUNT OF UPLIFT

Quantifying the amount of uplift of the Front Range during the various orogenic episodes is difficult if not impossible. Usually all that can be obtained are minimum values, though those can be useful in many cases. Analysis of structural relief versus topographic relief can also cause confusion as mountain ranges can have great structural relief but little topographic relief. It all depends on rates: rates of uplift, of erosion, and of sedimentation in adjacent basins. The Late Paleozoic ancestral Frontrange is thought to have had both great structural as well as topographic relief. As previously mentioned, a minimum of 3000 m (10,000 ft) of structural relief is estimated for the western margin of the Frontrange along the Gore Fault (Figure 2D). Paleoclimatological studies (Mack and others, 1979) suggest that the Frontrange also had significant topographical relief, though no elevations have been suggested.

The Laramide Front Range is thought to have had significant structural relief but little topographic relief. The amount of structural relief is difficult to separate out from the Neogene uplift, but we can attempt rough estimates. Based on fission-track ages of apatite from the Precambrian Mt. Evans batholith and the position of the 100°C isotherm, Bryant and Naeser (1980) suggest that a total of 6500 m (21,325 ft) of structural relief between Mt. Evans and the deepest part of the Denver Basin was produced since the Upper Cretaceous Fox Hills Sandstone was deposited in the Cretaceous Interior Seaway (Figure 2C). If we accept the present top of Mt. Evans at 4346 m (14,260 ft) as being close to the level of the late Eocene erosion surface (though it may have been exposed as an erosional monadnock) and accepting that it exists near the base of the Wall Mountain Tuff in the vicinity of Castle Rock, Colorado at 2025 m (6650 ft) (Epis and others, 1976, 1980; Trimble, 1980), then post-Eocene differential uplift accounts for a maximum of about 2320 m (7610 ft) of the structural relief leaving 4180 m (13,715 ft) as the amount of Laramide structural relief. Trimble (1980) calculated as much as 6100 m (20,000 ft) of Laramide age structural relief for the Front Range and only about 770 m (2526 ft) of post-Eocene differential movement for the Rampart Range. Since the Eocene erosion surface was probably not flat and was tilted to the east (depositional slope) at, for example, 3.8 m/km (20 ft/mi) (Trimble, 1980) then 266 m (873 ft) could be subtracted from the post-Eocene offset to get 2054 m (6739 ft) for Neogene movement, leaving 4446 m (14,586 ft) for Laramide structural relief. As mentioned earlier, considering that Mt. Evans may have projected above the Eocene erosion surface, the post-Eocene structural offset of 2054 m (6739 ft) is a maximum and depends on the position of the erosion surface with reference to the top of Mt. Evans. Mt. Evans probably did not project more than 600 m (1968 ft) above the surface as the topography was considered to be low. Epis and others (1976, 1980) estimate maximum relief of only a few hundred meters where canyons became incised or monadnocks existed. Even with these considerations, the numbers derived by Trimble (1980) are high with respect to Laramide structural relief and low with respect to Neogene differential uplift of the Front Range (with reference to Mt. Evans). It should also be emphasized that not all parts of the Front Range were uplifted the same amount during these orogenic events.

Though some of the post-Eocene uplift must have taken place in the Oligocene and early Miocene, most of it probably has occurred within the past 5 Ma, since the end of deposition of the Ogallala Formation on the Great Plains (Trimble, 1980). Since that time, the rivers and streams in both the mountains and plains have been downcutting continuously (Scott, 1975, 1975; Epis and others, 1976, 1980; Trimble, 1980). This downcutting is estimated as about 460-610 m (1500-2000 ft) in the vicinity of Denver and is the result of regional uplift. It is estimated that the entire region, including both the Front Range and the Great Plains near Denver, has been uplifted an additional 1330 m (4370 ft) mostly during the past 5-6 Ma (Trimble, 1980). It is also interesting to note that the Castle Rock Conglomerate of Oligocene age has been tilted to the northwest since it was deposited 30-35 Ma, a direction opposite to its depositional dip (Morse, 1985).

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TECTONIC STRESSES IN COLORADO AND THEIR IMPLICATIONS TO SEISMICITY

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ABSTRACT

New stress information in the form of earthquake focal mechanisms has allowed an improved understanding of the tectonic stresses in Colorado. Much of western and central Colorado appears to locate within a regime of rather uniformly NNE- to NE-oriented tectonic extensional stress. How this regime fits within the framework of stress provinces as defined by Zoback and Zoback (1980) will require additional stress data. Generally, earthquakes in Colorado appear to be the result of the tectonic reactivation of pre-existing faults in response to these contemporary stresses. Thus knowledge of the nature and orientation of tectonic stress regimes within Colorado can provide a basis for assessing the capability of faults, such as those within the Colorado lineament, to slip seismically and produce earthquakes.

INTRODUCTION

Knowledge of the state of tectonic stress within a region can provide the basis for assessing the contemporary style and orientation of active faults and for determining their potential for producing earthquakes. In the past, very little stress information has been available for Colorado. However, recent data, primarily in the form of earthquake focal mechanisms, have provided (1) new insight into the stress domains in which Colorado is located, and (2) a tool for evaluating the potential seismic hazard within the state.

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TECTONIC STRESS PROVINCES

In 1980, Zoback and Zoback (1980) published their landmark paper on the state of stress in the conterminous United States. In that study, they defined tectonic stress provinces based on the orientation and relative magnitude of the principal stresses determined from geologic observations, in situ stress measurements, and earthquake focal mechanisms (Figure 1). Within the estimated range of accuracy of the various methods, the stress observations exhibited a significant uniformity over broad regions (Zoback and Zoback, 1980). Although the stresses in any given area probably represent a superposition from several different sources, such broad regions of uniform stress in the intracontinental U.S. probably represent the predominant influence of plate tectonic forces. Local stresses, possibly due to topographic effects or remnant (residual) stresses from previous tectonic episodes, are most likely second-order effects dominated by the greater regional stresses.

Zoback and Zoback (1980) defined four apparent stress provinces with Colorado: (1) the Colorado Plateau province in the western portion of the state; (2) the Rio Grande rift portion of the Basin and Range-Rio Grande rift province in south-central Colorado; (3) the Southern Great Plains province in central and southeastern Colorado; and (4) the Midcontinent province in the northeastern portion of the state (Figure 1). The stress fields of these provinces can be characterized as (Zoback and Zoback, 1980):

$S_1^{WNW} > S_2^{NNE} \simeq S_3^{V}$	Colorado Plateau
$S_1^{V} > S_2^{NNE} \gg S_3^{WNW}$	Basin and Range-Rio Grande rift
$S_1^{V} > S_2^{WNW} > S_3^{NNE}$	Southern Great Plains
$S_1^{NE} \gg S_2^{NW} > S_3^{V}$	Midcontinent

where S_1, S_2 and S_3 are the greatest, intermediate, and least principal stresses, respectively. However, these stress province boundaries are only approximate because of the relatively few stress indicators available at the time for the intermountain U.S., especially Colorado. Only five stress indicators were known for Colorado up through 1980, and these were confined to only two areas of the state: near Rangely and Denver (Zoback and Zoback, 1980) (Figure 1). Of these indicators, the most pertinent to this study were focal mechanisms determined for (Figure 2): (1) the earthquakes induced by secondary oil recovery operations at Rangely (Raleigh et al, 1972); and (2) the earthquakes induced by injection of waste fluids at the Rocky Mountain Arsenal near Denver (Herrmann et al, 1981). A focal mechanism determined for the 1966 body-wave magnitude 5.5 Dulce, New Mexico earthquake, which occurred at the state border (Herrmann et al, 1980), is also significant in the delineation of stress provinces for Colorado and the region (Figure 2).

NEW DATA AND OBSERVATIONS

Several focal mechanisms have recently been determined for Colorado and adjacent areas that provide significant information on the state of stress within Colorado. These mechanisms, both single event and composite, shown on Figure 2, include:

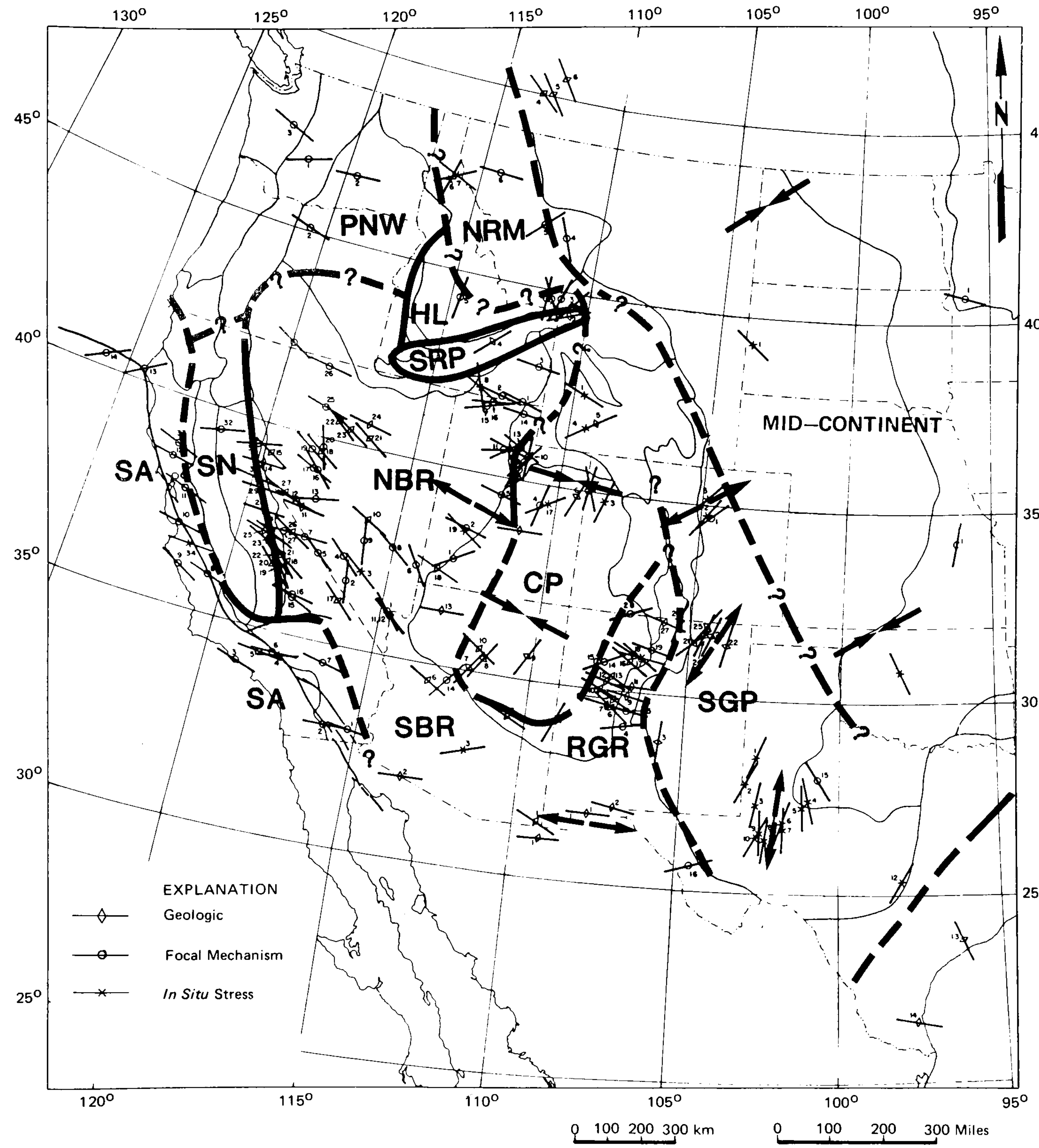

Figure 1. Least horizontal principal stress directions for the western U.S. from Zoback and Zoback (1980). Heavy shaded lines define stress province boundaries, dashed lines where approximate. Physiographic provinces shown by light solid lines. Bold arrows represent average direction of either the least (outward directed) or greatest (inward directed) principal horizontal stress.

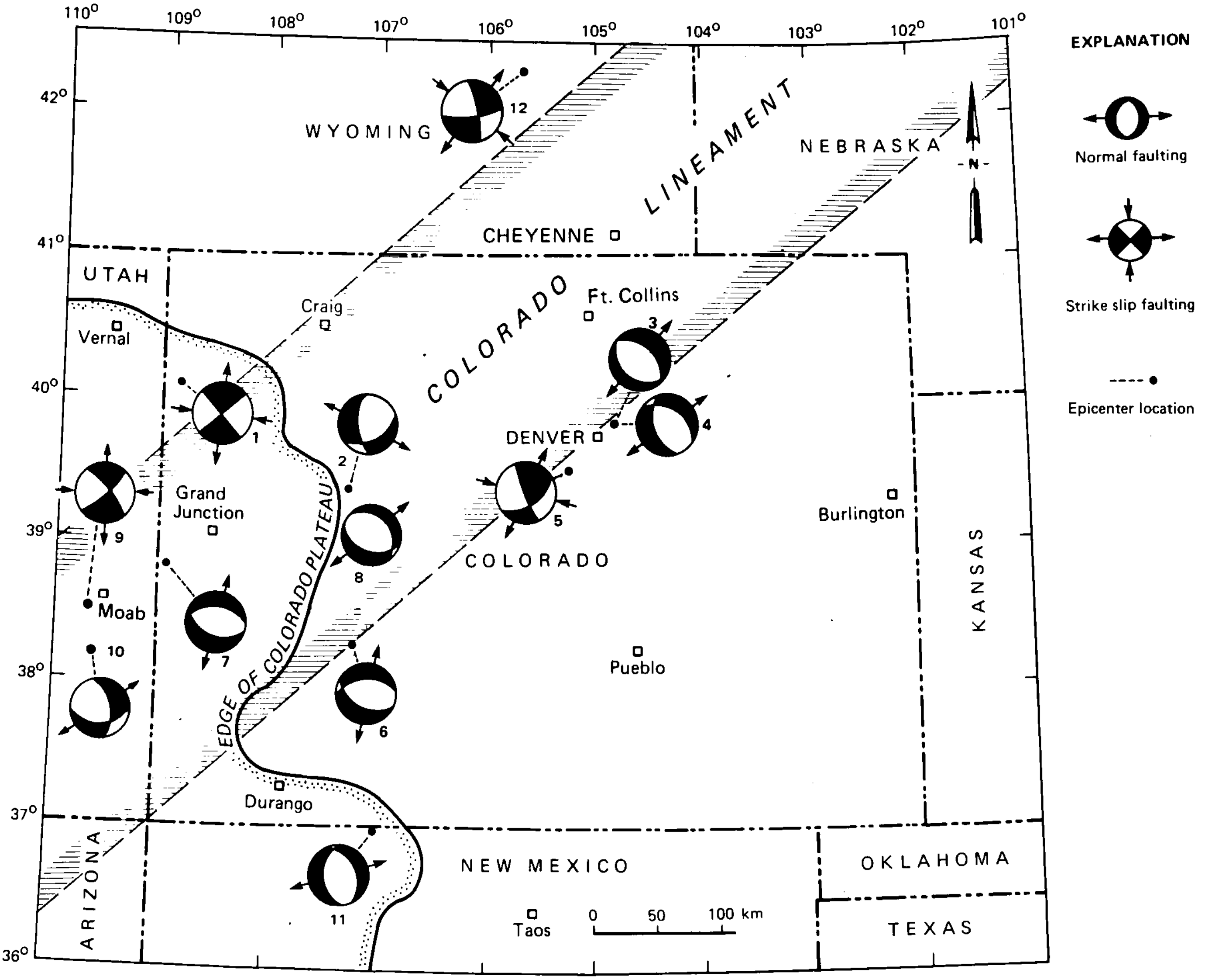

Figure 2. Earthquake focal mechanisms for Colorado and adjacent regions. Dashed lines represent boundaries of the Colorado Lineament as defined by Warner (1978). The inward and outward directed arrows represent the horizontal projections of the P and T axes, respectively. Numbered mechanisms correspond to: (1) Rangely, (2) Carbondale, (3) and (4) Rocky Mountain Arsenal, (5) Conifer, (6) Cimarron, (7) Gateway, (8) Crested Butte, (9) and (10) southeastern Utah, (11) Dulce, and (12) Laramie Mountains. Solutions (1), (3), (4), (5), (10), (11) and (12) are based on other studies and are referenced in the text.

1) The 14 August 1983 local magnitude M_L 3.4 Cimarron earthquake, which occurred in southwestern Colorado and appeared to be the result of normal fault displacement on the Cimarron fault (Wong and Humphrey, 1986) (Figure 3);

2) A M_L 3.2 event on 14 May 1984 that was part of an intense month-long earthquake sequence that occurred in the vicinity of the Grand Hogback monocline near Carbondale. This event also exhibited normal faulting with a minor component of strike-slip displacement (Figure 3);

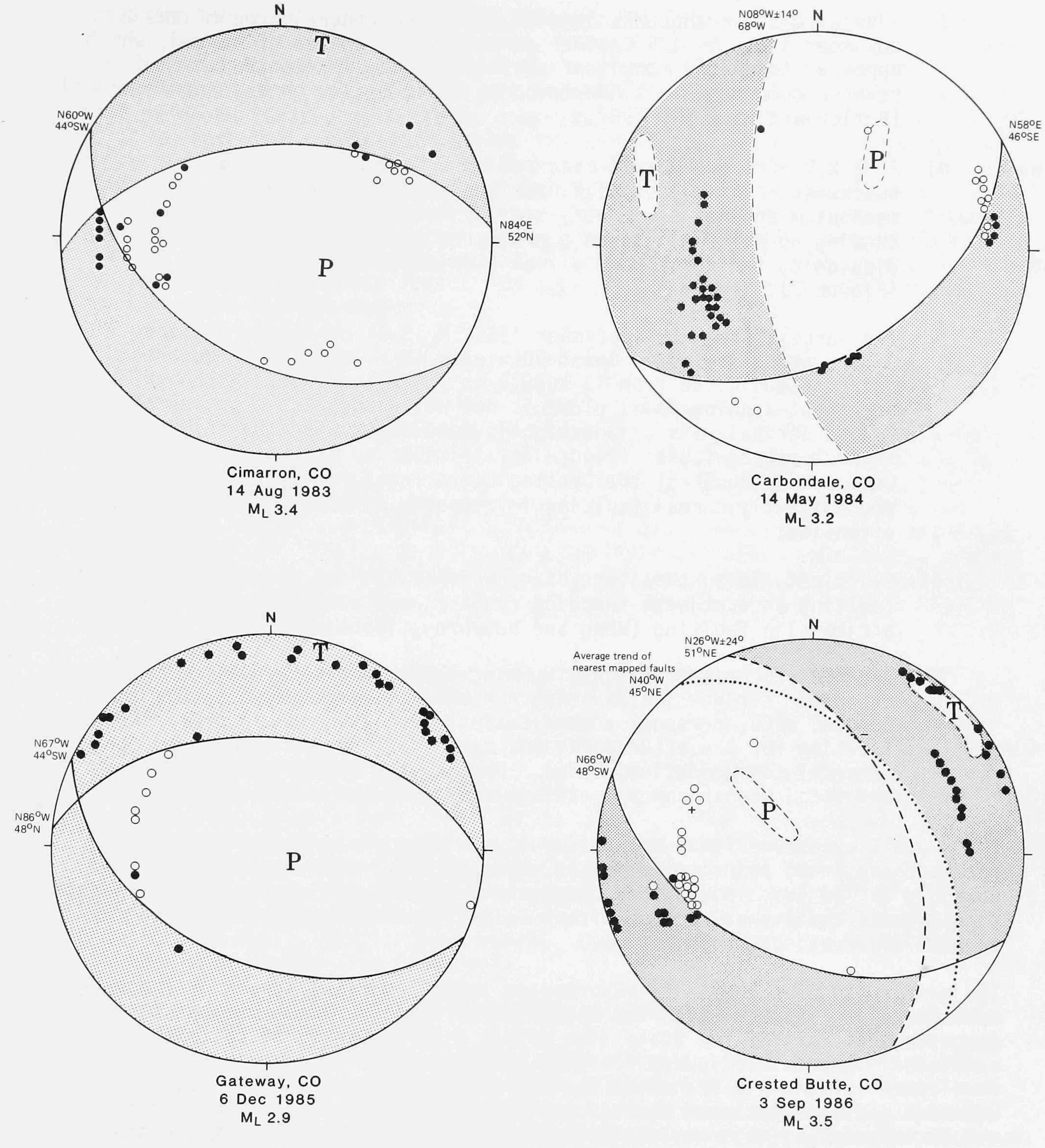

Figure 3. Recently determined focal mechanisms (lower hemisphere projection) for Colorado. All mechanisms exhibit normal faulting. Solid and open circles represent compressional and dilational first motions respectively; pluses and minuses represent arrivals of less certainty. P and T represent pressure and tension axes, which approximate the greatest and least principal stresses, respectively. Shaded areas are the compressional quadrants. Nodal planes are dashed where uncertain.

3) Several microearthquakes located in the epicentral area of the 2 November 1981, M_L 2.8 Conifer earthquake southwest of Denver, which appeared to be the result of strike-slip displacement with a minor reverse component on a NNW-trending fault (based on epicentral trend) (Butler and Nicholl, 1987);

4) A M_L 2.9 earthquake that occurred on 6 December 1985, 46 km southwest of Grand Junction near the town of Gateway. The focal mechanism appears to be very similar to the Cimarron earthquake, showing normal faulting on a preferred plane trending east-west and dipping to the north, and a T-axis oriented NNE (Ely et al, 1987) (Figure 3);

5) The largest event (3 September 1986, M_L 3.5) of another intense earthquake swarm of at least 30 events ($M_L \geq 1.6$) which occurred near Crested Butte from 13 August to 7 October 1986. Although the northeast-dipping nodal plane is not well constrained (uncertainty of 24° in strike), its orientation is consistent with the trends of the nearest mapped faults (Figure 3). Similar to the Cimarron and Gateway earthquakes, the Crested Butte focal mechanism displays predominantly normal faulting in response to northeast-directed extension;

6) Seismicity in southeastern Utah, which exhibited predominantly normal faulting on northwest-trending fault planes with some occurrences of strike-slip faulting (Wong and Humphrey, 1985); and

7) The 1984 Laramie Mountains, Wyoming earthquake sequence, which exhibited strike-slip faulting for the mainshock (M_L 5.5) (D. Gordon, USGS, personal communication, 1986) and normal or strike-slip faulting for the aftershocks (C. Wood, U.S. Bureau of Reclamation, personal communication, 1986). Despite the variation in faulting, the focal mechanisms all exhibited a northeast-trending T-axis.

The P and T axes from focal mechanisms approximate the orientation of the greatest and least principal stresses, respectively, with an uncertainty of possibly 35° to 40°. Given this uncertainty and the need for more stress data to delineate the stress regimes within Colorado, it is possible to make several observations at this time.

The uniformity of the NNE- to NE-trending least principal stress of the focal mechanisms in Colorado (with the exception of the Carbondale mechanism) suggests that most of the state lies within a large region of tectonic extension. A possible source for this tectonic extension may be the development of the Rio Grande rift, which began approximately 28 m.y.a. in Colorado and has continued through the Neogene (Tweto, 1979). This episode was accompanied by major extensional faulting. A large part of the western North American plate was in a state of extension during the late-Cenozoic and still appears to be at present (Eaton, 1979). The extension in Colorado is in marked contrast to the east-west compression responsible for the uplift of the Rocky Mountains during Laramide time (approximately 40 to 80 m.y.a.) (Zoback and Zoback, 1980).

Based on these new results, the stress province boundaries as suggested by Zoback and Zoback (1980) based on limited data within Colorado will require revision (Wong and Humphrey, 1985) (Figure 1). The normal faulting focal mechanisms for the Gateway, Cimarron, Crested Butte, and possibly Carbondale earthquakes in western Colorado, which are similar to the mechanisms in southeastern Utah, suggest that the Colorado Plateau stress province should not be characterized by tectonic compression as was originally thought (Figure 2). Whether the extensional regime in Colorado can or should be subdivided between the Colorado Plateau, Rio Grande rift and Southern Great Plains stress provinces as defined by Zoback and Zoback (1980) will require additional data. As of yet, no stress data is available for eastern Colorado (Figures 1 and 2). Thus, the inclusion of eastern Colorado within the Midcontinent stress province is probably based upon the apparent low level of tectonism and seismicity and the gross crustal structure common to both the eastern portion of the state and the central U.S.

The existence of both normal and strike-slip faulting in close proximity to each other, as near Denver (mechanisms 3, 4 and 5; Figure 2), suggests that in these areas, the greatest and intermediate principal stresses may be approximately equal in magnitude and thus may be capable of interchanging positions. Thus when S_1 is vertical, normal faulting results; strike-slip faulting occurs when S_2 is vertical. Apparently S_3 remains invariant in both orientation and relative magnitude in most of Colorado. Such mixed normal and strike-slip faulting is common in the extensional Basin and Range stress province. The Laramie Mountain earthquakes, which exhibited a mixture of faulting in an area approximately 5 km across, appear to be in response to tectonic extensional stresses, although both normal and strike-slip faulting occurred together.

Another significant aspect of the Laramie Mountains earthquakes is their unusual depth range of approximately 20 to 25 km (Langer et al, 1985). The vast majority of earthquakes in the western U.S. occcur in the upper crust, above a depth of 15 to 20 km (Wong and Chapman, 1986). A possible implication of these earthquakes is that the nature of the tectonic stress field remains constant down to at least to mid-crustal depths, assuming a northeast-trending T-axis in the upper crust. The lack of upper crustal stress observations for southeastern Wyoming, however, precludes a definitive statement. The state of stress has been observed to change with depth due to the increasing lithostatic stress. As observed in western Nevada, the greatest principal stress rotates from horizontal to vertical at a depth of approximately 9 km (Vetter and Ryall, 1983). As a result, the predominant mode of faulting changes from strike-slip to normal.

RELATIONSHIP BETWEEN SEISMICITY AND THE TECTONIC STRESS FIELD

The current and most widely accepted seismotectonic model for earthquake occurrence in the midcontinent and perhaps eastern U.S. involves the reactivation of pre-existing zones of weakness. Based upon this model, at least two factors appear to determine whether a pre-existing zone of weakness (i.e., fault) is seismogenic within its contemporary regional tectonic stress field (Braile et al, 1982): the physical properties that control the strength of the fault, and the orientation of the fault relative to the tectonic stress field. With respect to the latter, Raleigh et al (1972) have suggested that failure (seismic slip) along pre-existing zones of weakness is favored over fracture of intact rock if the zone is oriented within 10 to 50 degrees of the greatest principal stress.

Consistent with this model, Braile et al (1982) note that earthquake zones in the central and eastern U.S. are favorably oriented to the present-day approximately N60°E trending compressive tectonic stress field. In response to these stresses, their model suggests that earthquakes may occur along reactivated strike-slip fault zones oriented approximately northeast to east and zones of reverse faulting trending approximately NNW. However, deviations from these orientations can also be expected due to secondary faulting and responses to local stress conditions (Braile et al, 1982).

It appears that this model is also applicable to Colorado in that much of the seismicity in the state may be the result of reactivation of pre-existing zones of weakness. For example, the 1983 Cimarron earthquake probably occurred on the Precambrian Cimarron fault (which has undergone several periods of reactivation) in response to favorably oriented extensional stresses (Wong and Humphrey, 1986). The 1985 Gateway earthquake appears to have occurred on a reactivated east-west-trending basement fault that is part of the complex northwest-trending Uncompaghre frontal fault zone (Ely et al, 1987). Although induced by fluid injection, the earthquakes at the Rocky Mountain Arsenal occurred along a northwest-trending fracture zone within the Precambrian basement (Hsieh and Bredehoeft, 1981). The induced earthquakes at Rangely had their source along a northeast-trending fault of possible Precambrian age (Raleigh et al, 1976). These observations are consistent with abundant geologic evidence that suggests that much of the faulting in Colorado has undergone recurrent movement. Thus knowledge of the state of stress within portions of Colorado can provide a useful tool for assessing the seismogenic potential of any given faults.

As evidenced by the orientation of the T-axis and the possible fault planes in the focal mechanism of the largest of the Carbondale earthquakes (Figure 3), this sequence may be an exception to the reactivation model for earthquake occurrence. The direction of extension trends WNW in contrast to the NNE to NE trend of other Colorado earthquakes (Figure 2). The suspected fault plane, which trends NNW dipping to the west is consistent with the orientation of a series of parallel faults that occur along the Grand Hogback. A detailed analysis of several smaller events recorded by a temporary microearthquake network shows that the events were diffusely distributed between the depths of 2 to 7 km, suggesting that they occurred on multiple fault planes (Goter et al, 1987). Murray (1969) suggested that these faults were caused by flexural slip between sedimentary layers in the west-dipping hogback due to subsidence and unfolding of the strata in response to the removal of underlying evaporites. Abundant evidence indicates that these faults have been active in recent times (Stover, CGS, personal communication, 1986). It is possible that the flexural slip on these faults occurs in a brittle (seismic) manner resulting in these earthquakes. Thus focal mechanisms such as the 14 May event (Figure 3) might reflect local stress conditions rather than tectonic regional stresses. However, one of two composite focal mechanisms determined by Goter et al (1987) also exhibited normal faulting in response to northeast-directed extension, consistent with regional stresses.

Colorado Lineament

Brill and Nuttli (1983) have suggested that the Colorado Lineament may be a source zone for larger earthquakes (body wave magnitude 4 to 6) within the west-central U.S. As Warner (1978) has defined the Colorado Lineament, it trends northeast across the northwestern portion of Colorado (Figure 2) and consists of the Colorado Mineral Belt, the Homestake, Moose Mountain, Skin Gulch, and Soda Creek-Fish Creek shear zones. However based on only a few focal mechanisms, seismicity in Colorado generally appears to be the result of normal faulting oriented between WNW to NW, with some occurrences of strike-slip faulting. Assuming a NNE-to NE-oriented extensional tectonic stress field for much of Colorado and the reactivation model for earthquake occurrence, the segment of the Colorado Lineament in Colorado or other northeast-trending faults would not appear to be seismogenic based upon their less than favorable orientation (Wong, 1981; 1984).

In a sense this view may be too simplistic; however, the Gateway and Crested Butte earthquakes, which are located within the lineament, and the Cimarron, Rocky Mountain Arsenal and Conifer earthquakes, which locate on the southern boundary of the lineament appear to be due to seismic slip on NW- to WNW-trending faults (mostly normal) oblique to the trend of the lineament (Figure 2). Further characterization of tectonic stresses and detailed evaluations of earthquakes in Colorado will be required to evaluate the Colorado Lineament as a seismogenic source.

CONCLUSIONS

Colorado's location between the rather uniform NE-oriented compressive stress field of the Midcontinent and the multiple stress provinces of the western Cordillera adds considerable complexity to the problem of characterizing the state of stress within the state. It appears that much of the state is located within a regime of tectonic extensional stress.

The source of the extensional stresses in most of Colorado as well as much of the U.S. east of the Basin and Range province is unknown. Additional stress data are required to determine whether the Colorado Plateau, Rio Grande rift and Southern Great Plains stress provinces are distinguishable in the state. A possible source of the tectonic extension observed in central Colorado may be the active extension of the northern extent of the Rio Grande rift. The residual Laramide compressive stresses (which formed the Rocky Mountains) do not appear to be significant on a broad regional scale but may on a local scale have a subordinate role to the contemporary tectonic stresses.

Based on a limited number of cases, earthquakes in Colorado appear to be due to the reactivation of pre-existing faults in response to the contemporary tectonic stress fields. Thus, knowledge of the nature and orientation of tectonic stresses within the state can provide a basis for assessing the seismogenic potential of faulting, and hence the hazard such structures may pose.

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STRAIN RATES, STRESS DISTRIBUTION, AND SEISMIC POTENTIAL IN CENTRAL COLORADO

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ABSTRACT

Central Colorado was affected by compressional tectonism in Laramide time and by uplift and extensional faulting in Neogene time. A high geothermal gradient prevailed throughout most of the Tertiary. Strain rate estimates for the tectonic episodes indicate that deformation was relatively mild as compared to regions of high activity. Evidence points to a marked decline in strain during the Quaternary.

Several moderate earthquakes (M=4 to 6) have been recorded in Colorado during historic time. The compatibility of stress regimes revealed by seismic monitoring with those deduced from Laramide and Neogene fault patterns, together with evidence for a very low strain rate, implies that modern seismicity may be explained in terms of decay of remanent stresses inherited from prior tectonism and thermal activity.

Future earthquakes are most likely to occur in those areas that were most affected by Neogene gravity faulting and volcanism and are least likely in areas where such activity was minor or lacking. The central Front Range emerges as an area with low seismic potential.

INTRODUCTION

The tectonic history and regional setting of central Colorado furnish a background for evaluating the state of stress and potential for earthquakes in the region. This report summarizes pertinent information obtained from previously published sources, supplemented by results of investigations conducted by the Denver Water Department during the period 1982 to 1985. Details regarding the geotectonic evolution and stress history of the region are given in an earlier report (Warner, 1985). The study was designed to furnish background information regarding potential seismicity in areas where future water storage facilities are under consideration, mainly in the central Front Range.

The Cenozoic tectonic history of Colorado included two major episodes of diastrophism (Tweto, 1980): 1) Laramide orogeny (70 to 50 m.y. ago)(million years ago), characterized by lateral compression and crustal shortening, and 2) Neogene (Mio-Pliocene) uplift, rifting, and gravity faulting (25-5 m.y. ago), resulting in crustal extension. Available data indicate that in both instances the active force was oriented approximately east-west. The two episodes where separated by a period of relative quiescence that lasted for about 25 m.y. A widespread erosion surface had formed over much of central Colorado by late Eocene time. Volcanic deposits, resulting from a relatively high geothermal gradient in the region, accumulated on this surface during the Oligocene.

In comparison with other parts of the Cordilleran system, Cenozoic tectonism in central Colorado was relatively mild, and accompanying seismic activity is presumed to have been moderate. Modern activity is greatest on the Pacific margin and decreases in a general way to a minimum at the Rocky Mountain Front (Smith, 1978 a,b), representing what must have been an average situation for the system during Cenozoic time.

Gravity faulting of the Neogene type continued on a reduced scale into the Pleistocene in parts of central Colorado, but few Holocene displacements have been noted. A question of major interest is whether or not the present tectonic state represents an approach to crustal stability and the beginning of another quiet period like that of the middle Cenozoic.

CENOZOIC STRAIN RATES

The Front Range is the largest tectonic element in the Colorado Rockies, and an average strain rate for the range may be taken as an indicator of the rate for the region. Although pre-strain dimensions for the range are unknown, dates for the durations of Laramide and Neogene tectonic episodes have been established, and approximate total displacements, which were essentially vertical, have been determined. Assuming plane strain and assigning it entirely to brittle failure, the aggregate slip on faults within the Front Range block may be used to calculate a slip rate, which may be taken as an index of strain rate. To simplify the calculation, movement is assumed to have been entirely dip slip and to have taken place entirely on faults bounding the deformed block.

The total structural relief for the Front Range due to Cenozoic deformation can be closely approximated from geologic data. The basement floor of the Denver Basin at its deepest part is about 2,500 m below sea level (Huan, 1968, p. 103). The projected level of the original basement surface above the present range crest is estimated from fission track data (Bryant and Naeser, 1980) to be abojut 5,000 m above sea level. Assuming this surface to have been horizontal prior to deformation, structural relief resulting from tectonism was about 7.5 km. Of this, about 4.5 km is estimated to have developed in Laramide time and the remaining 3 km in Neogene time, based on assumed displacement of the late Eocene erosion surface (Scott, 1975).

In order to calculate dip-slip displacements corresponding to the estimated vertical intervals, dips must be assigned to the hypothetical boundary faults assumed for the Front Range block. Combining observation and theory, average dips of 45° and 60° are assumed for Laramide reverse and Neogene normal faulting respectively. The dip slips then become 6.4 km for Laramide and 3.45 km for Neogene faulting. Corresponding slip rates for the two 20 m.y. intervals are then 0.032 and 0.017 cm per year. The average slip rate for Cenozoic time is 0.014 cm per year. By comparison, estimates for the Cenozoic slip rate on the San Andreas system in central California average about 1.0 cm per year (Suppe, 1970).

Quaternary faulting in parts of central Colorado has been cited by Scott (1970), Kirkham and Rogers (1981), and McCalpin (1982). Trimble (1980) related the Quaternary faulting to renewed uplift, suggested by rejuvenation of stream erosion and coarsening of fluvial deposits along the east margin of the Front Range. However, the texture of the deposits and increase in erosion could be accounted for by climatic change, from warm-moist to cool-dry, preceding the Pleistocene, leading to restricted vegetation and torrential rains interspersed with lengthy dry periods (Donnelly, 1982). The extent to which glaciation may have influenced the observed activity is a matter for consideration. Harrison (1976) noted that records obtained from strain gauges installed in the Poorman Mine west of Boulder could be correlated with seasonal accumulation and melting of snow along the crest of the Front Range. Repeated accumulation and wasting of Pleistocene ice on the high ranges in Colorado may have triggered movements on faults bounding upper crustal blocks that were gravitationally unstable. Seismicity related to modern glaciation has been noted in Alaska (Wolf and Davies, 1986).

Several moderate earthquakes, in the range M = 4 to 6, have been reported in central Colorado during historic time. However, a combination of factors points to a very low Holocene strain rate and suggests an approach to crustal stability:

1) Even though average strain rates for Laramide and Neogene deformation were below those in active seismic regions, they were accompanied by volcanism related to a high geothermal gradient which continued through most of the Tertiary. During the Pleistocene, volcanism became vanishingly small (Larson and others, 1975; Lipman and Mehnert, 1975). The latest eruption, a small flow near Dotsero, occurred about 4,000 years ago (Giegengack, 1962).

2) Fault offsets beyond the initial Holocene have not been reported; paleoseismic evidence for recent faulting, like that reported for Utah and Nevada (Wallace, 1981), appears to be lacking.

3) Recent mapping of Pleistocene-Holocene stream terraces in the central Front Range reveals no displacements where they are crossed by major faults. The terraces are separated by vertical intervals that remain constant, and terrace gradients are parallel to the present stream gradients, suggesting little or no uplift of the range during terrace development.

4) In contrast to those in some regions of active faulting, major reservoirs in Colorado have not induced destructive earthquakes. A minor event (M=3.4) may have been induced by Blue Mesa Reservoir (Wong and Humphrey, 1986).

5) Patches of bouldery Pinedale glacial till that would tend to be dislodged by strong ground motion from large earthquakes (Keefer, 1984) have remained perched on canyon walls in the Front Range for 20,000 years or more. Fault slumping of similar till was observed by Tweto and others (1970) in the Gore Range, where Neogene faulting continued into the Quaternary.

6) Secular strain data for the region, although fragmentary, tend to corroborate the above.

STATE OF STRESS IN CENTRAL COLORADO

Stress measurements assembled from various parts of the United States (Zoback and Zoback, 1980) indicate that much of the intracontinental region is in a state of compressional stress that cannot be attributed to lithostatic load. At some localities, the stress regime was inherited as a remanent stress from tectonic events extending as far back as the Precambrian (Eisenbacher and Bielenstein, 1971). Most of the stress measurements were obtained by the hydrofrac method (Haimson, 1977), the only technique for measuring stresses below shallow depths, except in mines. The method is difficult to apply for evaluating the regional stress state in central Colorado because of the effects of rugged terrain, diverse structure and lithology, and a complex stress history extending back to the middle Precambrian. A study of fault patterns and the results of seismic monitoring appear to give more reliable data regarding stress distribution over a large area at a much lower cost.

Patterns of Laramide and Neogene faulting in central Colorado are shown on Figure 1. Three major trends are indicated: 1) a N50°E trend represented by the Homestake shear zone, the Berthoud-James Peak system, and the Ralston shear zone; 2) a N55°W zone represented by the Kennedy Gulch, Floyd Hill, and related faults; and 3) a N25°W trend represented by the Ilse-Currant Creek-South Park system and faults along the Blue River Valley. Fault members of all three trends are of known Precambrian origin. Many were reactivated, and perhaps others formed, during Ancestral Rocky Mountain deformation in late Paleozoic time.

All of the fault trends were rejuvenated during Laramide orogeny. Those of N50°E and N55°W trends were affected by strike-slip movement, mainly in early Laramide time and those of N25°W trend by reverse dip-slip movement in later Laramide time. Faults of the latter type are those that bound the mountain uplifts.

Neogene activity was restricted largely to normal (gravity) movement on faults of the N25°W group and is concentrated mainly on faults bounding the Arkansas, San Luis, and Wet Mountain grabens, where displacements amounted to thousands of feet (Tweto, 1979). These grabens are an extension of the Rio Grande Rift system (Figure 2), which is best developed in New Mexico (Chapin, 1979). Displacements diminished northward along the rift axis and laterally away from it. Small displacements occurred in a broad zone parallel to the rift, the zone narrowing to the north. The graben system pinches out about 20 miles north of Leadville, but normal faulting related to rift activity may have extended to the Wyoming border. Neogene faulting also affected the southern Front Range, notably on the Rampart Range-Jarre Canyon faults and in the Manitou half graben (Taylor, 1975) along the extension of the Ute Pass fault. All of these had sustained reverse movement in Laramide time.

In the central Front Range west of Denver, faults parallel to the favored Neogene trend are poorly developed. Instead, the major faults trend N50° to 60°W, and most of them show left-lateral, strike-slip movement related to early Laramide compression (Bryant and others, 1981). Scott (1970, 1975) postulated late Cenozoic movement on the Kennedy Gulch and Floyd Hill faults, but the results of recent field studies conducted by the Denver Water Department preclude displacements in late Pleistocene-Holocene time and raise doubts regarding Neogene activity.

Seismic monitoring has been conducted in the central Front Range by Microgeophysics Corporation of Wheatridge since 1978. Fault plane solutions obtained for microearthquakes and a small felt earthquake indicate strike-slip movement conforming with early Laramide compression (Nicholl, 1983; Butler and Nicholl, 1984). The monitoring network, which has been expanded to extend over several thousand square miles, has not detected any dip-slip movement in the central Front Range that can be related to the Neogene stress regime. The result came as a surprise, considering that monitoring of the Derby earthquakes by the U. S. Geological Survey (Healy and others, 1968; Herrmann and others, 1981) established that the stress regime in the deep part of the Denver Basin is extensional.

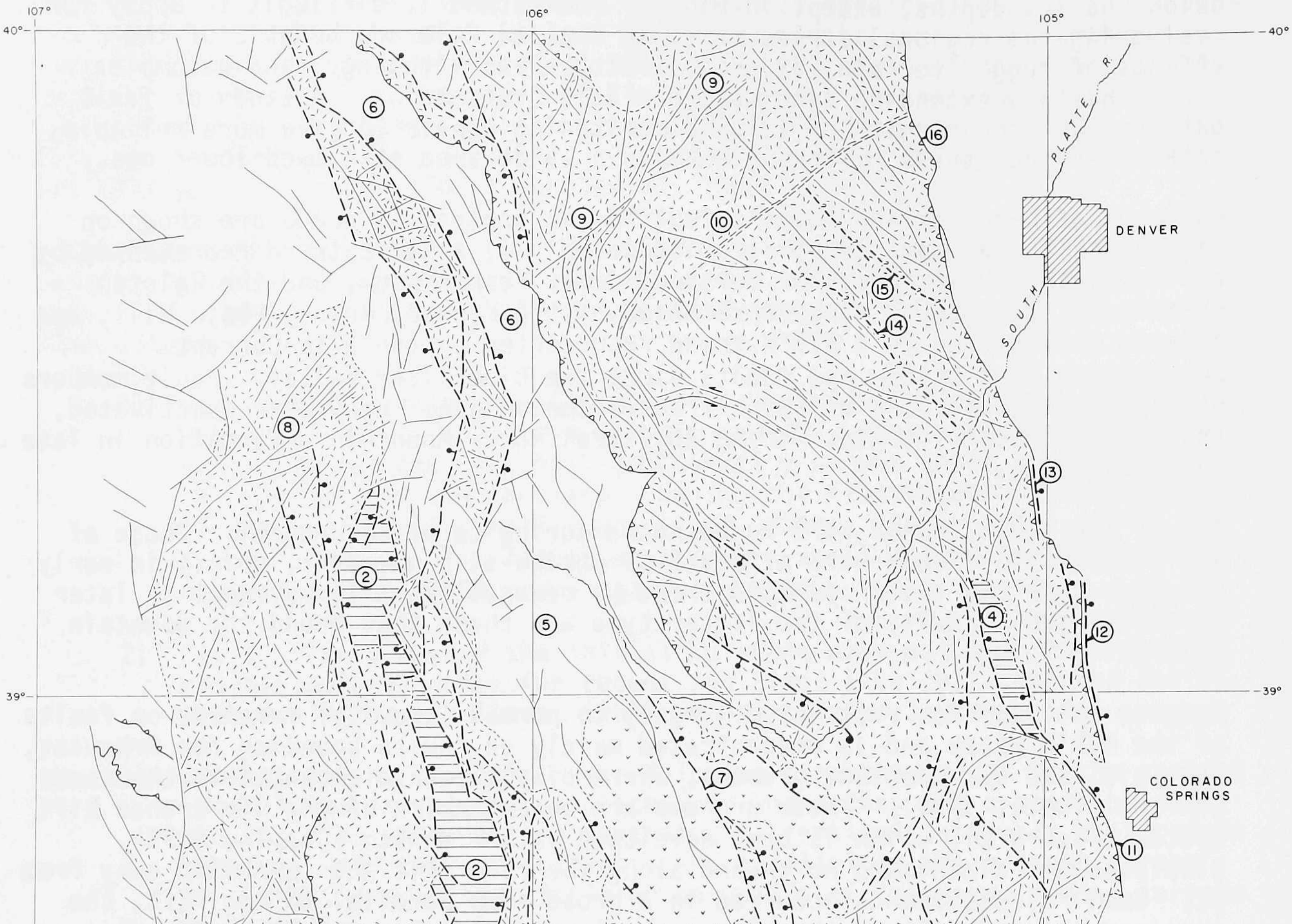

Figure 1. Tectonic map of central Colorado.

EXPLANATION

NEOGENE GRABEN CONTAINING DEPOSITS OF SEDIMENTARY AND/OR VOLCANIC MATERIAL

VOLCANIC ROCKS; MAINLY EARLY TERTIARY

UNCLASSIFIED SEDIMENTARY ROCKS; MAINLY PALEOZOIC AND MESOZOIC

INTRUSIVE AND METAMORPHIC ROCKS; MAINLY PRECAMBRIAN

DEPOSITIONAL CONTACT

NEOGENE FAULTS

OBSERVED OR PROBABLE NEOGENE ACTIVITY; BALL ON DOWNTHROWN SIDE

NEOGENE ACTIVITY DOUBTFUL

LARAMIDE FAULTS

REVERSE FAULT OR THRUST; BARBS ON UPTHROWN SIDE

STRIKE-SLIP FAULT; ARROWS INDICATE RELATIVE MOVEMENT

UNCLASSIFIED FAULT

FEATURES CITED IN TEXT

1. SAN LOUIS VALLEY GRABEN
2. ARKANSAS VALLEY GRABEN
3. WET MOUNTAIN GRABEN
4. MANITOU PARK HALF-GRABEN
5. SOUTH PARK
6. BLUE RIVER VALLEY
7. ILSE-CURRANT CREEK-SOUTH PARK FAULT SYSTEM
8. HOMESTAKE SHEAR ZONE
9. BERTHOUD-JAMES PEAK FAULT SYSTEM
10. RALSTON SHEAR ZONE
11. UTE PASS FAULT
12. RAMPART RANGE FAULT
13. JARRE CANYON FAULT
14. KENNEDY GULCH FAULT
15. FLOYD HILL FAULT
16. GOLDEN FAULT

MAP SOURCES: USGS 1°x 2° QUADRANGLE MAPS I-999, I-1022, I-1163, MF-761; USGS OPEN FILE REPORT 77-750.

Figure 1. Tectonic map of central Colorado.

Recently seismic monitoring was extended into the southern Front Range west of Colorado Springs. In this region, microearthquake motion corresponding to Neogene displacements has been detected. Similar monitoring results were obtained along the Rio Grande Rift in central New Mexico (Sanford and others, 1979, Figure 2).

The close correlation between Laramide and Neogene paleostress regimes inferred from fault patterns and present stress regimes detected by seismic monitoring serves as a basis for postulating a generalized stress distribution in the Colorado Rocky Mountains (Figure 3). The correlation suggests that the fault patterns revealed by geologic mapping may be trusted to indicate the present state of stress. It also implies that the present stress regimes were inherited as remanent stresses from earlier tectonism, a conclusion that is supported by evidence regarding decline of the regional strain rate to a minimal value during the Quaternary. One may surmise that modern seismic activity in Colorado, such as that recorded during the past century, may be explained in terms of the decay of remanent tectonic stresses. Model studies for the Appalachian region account for historic seismicity in terms of strain release by surface denudation (Anderson, 1986).

FAULTING IN RELATION TO SEISMIC POTENTIAL

Faulting is the mechanism by which seismic energy is released in the earth's crust. However, faulting may occur with or without a seismic response, depending upon whether stick-slip or stable sliding prevails (Brace, 1974). Stick-slip is favored by high pressure - low temperature conditions and strong rocks. Where normal stress across the fault is low; or where the material is weak or temperature is high, stick-slip gives way to stable sliding. Two major factors influence the seismic response to stick-slip. One is the tectonic style, which determines the fault type. The other is the complexity of the fault structure. Both are inherently related to stress-energy requirements for producing a major earthquake on a given fault.

Tectonic style is related to the orientation of principal stress directions in a region, assuming plane strain and a single tectonic event. For strike-slip faulting, the intermediate principal stress (s_2) is vertical; for dip-slip, it is horizontal. For normal (gravity) dip-slip, the maximum principal stress (s_1) is vertical; for reverse dip-slip, it is horizontal. There are regions in which all three fault styles are represented, but one (most recent) is primary, the others being related to secondary stresses or to prior deformation.

The energy requirements for faulting differ markedly, depending upon the tectonic style (Sibson, 1974). For a given depth, and assuming a static frictional coefficient of 0.75, the ratio of deviatoric stresses required to initiate sliding on reverse, strike-slip, and normal faults is 4:1.6:1. For the same assumptions, the critical depths for transition from brittle to plastic behavior (stick-slip to stable sliding) for reverse, strike-slip, and normal faults is 1:2.5:4. The average stress requirement for normal faulting is then only one-fourth that for reverse movement, and the depth range for seismic response on a normal fault may exceed that for a comparable reverse fault by a factor of four. Therefore, normal faults may be expected to have larger seismic moments than reverse or strike-slip faults of similar length, and the ratio of seismic energy released to stress required for failure is highest on normal faults.

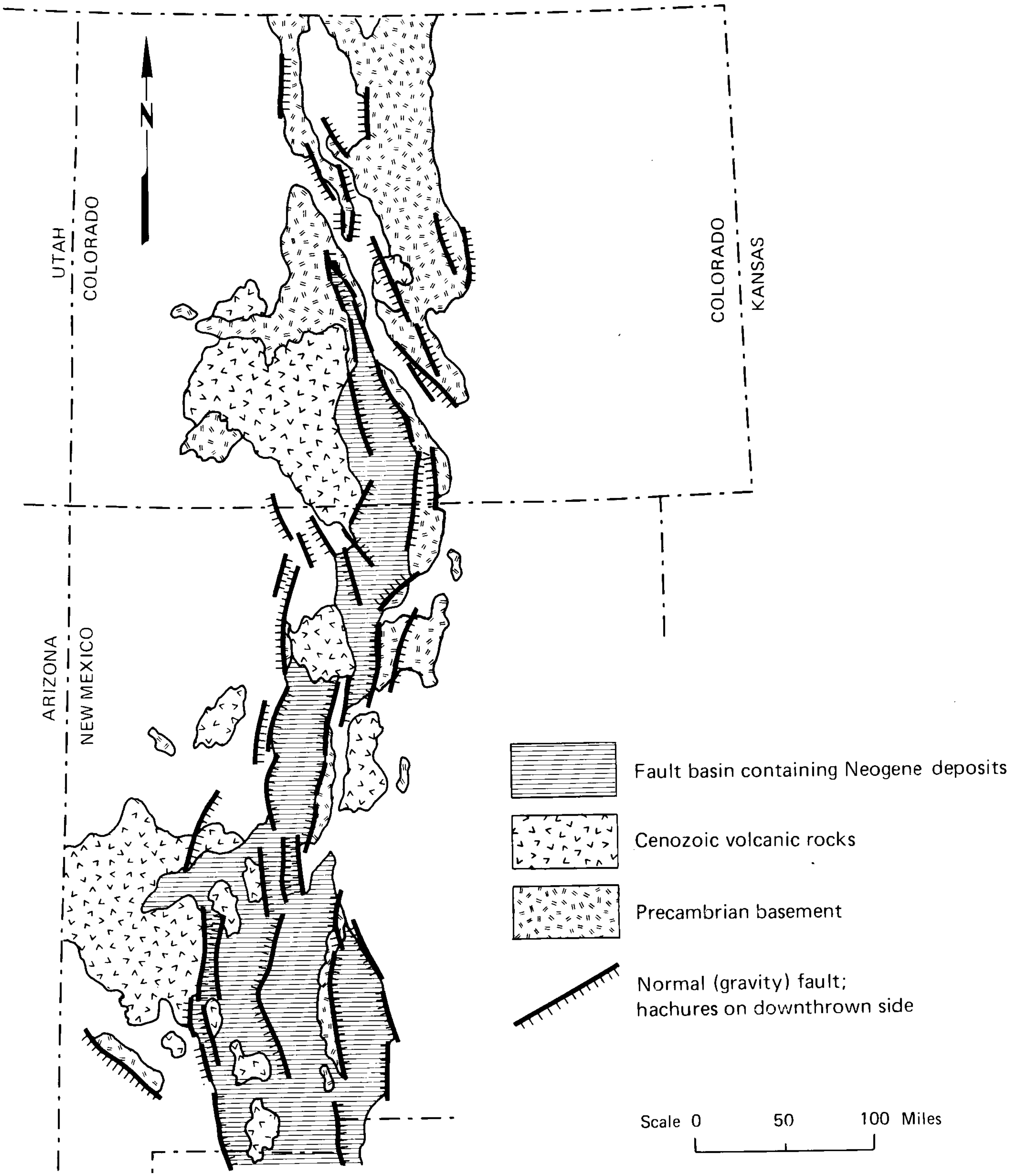

Figure 2. Generalized geologic map of the Rio Grande Rift system, New Mexico and Colorado, compiled from Tweto (1979), Baldridge and others (1983).

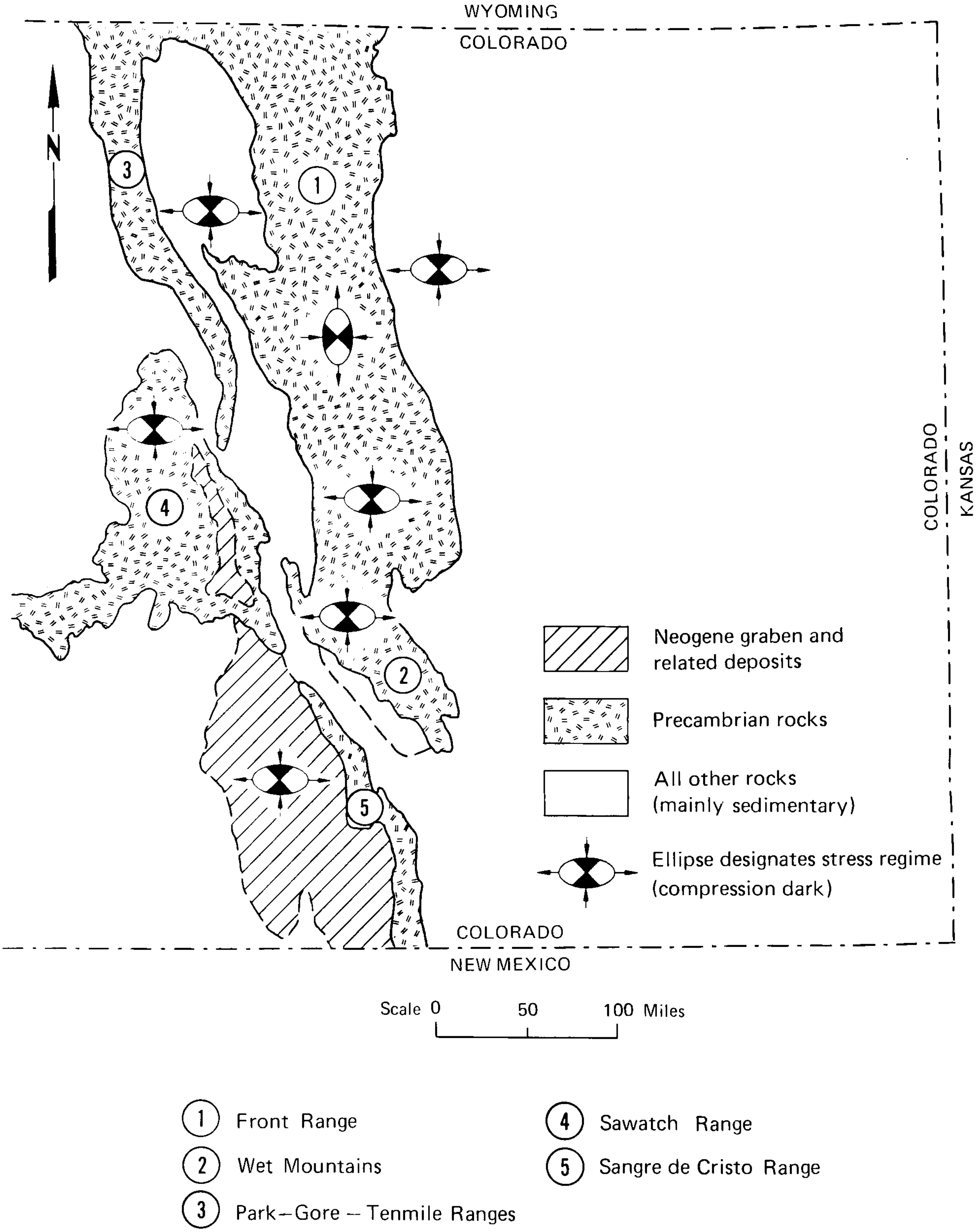

Figure 3. Generalized map of Colorado Rocky Mountains showing probable stress distribution.

The structure of a fault zone also becomes important in assessing its seismic potential. For a complex zone containing a large number (n) of potential slip surfaces with average slip area (a), one may assume that total slip (S) on the zone will be distributed among the surfaces such that the average slip will be S/n. The average seismic moment for a slip surface in the zone will then be $M_o = m(S/n)a$, where m is the shear modulus. Assume that the sum of the slip areas ($a_1 + a_2 + \ldots a_i$) is equal to the area (A) of slip on a simple fault of the same dimensions, for which the seismic moment is $M_o = mSA$. Summing the moments for the slip surfaces in the complex structure we obtain $M_{oi} = m(S/n)A$. Accordingly, the seismic moment of a complex fault differs from that of a comparable simple structure as a function of the number of slip surfaces (n). Since the seismic energy released is proportional to moment, substantially more energy will be required to produce a major earthquake on a complex fault than on a simple one of the same dimensions.

With regard to tectonic style and fault structure, the central Front Range appears to have a low potential for major seismicity. The stress regime deduced from seismic monitoring is compressional, assuring a low probability for normal faulting. The major fault zones are sub-parallel to foliation, leading to formation of complex structures with branching and en-echelon segments containing numerous surfaces of potential slip. Energy requirements for a major earthquake in this area are therefore higher than in adjacent parts of central Colorado where the stress regime is extensional and fault structures are more simple.

POTENTIAL FOR INDUCED SEISMICITY

It has been known for several decades that seismic activity in an area may increase following construction of a dam that impounds a large volume of water. Two points should be cited in this connection:

1) Seismic activity is not an inevitable consequence of reservoir impoundment. Of more than 10,000 reservoirs in the world, fewer than 50 are known to have had related seismicity, although the probability for its occurrence increases with increase in reservoir depth and volume (Baecher and Keeney, 1982).

2) The reservoir does not of itself generate seismic energy, but under appropriate conditions, impoundment of water tends to abet the release of elastic energy stored in an adjacent rock mass. Release is most likely where the stress due to stored energy is close to the level required for failure in the mass. In order for a reservoir to induce a major earthquake, sufficient energy to generate the earthquake must be stored in the rock and the impounded water must influence the environment at seismic depth in a way that will lead to movement on a fault.

The ways in which a reservoir induces seismicity are poorly understood and may differ from one site to another. An appropriate combination of factors at the site may be responsible, rather than a single cause. The following have been cited as having influenced seismicity due to reservoir impoundment:

Crustal Loading

Water in a reservoir constitutes an extra load on the earth's crust that strains the subjacent rock in a way that may trigger seismicity. However, even for the largest reservoirs, the induced vertical stress is less than 10 bars and the shear stress is less than 2 bars. It is unlikely that these stresses are transmitted to seismic depths in amounts that would be effective, except in rare circumstances and in combination with other causes.

Physico-chemical Effects of Water

The principal effect of water is to weaken the rock material through static fatigue or by introducing hydroxyl into mineral lattices. At shallow depth, water may reduce frictional resistance to faulting on zones containing clay materials. Assuming that the rock mass was water saturated at depth prior to reservoir impoundment, it seems doubtful that the influence of the reservoir would be a major factor in this regard.

Increase in Pore Pressure

Water in the deep hydraulic system is contained in cracks and pores in the rock. Assuming that these are interconnected, the pore pressure at a given depth might approximate the hydrostatic head. Reservoir impoundment would tend to increase this value by an amount depending on the depth of the reservoir and the hydraulic conductivity of the rock. The effective stress law states that $S_e=S_n-P_p$, where S_e is effective stress on any plane through a solid, S_n is normal stress across the plane, and P_p is pore pressure in the solid. Since S_n inhibits fault movement, its reduction to S_e by increase in pore pressure tends to promote sliding.

Of the factors mentioned, a decrease in effective stress due to increase in pore pressure has been demonstrated as a plausible cause of induced seismicity (Raleigh and others, 1976). Since the terrain in central Colorado is comprised mainly of fractured Precambrian crystalline rocks, the capacity of such rocks to transmit a reservoir head to seismic depths becomes a matter of interest (Gale, 1982). Observations on wells in crystalline rock indicate that fracture porosity tends to decrease exponentially with increase in depth (Snow, 1968). There is a corresponding reduction in hydraulic conductivity, which results in a loss of effective head. Groundwater movement may be defined in terms of a work factor related to the flow potential (Hubbert, 1953). Energy expended in flow increases with decrease in hydraulic conductivity and is supplied at the expense of the hydrostatic head. Few data are available, but observations indicate that the head loss, even at shallow depth (1 km), may be as much as 40 percent. The world's deepest reservoir (about 300 m) generates a head of about 30 bars. The probability that a substantial fraction of such pressure can be transmitted as an increase in fluid pressure in the hydraulic system at seismic depth (5 km or more) appears to be small. For this to happen the reservoir would need access to a major fracture zone that remains open to a depth of 5+ km. Data regarding the rheological properties of crystalline rocks suggest that such structures are very unlikely, except perhaps where activated by recent faulting.

Tectonic State

The tectonic state of a region has an important bearing on the potential for induced seismicity (Castle and others, 1980). It includes the fracture geometry, the state of stress, and the tectonic style. The importance of tectonic style is indicated by the fact that all of the reservoirs related to major earthquakes ($M \leq 5$) are in regions where recent movement has occurred on normal or strike-slip faults (Simpson, 1976). The normal style appears to be the more formidable because of the lower energy requirement. Areas in central Colorado that were most affected by Neogene gravity faulting are probably the most vulnerable to induced seismicity.

CONCLUSIONS

Central Colorado was affected during the Cenozoic by two episodes of tectonism: Laramide orogeny, resulting from lateral compression; and Neogene uplift and block faulting, related to crustal extension. A high geothermal gradient, accompanied by volcanism, was maintained throughout most of Tertiary time. Faulting related to the Neogene episode continued into the Pleistocene on a reduced scale, perhaps activated by accumulation and wasting of glacial ice. Evidence for faulting since the earliest Holocene has not been reported. This and other factors, including cessation of volcanism, point to a marked decline in regional slip rate since the Neogene, for which the average rate was 0.017 cm per year. However, earthquakes of moderate magnitude have occurred in Colorado during historic time, indicating that a stressed state exists.

Two factors appear to reconcile modern seismic activity with a very low regional strain rate: 1) Many of the recent earthquakes have occurred west of the Front Range in areas of Neogene igneous activity and probably resulted from cooling and contraction in and below the seismic zone; 2) the close correlation between stress regimes revealed by seismic monitoring and those deduced from Laramide and Neogene fault patterns, combined with evidence for a low strain rate, implies that the present stress regimes are mainly remanent states inherited from earlier tectonism. Modern seismicity can then be accounted for in terms of decay of remanent tectonic stresses and reduction of a geothermal gradient inherited from the Tertiary.

To assist in identifying areas in which future damaging earthquakes are most likely to occur, the following considerations are recommended:

1) Areas that were affected by Neogene gravity faulting and volcanism are more suspect than those in which these features are absent.

2) Neogene activity was most intense along the Rio Grande Rift, decreasing northward along, and laterally away from the rift axis.

3) Simple faults tend to have higher seismic moments and to require lower initial stress to generate a damaging earthquake than do complex fault zones of similar dimension.

In summary, areas in which simple faults of the north-northwest Neogene trend are numerous or well developed, or in which a widespread thermal anomaly can be identified or inferred, should be regarded as suspect. This applies mainly to areas in close proximity to the Rio Grande Rift.

It follows that earthquakes, natural or induced, are least likely in areas where the criteria outlined do not apply. The central Front Range appears to qualify in this regard as an area of low seismic potential. The major faults trend northwest and are complex; simple faults of the north-northwest trend are lacking. The area is free of Neogene igneous activity, and the thermal gradient is assumed to be stable. The stress regime is compressional, representing a relatively weak Laramide remanent state that is incompatible with normal faulting.

Similar areas of low seismic potential probably exist in the northern Front Range and in parts of the Sawatch Range. Determining their locations and extents may become matters of importance in connection with the siting of future reservoirs and other facilities for which seismic safety is a major concern.

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MORPHOLOGY AND AGE OF FAULT SCARPS IN THE RIO GRANDE RIFT, SOUTH-CENTRAL COLORADO

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ABSTRACT

Fault scarps in the Rio Grande rift of Colorado provide most of the evidence of paleoseismicity in the state, and are thus a major focus of assessments of earthquake hazards. Critical components of such assessments are the ages of past faulting events; age control is scarce and generally coarse for the Rio Grande rift in Colorado. Ages estimated from fault-scarp morphology are thus valuable, partly because they are directly related to the fault events, and partly for want of alternative methods.

The processes responsible for scarp degradation are poorly understood and the many variables that affect the rates and relative importance of those processes limits the precision and accuracy of age estimates derived from scarp morphology. Both analytical and empirical methods are available for relating scarp degradation processes to scarp morphology and age. Diffusion-equation models that have been derived for scarp degradation are useful for their predictive value and for the insight they provide about the degradation processes. However, because of the limitations mentioned above and because of the multiple-event nature of the scarps in the Rio Grande rift, the simpler empirical approach involving the relation between scarp angle and the logarithm of scarp height is used here.

The scarp-morphology data from the Rio Grande rift suggest that the youngest movements on all of the scarps examined occurred less than 15,000 years ago, with the exception of two scarps that are formed on lithologically dissimilar deposits. This age estimate is consistent with the observation that all of the scarps occur at least in part on deposits of Pinedale age. The scarp-morphology data suggest that some of the scarps are closer to 5,000 years than to 15,000 years in age; several of these scarps occur on deposits of early Holocene age and are associated with early Holocene radiocarbon dates. One scarp occurs on deposits with radiocarbon dates of only a few thousand years, although the morphology of this scarp is unusual for its age. Three scarps have morphologies that suggest that they may represent fault events younger than 5,000 years old. Although no corroboration is available, these scarps may represent some of the youngest fault movements in Colorado.

INTRODUCTION

Recent interest in paleoseismicity and earthquake hazards in Colorado has resulted in considerable geologic investigation into the history of tectonics and late Cenozoic faulting in the state. General compilations of the late Cenozoic faults and tectonic features in Colorado have been made by Witkind (1976), Kirkham and Rogers (1981), and Colman (1985). These compilations show that the Rio Grande rift was the most tectonically active area in Colorado in late Cenozoic time and that most faults with known Quaternary movement in the state occur in the rift. The Rio Grande rift is thus one of the primary focuses for earthquake-hazard and paleoseismicity research in Colorado.

Age estimates of Quaternary fault movements are critical for deciphering the neotectonic history of an area and for assessing paleoseismicity and earthquake hazards. Unfortunately, such age estimates are commonly difficult to make. Geologic conditions rarely allow estimates of the age of the faulting itself; rather, ages of the youngest faulted materials and of the oldest unfaulted materials are used to bracket the age of faulting. However, ages of Quaternary deposits are difficult to determine reliably and many do not closely bracket the age of faulting. Materials suitable for dating of deposits by established numerical methods are rare in the Rio Grande rift. Most age estimates for fault events in the rift have been derived from soil development and weathering data for Quaternary deposits that bracket the fault events, supplemented by regional correlations to glacial or alluvial events whose ages are approximately known.

Under such circumstances, any method of directly estimating the ages of fault movements is valuable for paleoseismicity and earthquake-hazard studies. Recent work has shown that the morphology of fault scarps in unconsolidated deposits is related to the age of the faulting event that created the scarps. The purpose of this paper is to examine the age information that can be gained from fault-scarp morphology in the Rio Grande rift in Colorado.

SETTING

Quaternary faulting in the Rio Grande rift has been recently discussed in detail by Colman and others (1985). Additional major work pertinent to the Cenozoic history of faulting in the Rio Grande rift includes Scott (1970), Lipman and Mehnert (1975), Huntley (1976), Knepper (1976), and Tweto (1979). The following brief overview of the tectonic setting and history of the Rio Grande rift is summarized from the work of these authors and references therein.

The active part of the rift in Colorado (Figure 1) consists of two major units that are topographically and structurally distinct: the upper Arkansas River Valley and the San Luis Valley. The upper Arkansas River Valley is essentially a complex graben, although no Quaternary faults are known along the east side of the part of the valley shown in Figure 1. The San Luis Valley is a half-graben, with the main fault zone on its eastern side. Numerous secondary faults offset the major structures and form secondary horsts and grabens. The two main rift areas are separated by a complex zone of normal faults in the structurally high area of Poncha Pass. Late Cenozoic fault displacements generally decrease northward in Colorado and gradually die out north of the upper Arkansas River Valley. Quaternary faulting probably occurred north of and within the northernmost part of the upper Arkansas River Valley, but well-defined fault scarps are found only in the southern part of the upper Arkansas River Valley and in the San Luis Valley. The most prominent Quaternary fault scarps are found at the foot of the Sawatch Range (Figure 1) along the western side of the southern part of the upper Arkansas River Valley and at the foot of the Sangre de Cristo Range along the eastern side of the San Luis Valley.

Faulting and regional uplift associated with the initiation of the Rio Grande rift ended a long period of tectonic quiescence in the Eocene. During this stable period, erosion reduced large areas in Colorado and surrounding regions to surfaces of low relief, which were subsequently buried by voluminous Oligocene and lower Miocene volcanic rocks. The Rio Grande rift in Colorado apparently began to form just prior to Miocene time, sometime between about 26

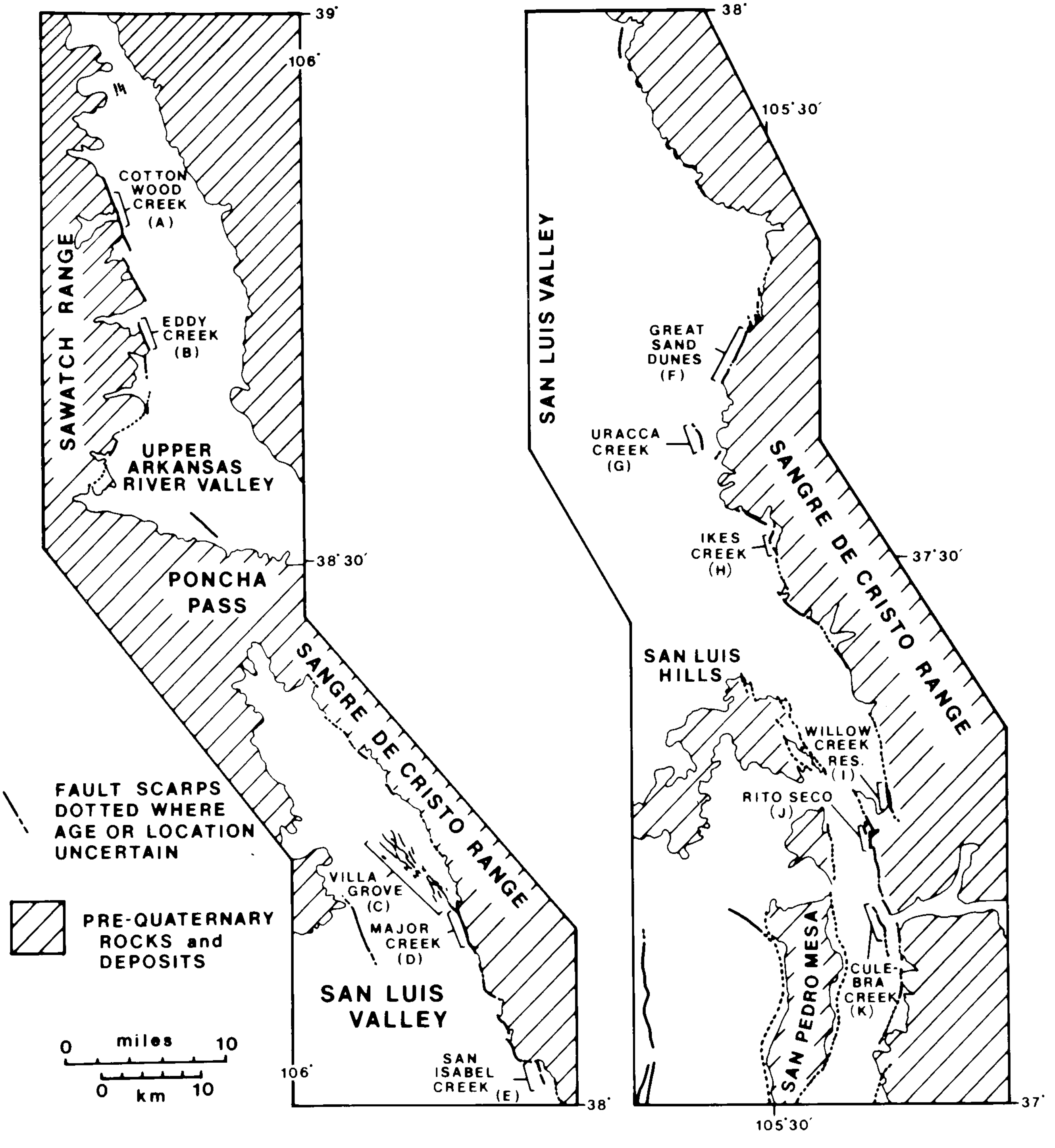

Figure 1. Map of the Rio Grande rift in Colorado, showing the location of major Quaternary fault scarps. All faults are normal, down towards the basins. Labeled scarps are discussed in the text.

and 29 m.y. ago, although a depositional basin may have existed before then in the area of the present San Luis Valley. Faults associated with the development of the rift rapidly outlined grabens in which the Miocene and Pliocene basin-fill sediments of the Dry Union and Alamosa Formations and the Santa Fe Group accumulated. Faulting, coupled with regional uplift, apparently accelerated in late Miocene and Pliocene time. During formation of the grabens, as much as 3,000 m of sediment was deposited in the upper Arkansas River Valley and 5,000 m in the San Luis Valley. Total late Cenozoic throw on some of the valley-bounding faults may be as much as 5,000-7,000 m. Fault scarps are common in Quaternary deposits in the rift and suggest a history of recurrent faulting through the Quaternary. Faulted deposits of Holocene age suggest that the late Cenozoic period of extensional tectonics continues to the present.

Virtually all known or inferred Quaternary faults in the Rio Grande rift of Colorado (Figure 1) are documented by their topographic expression; natural exposures showing stratigraphic offset of Quaternary deposits are rare. Topographic expressions of Quaternary faults include fault scarps, drainage anomalies, topographic lineaments, and steep linear contacts with bedrock along mountain fronts. Fault scarps in the Rio Grande rift in Colorado are generally short and discontinuous, although along mountain fronts, they must be underlain by continuous fault zones. All faults scarps in the Rio Grande rift in Colorado show evidence of recurrent movement: fault scarps whose heights increase in successively older deposits and, as discussed later, scarps whose heights in older deposits exceed what could be reasonably expected from a single earthquake event. In addition, trenches dug across some of the faults invariably showed stratigraphic evidence of multiple fault movements (Ostenaa and others, 1981; McCalpin, 1982).

SCARP MORPHOLOGY AND AGE OF FAULTING

Recent research on fault scarps has shown that their morphology changes systematically with time. Descriptive work has shown that fault scarps in environments similar to those in the Rio Grande rift in Colorado proceed through a sequence of predictable morphological changes (Wallace, 1977). Scarps are created with steep faces, called free faces, that vary in steepness from vertical to as gentle as 50° (Wallace, 1977). The free face is rapidly removed by slumping and other mass movement processes, leading to a planar profile at the angle of repose (commonly 33-35°). This process appears to take from a few tens to perhaps a thousand years in the western United States (Wallace, 1977, 1980). The scarp then degrades by creep, slope wash, and other processes, and becomes progressively gentler and more rounded. The rates at which scarps degrade clearly depend on climate and the materials on which the scarp is developed.

Measurements of scarp morphology have shown that the maximum scarp angle is empirically related to both scarp height and age of faulting (Bucknam and Anderson, 1979; Colman and others, 1981, 1985; McCalpin, 1982; Mayer, 1984; Machette, 1982, 1986; Personius and Machette, 1984). Regression lines that relate maximum scarp angle to the logarithm of scarp height generally form a set of subparallel lines whose relative positions are related to the ages of the fault scarp (Bucknam and Anderson, 1979). The positions of regression lines for scarps of a given age depend on scarp materials, climate, aspect, and other variables whose affect has not been well documented. The position of the regression line for a scarp of a given age changes with time as the maximum scarp angle for a given height decreases. Apparently, the slope of the regression line also slowly decreases with time (Bucknam and Anderson, 1979; Colman and Machette, 1981).

Much recent work has focused on mathematical models of scarp degradation and ages estimated from such models (Nash, 1980a, 1980b, and 1984; Colman and Machette, 1981; Colman and others, 1981; Colman and Watson, 1983; Mayer, 1984; Hanks and others, 1984; Andrews and Hanks, 1985; Pierce and Colman, 1986. These studies have shown that degradation of scarps with time could be modeled by a diffusion-type equation, and provide a theoretical basis for the empirical maximum-scarp-angle versus log-height relation first developed by Bucknam and Anderson (1979). These diffusion-equation models, whether solved numerically (Nash, 1980a, 1980b, and 1984) or analytically (Colman and Watson, 1983; Meyer, 1984; Hanks and others, 1984; Andrews and Hanks, 1985; Pierce and Colman, 1986 incorporate a single, constant rate coefficient that integrates the effects of lithology, climate, and other environmental factors that affect rates of scarp degradation. The models assume that processes whose transport rates are a linear function of slope angle (primarily creep-type processes) are dominant on the scarps. The models also assume that the initial scarp has a simple form created by a single fault event. Clearly, these necessary simplifications limit the applicability of the diffusion-equation models for fault scarps in the Rio Grande rift as well as many other areas.

The texture, cohesion, and other lithologic properties of the deposits on which scarps are formed obviously affect the rates at which they degrade. Many of the scarps that have been studied in the western United States, including those in the Rio Grande rift, are formed in deposits of a similar character: coarse, poorly sorted, weakly consolidated, sandy fan gravel. No major affect of lithologic variables on rates of scarp degradation has been documented for these deposits. However, major differences in rates have been noted where deposits differ significantly in texture, for example, clay versus gravel (Dodge and Grose, 1980). Nash (1984) suggested that differences in degradation rates among different areas were partly due to differences in grain size. Also, McCalpin (1982) noted that departures from the regression lines of scarp angle against the logarithm of scarp height were related to the modal clast size on the scarp. Finally, as discussed later, two of the areas in the Rio Grande rift show a major effect of lithology on rates of scarp degradation.

Differences in climate and associated vegetation between areas also have a major effect on rates of scarp degradation. However, even within the restricted climatic range of the scarps discussed here, variations in local climate are important. The diffusion-equation models integrate the effects of climate over the time since a scarp formed. Because the scarps discussed here were formed during an interval of major climatic fluctuations, scarps of different ages in the same area have experienced different average climates. Machette (1986) has suggested that, all else being equal, average degradation rates may vary by a factor of 3 to 4 between Holocene and late Pleistocene scarps.

Pierce and Colman (1986) have shown that slope aspect (compass orientation) has a significant effect on rates of scarp degradation. The contrast in degradation rates is most apparent between north- and south-facing scarps (south-facing scarps degrade faster), so that the effect is minimal for scarps in the Rio Grande rift, which mostly face either east or west. However, these results emphasize the potential importance of microclimatic variables.

Pierce and Colman (1986) have also documented a systematic departure of scarp morphology from the predictions of the diffusion-equation model in some arid and semi-arid areas. The departure appears to be due to the effect of slope wash or other processes whose transport rates are not a simple, linear function of slope angle, as required by the diffusion-equation model with a constant rate coefficient. The departure requires modification of the age calculations based on the diffusion-equation model.

Because of these limitations and because of the fact that most of the scarps in the Rio Grande rift have formed by multiple fault events, the diffusion-equation approach seems to offer little advantage over the simpler empirical approach (Bucknam and Anderson, 1979) of relating slope angle to the logarithm of scarp height. Consequently, the latter method is used in the following analysis of scarps in the Rio Grande rift.

MORPHOLOGY OF SCARPS IN THE RIO GRANDE RIFT OF COLORADO

More than 100 scarp profiles were measured in the field using either the method described by Bucknam and Anderson (1979) or a similar method using a rod, Jacob's staff, Abney level, and tape. Additional profile data discussed here are taken from Ostenaa and others (1982) and McCalpin (1982). Definitions of morphologic terms are shown in Figure 2.

Comparisons of plots of scarp angle against the logarithm of scarp height (Bucknam and Anderson, 1979) are complicated by the multiple-event nature of scarps in the Rio Grande rift in Colorado. Multiple fault events can rarely be distinguished directly from the morphology of these scarps although, as discussed earlier, all Quaternary faults in the rift have experienced recurrent movement. This observation is supported by the diffusion-equation

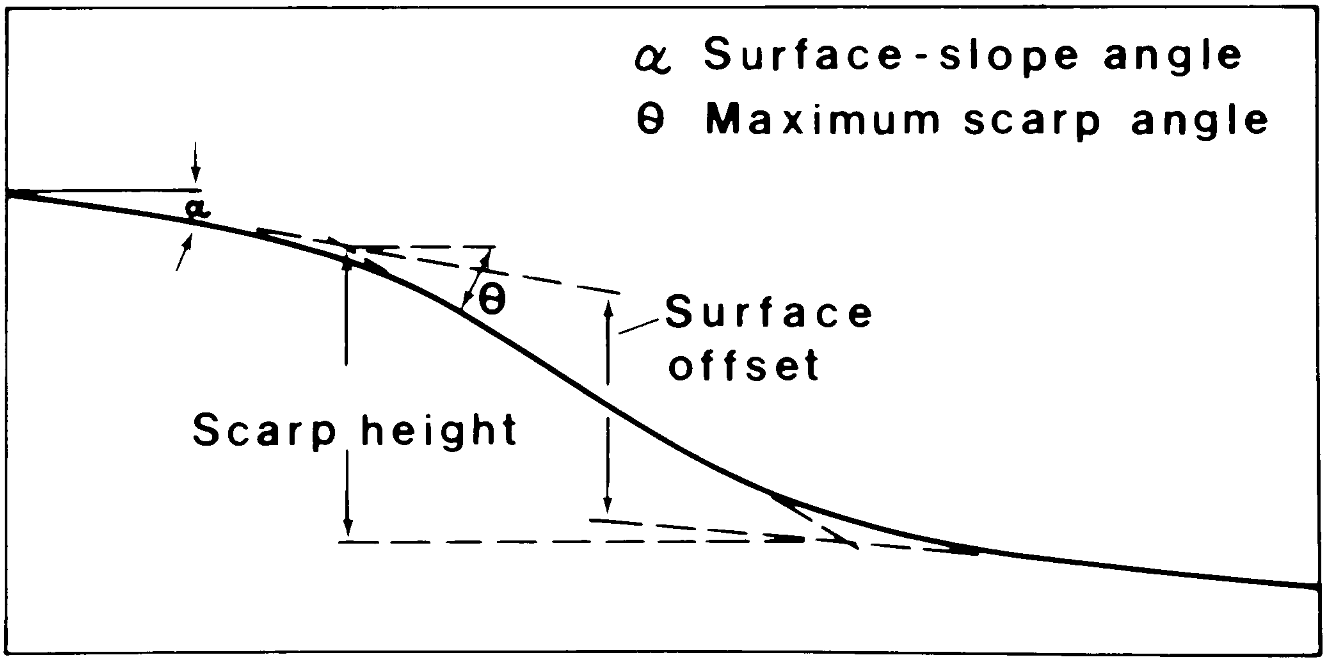

Figure 2. Diagrammatic definition of the morphological variables (maximum scarp angle and scarp height) plotted for scarps in this paper. Modified from Bucknam and Anderson (1979).

model, which predicts that the maximum changes in the profiles occur at points of greatest curvature. The result is that any irregularities in the profile, such as changes in slope caused by younger fault events, tend to be rapidly smoothed.

Diffusion-equation models show that regression lines for multiple-event scarps have lower slopes than those for single event scarps (Figure 3A), if the time since the last fault event is equal. Machette (1982) has shown similar relations empirically where the height due to the last displacement on a multiple-event scarp could be separated. Regression lines for multiple-event scarps are actually composite lines through groups of points related to each fault event (Figure 3B). In practice, however, different fault events can rarely be distinguished in the angle-height data unless the last event is very young or unless the first event is much older than the others. Examples of the former case are shown by Machette (1982, 1986), and examples of the latter case are probably represented by the dashed points in the plots for Culebra Creek and Ikes Creek (Figures 4H, 4K).

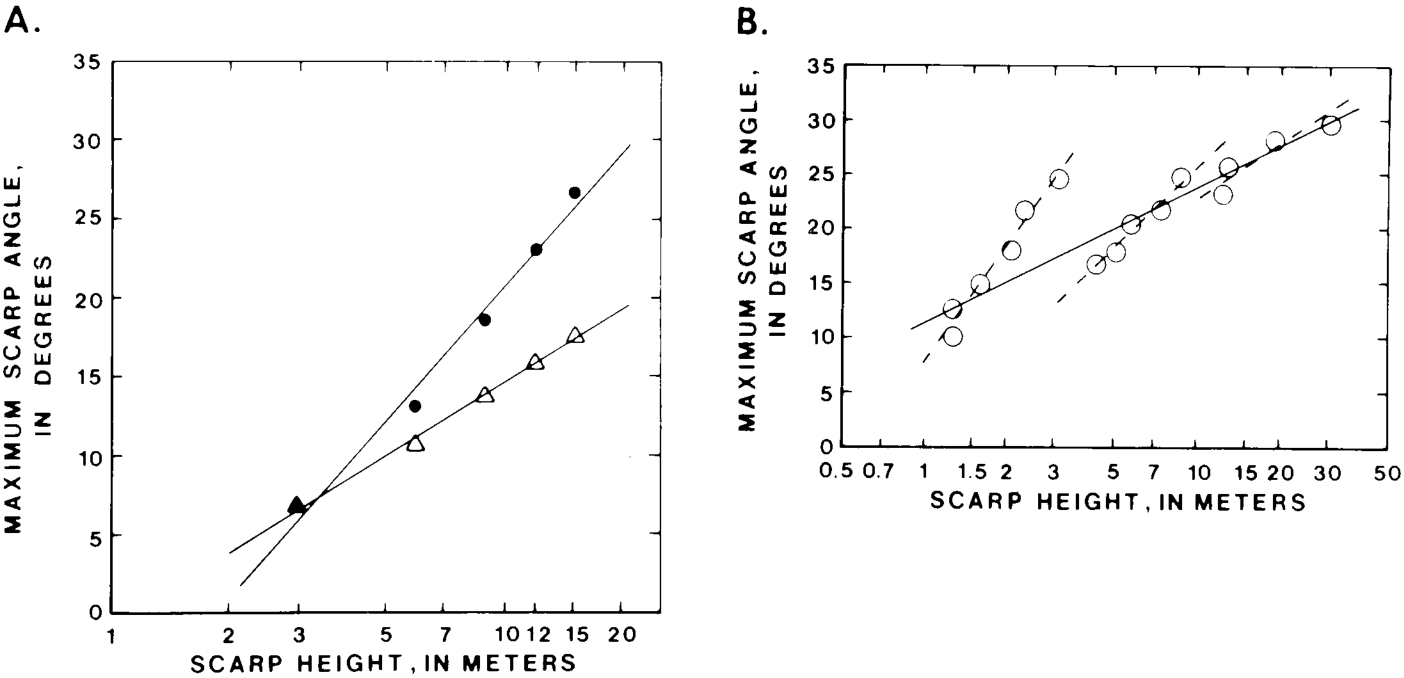

Figure 3. (A) Morphological data for scarps whose degradation was simulated using a diffusion-equation model (Colman and Machette, 1981; Colman and others, 1981). Filled circles represent a scarp with varying height formed by a single fault event. Open triangles represent a scarp of varying height formed by multiple 3-m fault displacements separated by equal amounts of time. The filled triangle is common to both sets of data. Diffusion coefficient and time since the last fault event are the same in both data sets. (B) Hypothetical data set for a multiple-event fault scarp. Each group of points associated with a dashed regression line represents a single fault event of varying displacement. Such groups of points can rarely be separated from each other in real data (see text). Solid line is the regression line for all the data; it has a lower slope and lower correlation coefficient than the regression lines for the single events.

Perhaps the simplest approach to examining the ages of multiple-event scarps is to try to isolate parts of the scarps that were formed only by the last fault event. For several reasons, this is difficult to do for the short, discontinuous scarps in the Rio Grande rift. First, the youngest extensive deposits in the rift are of late Pinedale age, perhaps 11,000 to 15,000 years old (Porter and others, 1983), although deposits of early Holocene age are locally present; late Pinedale deposits have been faulted more than once in many locations (Ostenaa and others, 1981; McCalpin, 1982). Second, single faulting events are difficult to identify based on height alone. Fault offsets revealed in trenches in the Rio Grande rift are 0.8-1.4 m in the Villa Grove fault zone (McCalpin, 1982), 1.2-2.9 m along the Sangre de Cristo fault zone (McCalpin, 1982), and 0.3-2.6 m along the Sawatch fault zone (Ostenaa and others, 1981). These displacements are similar to those along the Wasatch fault in Utah (1.6-2.6 m; Schwartz and Coppersmith, 1984) and to those associated with the 1983 Borah Peak earthquake in Idaho (0.5-2.7 m; Crone and Machette, 1984). Thus, a height below which a scarp likely represents a single fault event is difficult to define. Also, factors other than fault displacement, especially the slope of the faulted surface, affect scarp height, so that the same fault displacement may produce different scarp heights in different settings. Third, a range of scarp heights is needed to define a regression line of scarp angle against log height; such a range of heights is difficult to obtain for short sections of individual scarps in the Rio Grande rift. Data from sections of several scarps on the same age of deposit can be combined, as McCalpin (1982) did for sections of scarps on post-Pinedale deposits along the Villa Grove and Sangre de Cristo Fault zones. (McCalpin obtained regression equations of $Y = 13.2 + 12.8*X$ and $Y = 16.5 + 11.5*X$, respectively for the two data sets; compare with Table 1). However, there is no assurance that such composite sets of data represent single fault events, either for an individual scarp or for the fault zone as a whole.

Despite these difficulties, multiple-event scarps can be compared objectively to single-event scarps on the plots of scarp angle against the logarithm of height. Multiple-event scarps whose last fault event is about the same age as a single-event reference scarp should have regression lines that are mostly below that for the reference scarp, but which intersect the line for the reference scarp near the lower range of scarp heights (Figure 3A). Individual data points corresponding to low scarp heights (presumably those that represent the last fault event) for a multiple-event scarp should nearly coincide with those for a single-event scarp of the same age. Thus, the lower end of the range of points for multiple-event scarps is critical for age comparisons with dated single-event scarps.

Maximum scarp angle is plotted against the log of scarp height, with corresponding regression lines, in Figure 4 for several Quaternary fault scarps in the Rio Grande rift. Also plotted for reference and comparison are the regression lines for two scarps of known age: (1) the Bonneville shoreline in Utah (Bucknam and Anderson, 1979; R.C. Bucknam, written commun., 1982), a well-defined, wave-cut scarp about 14,000-15,000 years old (Scott and others, 1983), and (2) the line for the 5,000-year-old scarp along segment C of the La Jencia fault in the Rio Grande rift in New Mexico (Machette, 1982, 1986). If climatic and lithologic variables are similar for these scarps, the ages of the multiple-event scarps in the Rio Grande rift can be determined relative to the known ages of the reference scarps, as discussed earlier.

Compared to the reference data for the Bonneville shoreline and the La Jencia fault, the ages suggested by data for the scarps in the Rio Grande rift in Colorado are consistent with independent estimates of their ages (Figure 4 and independent age estimates in table 1). All of the regression lines for scarps in the Rio Grande rift of Colorado are well within the position expected for a multiple-event scarp whose last faulting event occurred 15,000 years ago (Figure 4), with the exception of those for the Willow Creek Reservoir and Rito Seco scarps, which are discussed later. This comparison suggests that the youngest movements of the associated faults are significantly younger than the 14,000 to 15,000-year-old Bonneville shoreline, if climatic and lithologic differences between the two areas do not have a major affect.

The regression lines for many of the scarps (Cottonwood Creek, Eddy Creek, Villa Grove, Major Creek, Uracca Creek, and Culebra Creek) lie below the 5,000-year-old reference line (Figure 3). Considering the relation between single-and multiple-event scarps, the youngest movements on the associated faults in these areas appear to be between 5,000 and 15,000 years old. All of these scarps occur on deposits of Pinedale age (Ostenaa and others, 1982; McCalpin, 1982), but younger limiting ages are scarce. At Major Creek and Uracca Creek, the scarps occur on early Holocene deposits, and radiocarbon ages of 7,660 and 10,100 years B.P. (Major Creek) and 5,640 years B.P. (Uracca Creek) have been obtained (McCalpin, 1982) for deposits that immediately post-date the faulting.

The regression lines for three scarps (San Isabel Creek, Great Sand Dunes, and Ikes Creek) plot in the same position or significantly above the 5,000-year-old reference line (Figure 4). This suggests that these scarps may represent fault events younger than 5,000 years, although no independent corroboration is available. If these scarps are actually younger than 5,000 years old, they represent some of the youngest known surface offsets due to faulting in Colorado.

The ages suggested by scarp morphology are thus generally consistent with the meager independent age information for faulting in the Rio Grande rift. In addition, scarps that are known to have similar histories, such as the Eddy Creek and the Cottonwood Creek scarps (Ostenaa and others, 1981 and 1982), have similar regression lines. These comparisons and consistencies suggest that the morphologies of the scarps may be validly used to estimate their ages. They also suggest that factors that affect the rate of scarp degradation, such as climate and materials, are effectively similar for many scarps in Utah and the Rio Grande rift in New Mexico and Colorado.

However, morphologic data for some scarps in the southern part of the Rio Grande rift in Colorado are inconsistent with the data for the scarps discussed above. The scarps near Willow Creek Reservoir and Rito Seco are known to be Holocene in age (table 1), but their regression lines plot below that for the late Pleistocene Bonneville shoreline. This discrepancy probably can be explained by differences in materials cut by the faults. The Rito Seco and Willow Creek Reservoir scarps are formed on loose, relatively well-sorted, sandy, non-gravelly alluvial fan deposits derived from the Santa Fe Group and thus probably degrade much faster than other scarps in the area, which are formed on coarse, gravelly, poorly sorted, somewhat cohesive deposits derived from competent bedrock. These two scarps, then, have a deceptively old appearance. In contrast, the nearby Holocene scarp at Culebra Creek is formed in cohesive alluvial-terrace deposits of that stream, which drains large areas of crystalline bedrock. The regression line for the Culebra Creek scarp plots well above that for the Bonneville shoreline.

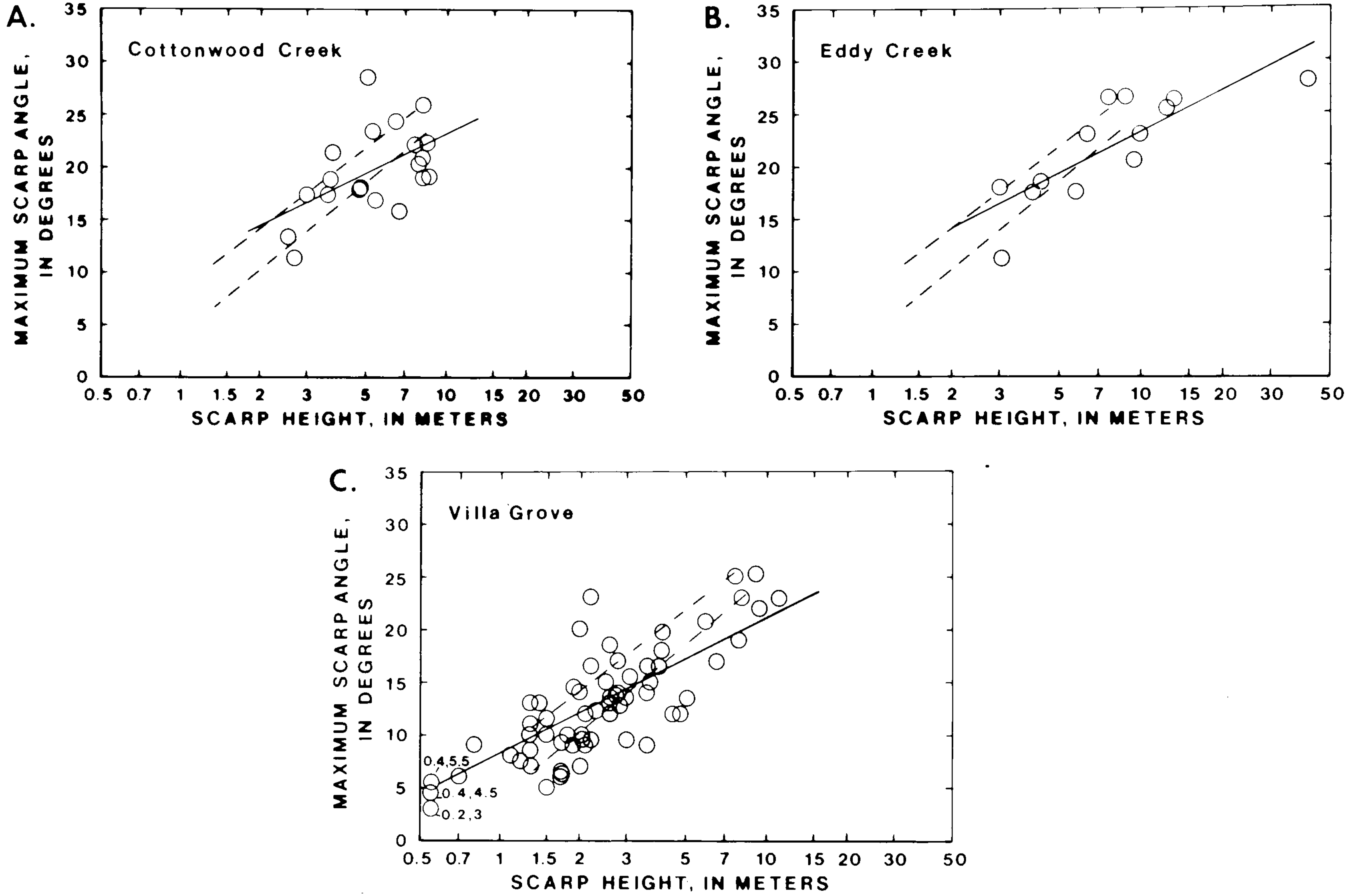

Figure 4. (A,B,C) Graphs showing maximum scarp angle plotted against log of scarp height for profiles measured along individual scarps. Solid line is least-squares regression line through solid-line points (table 1); points not included in regression are dashed (see text). Lower dashed line is regression line for the 15,000-year-old Bonneville shoreline in Utah (Bucknam and Anderson, 1979; R.C. Bucknam, written commun., 1982), and the upper dashed line is for a 5,000-year-old scarp in the Rio Grande rift in New Mexico (Machette, 1982, 1986). These well-defined, single event scarps of known age are used as reference lines for each plot.

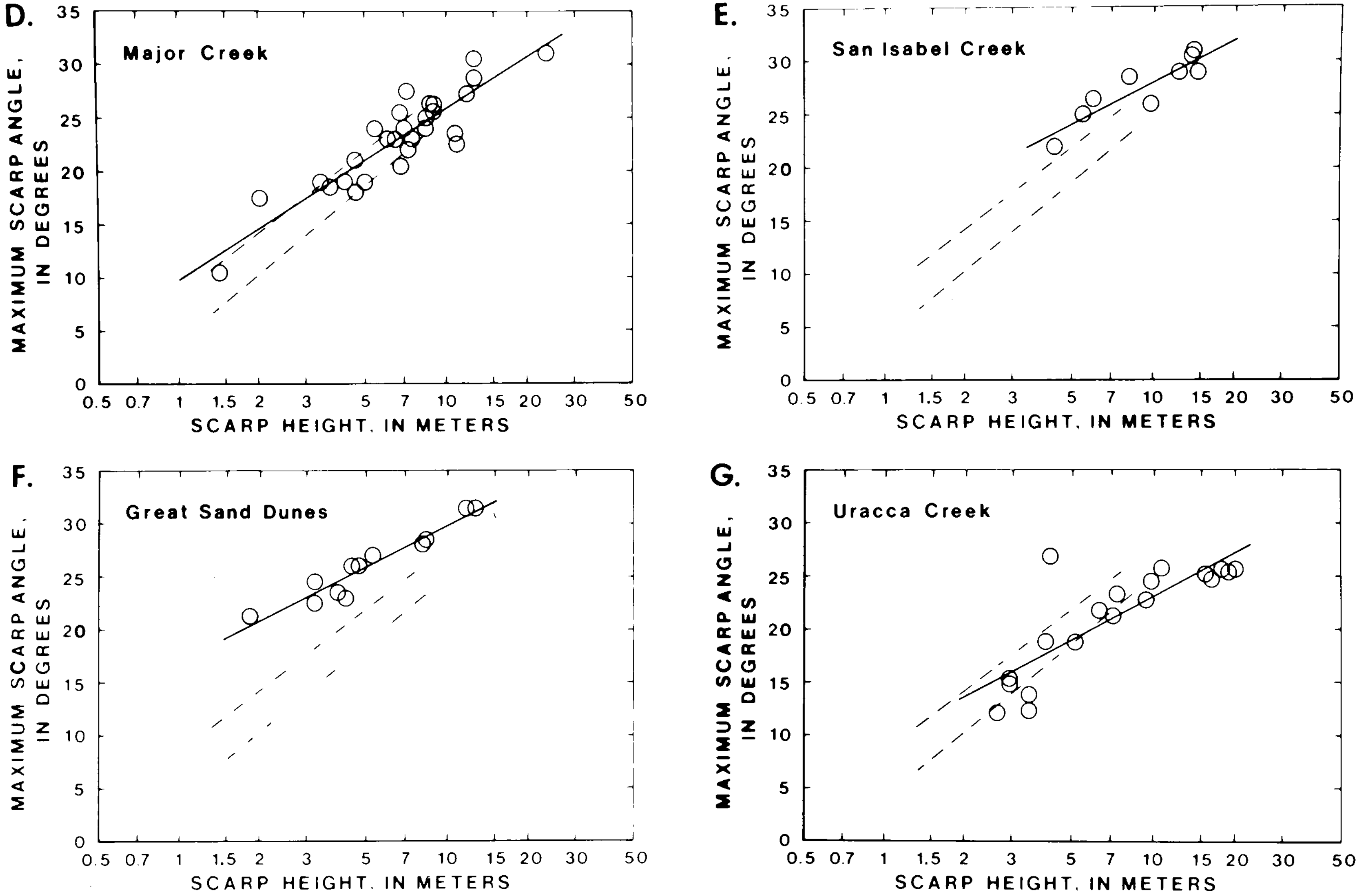

Figure 4. (D,E,F,G) Graphs showing maximum scarp angle plotted against log of scarp height for profiles measured along individual scarps. Solid line is least-squares regression line through solid-line points (table 1); points not included in regression are dashed (see text). Lower dashed line is regression line for the 15,000-year-old Bonneville shoreline in Utah (Bucknam and Anderson, 1979; R.C. Bucknam, written commun., 1982), and the upper dashed line is for a 5,000-year-old scarp in the Rio Grande rift in New Mexico (Machette, 1982, 1986). These well-defined, single event scarps of known age are used as reference lines for each plot.

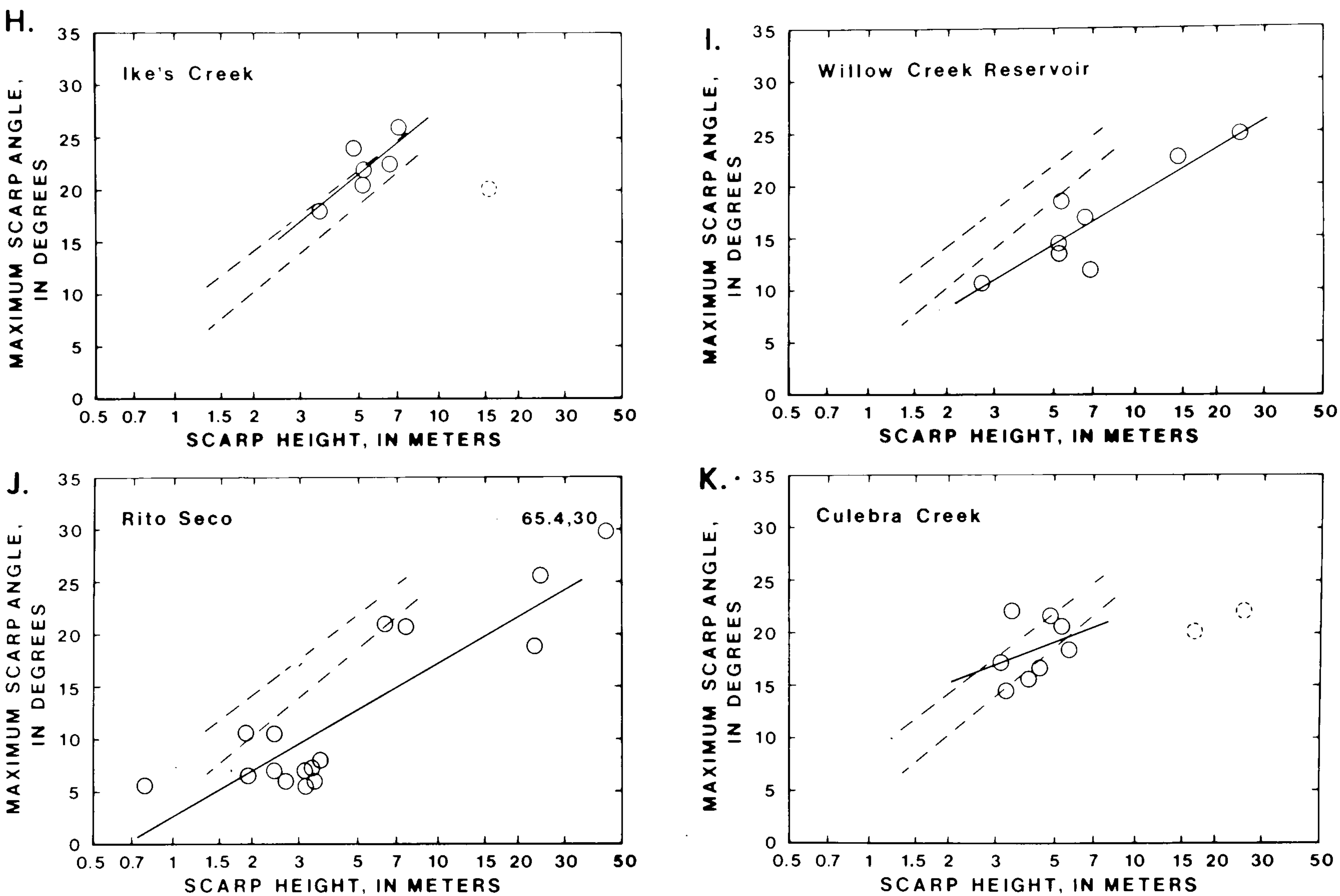

Figure 4. (H,I,J,K) Graphs showing maximum scarp angle plotted against log of scarp height for profiles measured along individual scarps. Solid line is least-squares regression line through solid-line points (table 1); points not included in regression are dashed (see text). Lower dashed line is regression line for the 15,000-year-old Bonneville shoreline in Utah (Bucknam and Anderson, 1979; R.C. Bucknam, written commun., 1982), and the upper dashed line is for a 5,000-year-old scarp in the Rio Grande rift in New Mexico (Machette, 1982, 1986). These well-defined, single event scarps of known age are used as reference lines for each plot.

Table 1. Summary of scarp morphology and age data.

Area	Regression equation data[1] Intercept	Slope	N	R^2	Independent age information (years B.P., where given)
		Rio Grand Rift, Colorado, scarps			
A. Cottonwood Creek	10.7	12.6	20	0.30	Post-Pinedale[2]
B. Eddy Creek	10.4	12.8	13	.66	Post-Pinedale
C. Villa Grove	8.2	12.8	64	.61	Post-Pinedale
D. Major Creek	9.9	15.8	29	.81	Holocene;(1)7,660 (2)10,100[3]
E. San Isabel Creek	15.0	12.9	9	.81	Post-Pinedale
F. Great Sand Dunes	17.0	12.7	13	.92	Post-Pinedale
G. Uracca Creek	9.6	13.8	19	.69	Holocene; 5,640[3]
H. Ikes Creek	7.4	20.5	6	.64	Post-Pinedale
I. Willow Creek Reservoir	3.6	15.3	8	.79	Holocene
J. Rito Seco	2.6	14.7	16	.79	Holocene; 1,940-4,115[4]
K. Culebra Creek	12.3	9.8	8	.10	Holocene
			Reference Scarps		
L. Bonneville shoreline	3.7	21.4	61	.91	late Pleistocene; 14,000-15,000[5]
M. La Jencia	7.8	20.2	11	.98	Holocene, 4,000-5,000[6]

[1]For least-squares regression of maximum slope angle on the log of scarp height; N, number of scarp profiles; R^2, coefficient of determination.
[2]Late Pinedale deposits are about 11,000-15,000 years old (Porter and others, 1983).
[3]Last fault event(s) occurred shortly before date(s) given (McCalpin, 1982).
[4]Last fault event occurred between dates given (Kirkham and Rogers, 1981).
[5]Scarp data from Bucknam and Anderson (1979) and R.C. Bucknam (written commun., 1982); age estimate from Scott and others (1983).
[6]Scarp data and age from Machette (1982, 1986).

CONCLUSIONS

The morphology of fault scarps is a useful tool for estimating the ages of faulting in the Rio Grande rift of Colorado, but it is not without its problems. Its main advantages lie in the scarcity of alternative methods, and in the association of the age estimates with the fault events themselves rather than with the ages of deposits that bracket the age of the fault event. The diffusion-equation model offers useful perspectives and predictions concerning the ways in which degradation of the scarps proceeds. However, in an area of short, discontinuous, multiple-event scarps that occur on various types of deposits, it probably offers no real advantage over the empirical relationships between scarp angle and the logarithm of scarp height for estimating the ages of the scarps.

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QUATERNARY TECTONICS OF THE SANGRE DE CRISTO AND VILLA GROVE FAULT ZONES

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LOCATION AND SETTING

The Sangre de Cristo and Villa Grove Fault Zones are located in the eastern San Luis Valley of south-central Colorado (Figure 1). The Sangre de Cristo Fault Zone (SCFZ) trends northwesterly for 120 km along the western base of the northern Sangre de Cristo Mountains. The Villa Grove Fault Zone (VGFZ) is a shorter zone of splay faults which leaves the range front fault and trends 10 km northwestward toward the valley floor.

The San Luis Valley is the major downdropped crustal block within the northern Rio Grande Rift Zone. On its western margin, lava flows of the San Juan Volcanic Field dip underneath the valley with no significant Neogene displacement. Internal faults generally do not displace the surface, dying out in the Plio-Pleistocene Alamosa Formation. The active bounding fault of this east-tilted half graben is the SCFZ, where Precambrian rocks are offset up to 7,000 m (Huntley, 1979) and Quaternary deposits offset by up to 87 m.

The glacial deposits and alluvial fans at the range front which are disrupted by fault scarps have been mapped by McCalpin (1981, 1983). Relative-dating data from 75 stations, as well as from 35 soil pits and seven radiocarbon dates, suggest that deposits of pre-Bull Lake (400 ka), Bull Lake (140 ka), early Pinedale (25-35 ka), mid-late Pinedale(15-25 ka), and Neoglacial (3-5 ka) age interact with the scarps. From estimates of the relative and absolute age of faulted deposits, the chronology of faulting and climate-induced erosion and deposition has been estimated. Previous summaries of neotectonic activity which include this area are Kirkham and Rogers (1981), Colman (1985) and Colman and others (1985).

SANGRE DE CRISTO FAULT ZONE

The Sangre de Cristo Fault Zone exhibits discontinous, west-facing, range-front normal fault scarps for about 120 km along the range base. Three fault segments are suggested by changes in the trend of the range front (Figure 1). The northernmost, Segment A, trends N 40° W for 90 km along a very linear range front. Segment B to the south strikes N 10° E for 20 km, then grades into Segment C which wraps eastward around the south flank of Blanca Peak. Because each segment may behave independently, they are discussed separately below.

Segment A

Individual fault scarps in Segment A range from 0.2 km to 3.2 km long, and are most prominent crossing large valley mouths which are embayed into the range front. Many scarps also traverse along the base of faceted spurs between valley mouths in the pinon-juniper scrub, but are in general less well preserved than valley-mouth scarps.

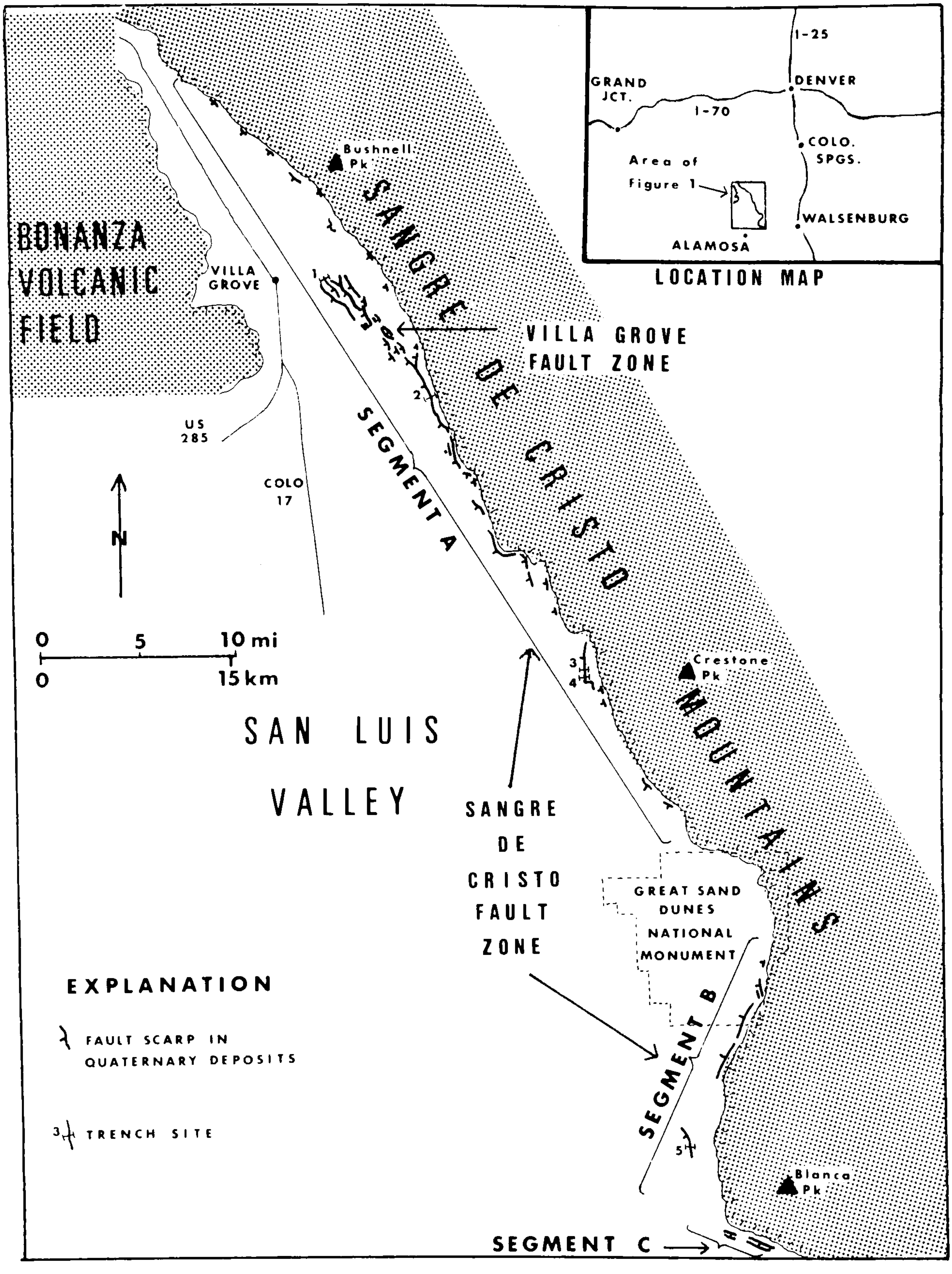

Figure 1. Map of fault scarps offsetting Quaternary deposits on the Sangre de Cristo and Villa Grove Fault Zones. Modified from McCalpin (1981), Plates 1 and 2.

Vertical net displacement on scarps ranges from 1.4 m in Holocene deposits, to 9 m in Pinedale, 16 m in Bull Lake, and up to 87 m in pre-Bull Lake deposits. At three key valley mouths (Major Creek, Trench 2, Figure 1; also see McCalpin, 1987; San Isabel Creek and Willow Creek, Trenches 3 and 4, Figure 1; also see McCalpin, 1983, p. 61-69) a single scarp offsets Quaternary deposits of up to five ages. The resulting geometry permits estimates to be made of displacement per event and time between events.

Displacements per event on Segment A range from 1.4 to 2.9 m, based on analysis of one- and two-event scarps. Such heights suggest earthquakes of magnitude (M_L) 7.0 to 7.3 (Slemmons, 1982, Figure 3). Combination of all scarp data suggests one event in the last 8 ka, another between 8 ka and 13 ka, and another between 13 ka and 35 ka (Pinedale time). This results in an average recurrence of 11 ka for the last 35 ka. By contrast, only three events are inferred to have occurred in the period 35 ka to 140 ka, giving a recurrence of about 35 ka. Possibly 6-12 events occurred between 140 ka and roughly 400 ka, giving a recurrence of 21 ka to 42 ka. Comparing the rates, it seems that the last 35 ka have been more active than the average for the past 400 ka. Alternatively, this apparent increase of recurrence times for older deposits may mean that evidence from some fault events has been obscured by erosion or deposition. This is especially likely if scarps climb up the faces of steep faceted spurs, and are quickly obliterated.

Segment B

The 20 km-length of segment B is dominated by a nearly continuous 10 km-long scarp which stretches southward from Great Sand Dunes National Monument to North Zapata Creek. Scarps maintain a relatively uniform 4 m to 7 m height across a bajada of coalescing Pinedale (undifferentiated) alluvial fans. Because no older or younger deposits are offset along this trace, little can be deduced of its history. However, Pinedale scarps here are very similar in height and morphology to Pinedale scarps of southern Segment A, suggesting some similarities in recent history.

Multiple Quaternary deposits are offset by recurrent faulting at Uracca Creek (Trench 5, Figure 1) but this subsidiary fault strand lies 1 km west of the main range front scarp. Notwithstanding, the inferred history of displacements is remarkably similar to that in Segment A: three events in the last 35 ka, three more events from 35 ka to 140 ka, and as many as 12 events from 140 ka to 400 ka. Individual displacements are estimated at 1.7 to 2.2 m, corresponding to magnitude 7.1 to 7.2 earthquakes (Slemmons, 1982).

Segment C

Segment C consists of some poorly connected, but spectacularly large south-and southwest-facing scarps which wrap around the south base of Blanca Peak. The 10-km long zone of scarps is bounded at nearly right angles by Segment B on the west, and by an unnamed south-trending segment on the east. Scarp heights range from 5-10 m across Pinedale deposits, and from 22-28 m across Bull Lake deposits. However, these large scarp heights are associated with grabens up to 50 m wide below the scarps; net vertical displacements based on graphical projection are less than 5 m for Pinedale and 6-8 m for Bull Lake deposits. If the smallest fault scarps reflect single-event displacements of roughly 1.5 m, then only about half as many events have occurred on Segment C in late Quaternary time as on the other two segments. Recurrence intervals since Pinedale time are roughly 35 ka (1 event from 0-35 ka), for Pinedale-Bull Lake time are 52 ka (2 events from 35 ka - 140 ka), and are 51 ka for pre-Bull Lake time (5 events from 140 ka - 400 ka). These longer recurrence times and smaller displacements per event suggest that Segment C is a relatively passive fault segment which serves to adjust displacement between larger and more active north-south-trending fault zones to the east and west.

Overall Patterns of Displacement

By plotting the amount of vertical displacement of various Quaternary deposits along the strike of the SCFZ, one gets an impression of spatial and temporal trends in range uplift (Figure 2). Within Segment A, scarp heights are considerably lower for pre-Pinedale deposits north of the point where the range front intersects the Laramide Major/Kerber Creek thrust fault zone (MKFZ). Post-Pinedale scarps maintain uniform heights across the boundary, suggesting that some pre-Pinedale surface ruptures died out rapidly at the MKFZ, whereas post-Pinedale ruptures have not. Segment A is actually composed of two segments, a 38 km-long segment north of the MKFZ, and a 52 km-long segment south of it. The largest scarp heights do not correlate well with increased crest elevation, indicating that either relief is a poor criterion for uplift rate, or that the uplift distribution of the last 400 ka is not representative of Cenozoic time.

Scarps of Segment B are similar to, but smaller than the scarps of central Segment A. As the Segment B/C boundary is crossed, scarps again rapidly lose height, more pronouncedly in older deposits. Overall, the fault segments A, B, and C defined by range front strike do not exactly coincide with discrete uplift domains defined by fault scarp displacements.

VILLA GROVE FAULT ZONE

The VGFZ consists of roughly 40 low scarps in a zone 1.5 km wide and 10 km long in the north-central San Luis Valley (Figure 1). Individual scarps range from 0.1 to 2.6 km in length, and from 0.4 to 11.3 m in height. The cumulative vertical displacement across the entire zone decreases consistently from about 7 m near the point of divergence from the range front fault to only 2.7 m 7 km to the northwest, suggesting a hinge-type displacement.

Displacement and Recurrence

Interactions between fault scarps and Quaternary deposits indicate five types of scarp-deposit geometries. Oldest scarps offset pre-Bull Lake fan remnants, but not the surrounding Bull Lake fan surfaces. Next younger scarps offset both pre-Bull Lake and Bull Lake surfaces, with scarp heights higher across older deposits. Some scarps traverse only Bull Lake surfaces, hence displacement age can only be dated as post-Bull Lake. Many scarps on Bull Lake surfaces are truncated by Pinedale channels indicating pre-Pinedale activity. Finally, youngest scarps offset both Bull Lake and Pinedale surfaces, with scarps smaller in the younger deposit.

Single-event scarp heights suggest that vertical displacements of 0.8 to 1.4 m are typical at rupture events on the VGFZ, corresponding to M_L 6.8-7.0 earthquakes (Slemmons, 1982, Figure 3,). Multiple-event scarps and a single trench (Trench 1, Figure 1) suggest the following: one event since mid Pinedale time (recurrence interval 20 ka), one event between 20 ka and 140 ka (recurrence interval 120 ka), and two or three events from 140 ka to 400 ka (recurrence interval 90-140 ka). These displacements are roughly half as

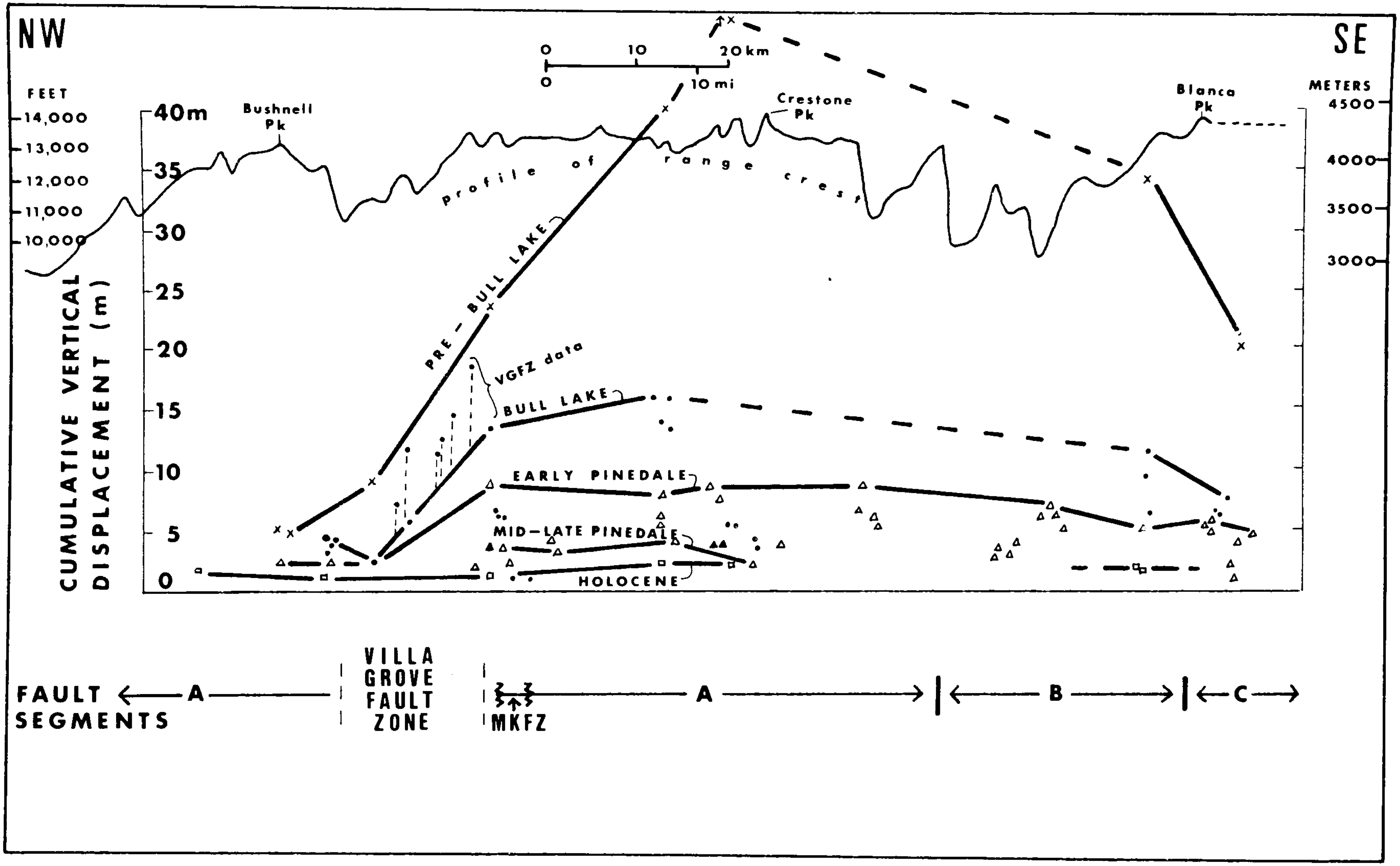

Figure 2. Diagram of the cumulative vertical displacement of Quaternary deposits of several ages along the trend of the Sangre de Cristo Fault Zone. Displacements were measured graphically from 150 fault scarp profiles by projecting the upthrown and downthrown alluvial fan surfaces into the inferred fault plane (70° dip) at the steepest profile segment. This procedure corrects for back-tilting, graben formation, and step-faulting (see McCalpin, 1983, p. 40-43). Heavy lines connect maximum displacement values for deposits of a given age: squares, Holocene; solid triangles, mid-late Pinedale; open triangles, early Pinedale and Pinedale, indifferentiated; solid circles, Bull Lake; X, pre-Bull Lake (includes deposits of several ages). Modified from McCalpin (1983), Fig. 86.

large, and recurrence times about four or five times longer than, for the range-bounding SCFZ.

CONCLUSIONS

Detailed study of 150 fault scarp profiles and 5 trenches suggests that M_L 7.0-7.3 earthquakes occur along the SCFZ every 10-40 ka. Smaller M_L 6.8-7.0 earthquakes occur every 20-140 ka along the less-active VGFZ. With the latest surface rupture at roughly 8 ka (Trench 2), and with multiple late Pleistocene ruptures, the SCFZ qualifies as one of Colorado's few documented active faults.

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SEISMOTECTONIC EVALUATION OF THE DUDLEY GULCH GRABEN IN THE PICEANCE CREEK BASIN

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INTRODUCTION

A seismotectonic evaluation of the Dudley Gulch Graben in the Piceance Creek Basin of northwestern Colorado was performed in 1981 (Eckert, 1982) in response to a report by Dames & Moore (1981). The Dames & Moore report suggested that the Dudley Gulch Graben could have been the source of a magnitude 6.5 earthquake on November 7, 1882. Numerous locations for this earthquake have been proposed previously, however, the epicentral location has not been satisfactorily identified due to differing interpretations of available data. The major reason that the graben was suggested as the possible epicentral location was the presence of a prominent linear formed by bluffs on the south side of the Dudley Gulch Graben on both LANDSAT imagery and aerial photography.

The seismotectonic evaluation discussed in this paper included detailed mapping of the graben and a micro-earthquake monitoring program consisting of one seismic station located on the graben for 8 weeks during the summer of 1981. Further details on the results of the micro-earthquake monitoring program are discussed in a paper by Clift and Billington in this volume.

LOCATION AND TOPOGRAPHY

The Dudley Gulch Graben lies in northwestern Colorado in the east-central part of the northern Piceance Creek Basin. The location of the graben is shown in Figure 1. The graben trends west-northwest from sec. 26, T.2S., R.96W. to sec. 1, T.2S., R.98W. The eastern part of the graben parallels Piceance Creek. The western end of the graben intersects Piceance Creek and Ryan Gulch approximately 1 mile south of their confluence.

The elevation in the Piceance Creek Basin ranges from 6000 to 7000 feet m.s.l. The basin is characterized by low rolling hills and flat-floored valleys. Arroyos are common and alluvial fans are well developed. Generally, the hills in the basin stand several hundred feet above the Piceance Creek valley floor. However, prominent bluffs along the south side of the graben (Dudley Bluffs) reach as high as 600 feet above the valley floor.

GEOLOGIC SETTING

The Piceance Creek Basin is an asymmetric sedimentary and structural basin which is roughly divided into northern and southern parts by the Colorado River. The Dudley Gulch Graben lies in the northern Piceance Creek Basin which is bounded by the Grand Hogback Monocline to the east, by the Douglas Creek Arch to the west, and by the folded Cretaceous rocks adjacent to the Axial Basin uplift to the north (Haun, 1962).

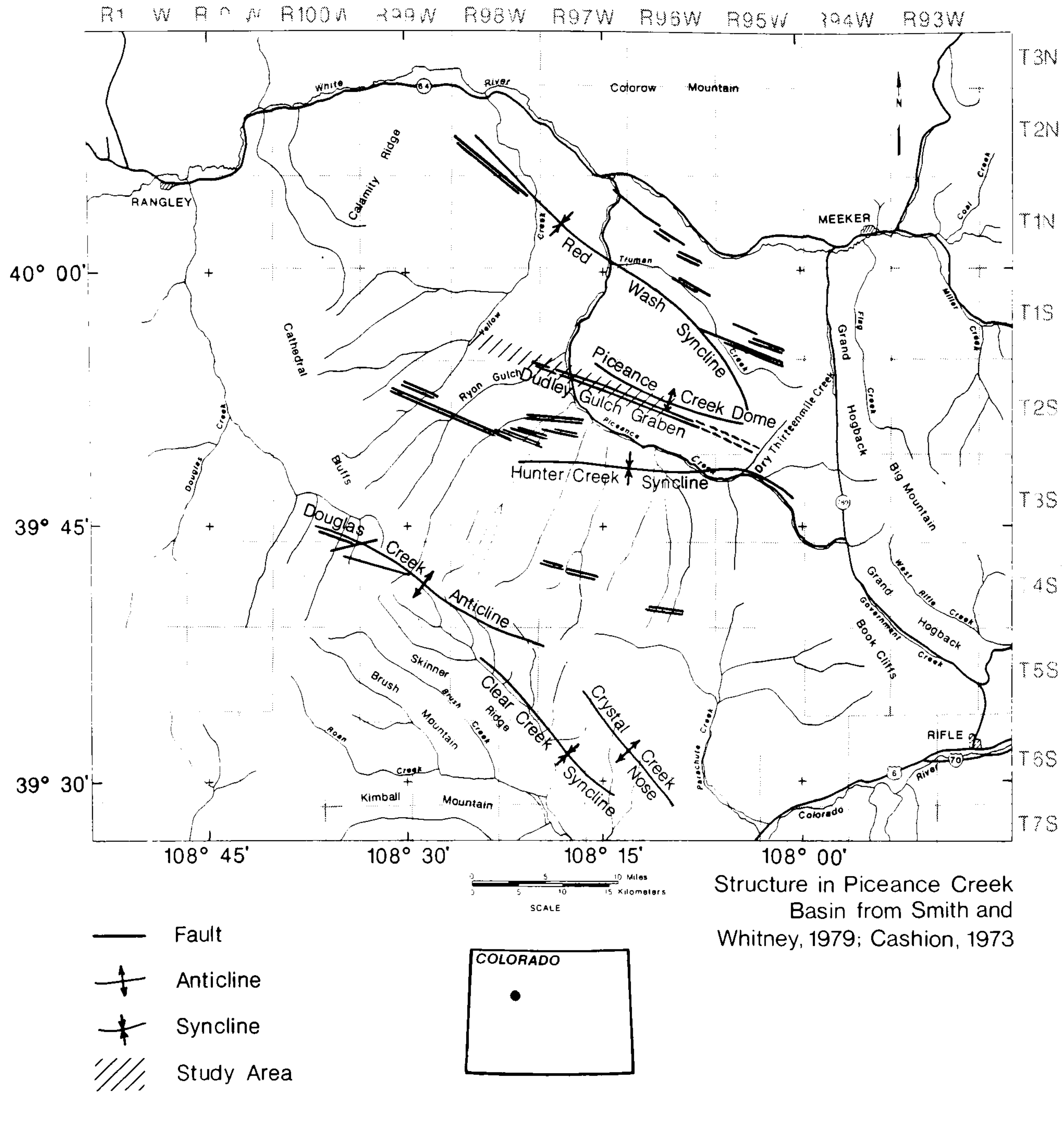

Figure 1. Map showing location of Dudley Gulch Graben within the Piceance Creek Basin.

Stratigraphy

The Eocene-age Green River and Uinta Formations crop out in the study area. The Green River Formation consists of approximately 2300 feet of medium-grained sandstone, calcareous shales, and marlstone. The Parachute Creek Member of this formation contains the rich zones of oil shale, which are of mining interest in the basin. The contact between the Green River Formation and the overlying Uinta Formation is transitional and at least five tongues of the Green River Formation have been identified in the Uinta (Duncan, 1976a). One of these tongues, the Thirteenmile Creek, crops out in the study area.

The total thickness of the Uinta Formation in the Piceance Creek Basin is unknown. The maximum measured thickness is about 1000 feet in the central part of the basin along the Colorado River. The formation consists of alternating beds of massive brown to buff sandstone, siltstone, and gray to brown marlstone. The sandstone occurs in discontinuous lenses throughout the formation, making correlation difficult (Juhan, 1960).

Pleistocene-age stream gravels on terraces 20 to 160 feet above the present Piceance Creek are preserved locally. These gravels range in thickness from 0 to 25 feet and characteristically contain rounded pebbles, cobbles, and boulders of chert, limestone, quartzite, and sandstone derived from the White River Uplift to the east and locally derived sandstone and marlstone (Duncan, 1976c). In some places, these gravels are carbonate-cemented. The gravels have tentatively been correlated with the aggradational episodes that occurred during the Illinoian Stage of the Pleistocene (Whitney and Andrews, 1983).

Floodplain and mudflow deposits of Holocene age are present in the larger valleys of the basin. Their thickness ranges from about 70 feet in Ryan Gulch and 90 feet in Piceance Creek to about 120 feet in Yellow Creek (Coffin, et al., 1968). Floodplain alluvium generally consists of gray, buff, and brown silt and sand. The mudflow deposits consist of angular boulders and pebbles of sandstone and marlstone mixed with silt and sand.

Structure

Tectonic forces began to form the Piceance Creek Basin at the end of the Eocene Epoch (Merriam, 1954). The presence of local unconformities and tighter folding with depth suggests that the structural development of the present-day basin was occurring during the deposition of the Uinta Formation (Duncan and Belser, 1950). Uplift has probably continued into the Quaternary, although the maximum deformation occurred in the Eocene and Oligocene (Verbeek and Grout, 1983).

Folds in the northern Piceance Creek Basin trend northwest. The doubly plunging asymmetric Red Wash Syncline trends northwest along the northeast side of the basin forming the axis of the basin. Bedding on the northeast limb of the syncline dips as much as 27° west (Bradley, 1931), while bedding on the southwest limb dips from 1° to 8° east. Several other, more gentle folds have been mapped within the basin. The maximum dip on the limbs of these folds is approximately 8° to 10°. The study area lies on the south limb of the Piceance Creek Dome, as shown in Figure 1.

High-angle normal faulting is the most common type of faulting in the basin. Commonly, the faults are paired, forming long narrow grabens trending about

N70°W. The maximum known displacement on the faults is about 237 feet, which was measured on a graben at Federal Oil Shale C-a Tract (Ziemba, personal communication, 1981).

DETAILED MAPPING OF THE GRABEN

The Dudley Gulch Graben is a narrow graben approximately 20 miles long and a maximum of about 1000 feet wide. Figure 2 shows the location and extent of the graben faults. The average attitude of the northern fault is N68°W 81°SW, while the average attitude of the southern fault is N70°W 81°NE. Normal displacement on the faults appears to be at least 80 feet as seen in the exposure at the west side of Piceance Creek. Slickensides along the faults indicate dip-slip movement.

Mapping of the western 10 miles of the graben was performed using 1976, 1:12,000 Bureau of Land Management (BLM) black and white aerial photography, supplemented by 1980, 1:24,000 BLM color aerial photography, and 1948, 1:27,600 U.S. Geological Survey (USGS) black and white aerial photography. The preliminary geologic maps of the Greasewood Gulch, Jessup Gulch, and Square S Ranch 1:24,000 quadrangles (Duncan, 1976a, 1976b, 1976c) were used as guides in mapping the graben faults. The faults were identified and traced by mapping a characteristic calcite and breccia zone, and by field-checking lineaments identified on aerial photography and conspicuous drainages trending along the projected faults. The faults were obscured in some areas east of Piceance Creek due to heavy vegetation, disturbances from drilling activity and roads on the Piceance Creek Dome.

The graben faults are best exposed in the Ryan Gulch and Piceance Creek areas. In these areas and along most of the western end of the graben, the faults are characterized by brecciated sandstone, thick deformed and undeformed calcite zones, and some jarosite and iron mineralization. The westernmost exposure of the graben is in NW 1/4 sec. 6, T.2S., R.97W., approximately 1 mile west of Ryan Gulch. Two lineaments were identified on aerial photography west of this exposure and extend for about 1.5 miles on strike with the two graben faults. There is a suggestion that the graben may extend as far as 5 miles further west into the Yellow Creek area. Two anomalous vertical electrical soundings (which measure resistivity) performed in the Yellow Creek area by D.L. Campbell (1975, 1977), suggested the presence of crushed rock at a depth of 60 to 1300 feet. Campbell noted that the two anomalous soundings are aligned along the strike of the Dudley Gulch Graben and, therefore, could indicate that the graben extends into this area. The area from the last exposure of the graben to Yellow Creek was field-checked, however, no surface evidence of the faults was found.

A cross section of the graben is exposed on the west side of Piceance Creek by the incising of Piceance Creek. This cross section is shown in the photograph in Figure 3. At this exposure, Duncan (1976c) shows the Uinta Formation to be downdropped at least 80 feet within the graben.

On east side of Piceance Creek, the southwest fault is overlain by about 2 feet of Pleistocene deposits. East of this exposure, the graben faults can be traced only sporadically. Mapping of the eastern section of the graben to the Collins Gulch area was accomplished mainly by inferences from color, lithology, and vegetation changes on the aerial photography and in the field. At least four other smaller faults paralleling the graben were also identified

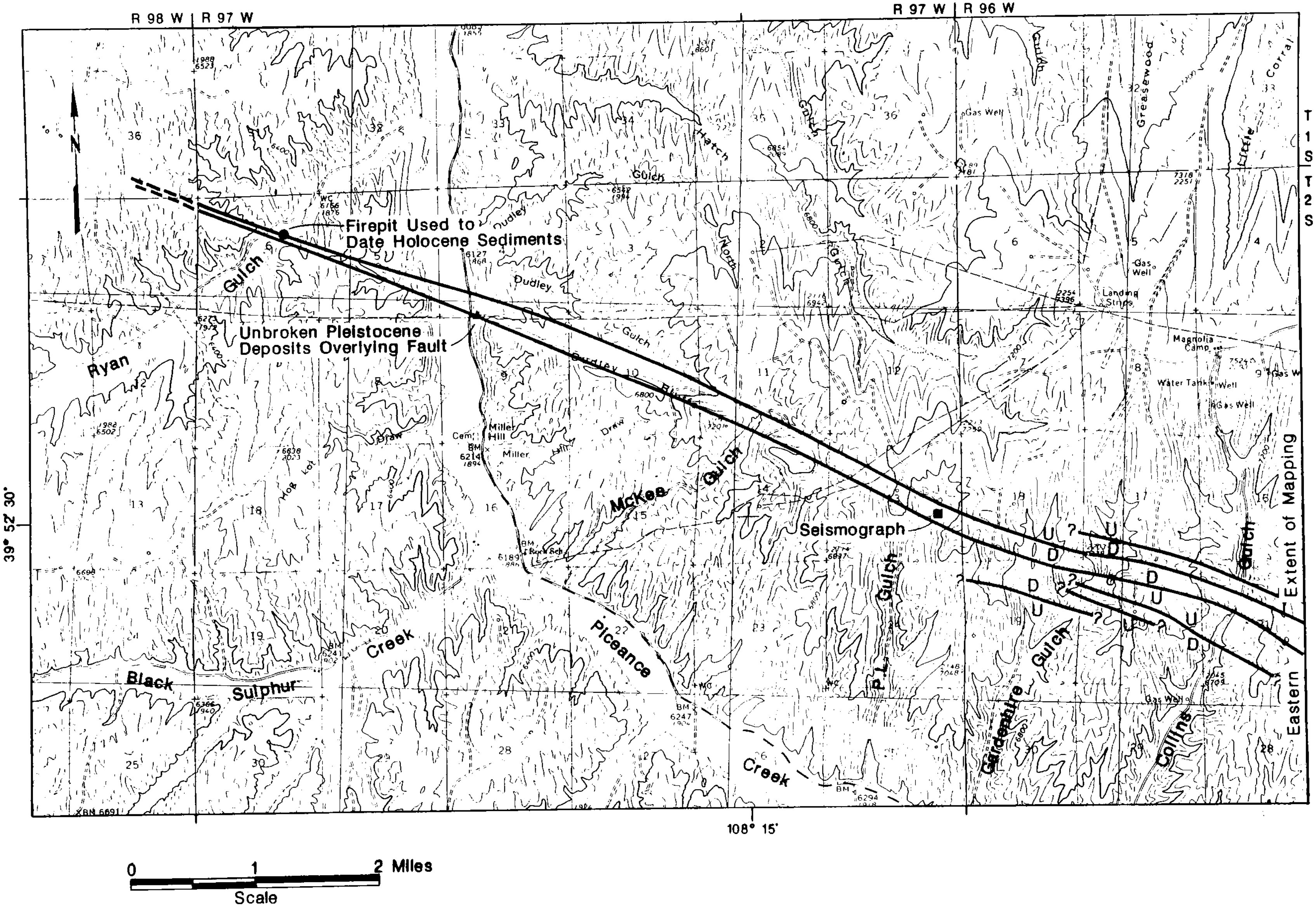

Figure 2. Detailed map of Dudley Gulch Graben showing location of graben faults.

Figure 3. Photograph of Dudley Gulch Graben outcrop in the Piceance Creek Valley. Massive rock in center of photograph (in shadow) is Uinta Formation downdropped into the less competent Thirteenmile Creek Tongue of the Green River Formation.

in the Collins Gulch area. The graben is actually thought to extend as far east as Dry Thirteenmile Creek in T.2S., R.95W., based on aerial photography lineaments and some preliminary fieldwork by Robert O'Sullivan of the USGS (Sullivan, personal communication, 1981).

EVIDENCE FOR MOST RECENT MOVEMENT

Three lines of evidence were evaluated to investigate the most recent movement along the graben. These included: 1) an evaluation of any peculiar geomorphologic features; 2) a determination of the presence or absence of offsets in young sediments; and 3) microseismic monitoring of the graben.

Geomorphology

The most striking geomorphic feature along the graben is Dudley Bluffs, which parallels the south side of the graben. Dames & Moore (1981) suggested the bluffs might be a fault scarp produced by historic fault movement. Large drainages such as Ryan Gulch, Piceance Creek, McKee Gulch, P.L. Gulch, Gardenhire Gulch, and Collins Gulch cut perpendicularly across the graben and Dudley Bluffs, as shown in Figure 2. If either or both of the graben faults had ruptured the surface historically, these drainages would show some evidence, such as deflections or knickpoints. None of these valleys presently exhibit any such characteristics.

During the field mapping program, several possible fault-related geomorphic features were identified. However, with closer examination, none of these were found to indicate historic surface rupture (Eckert, 1982).

Offset in Young Sediments

Holocene Sediments. The Dudley Gulch Graben crosses two large valleys filled with Holocene alluvial sediments (Piceance Creek and Ryan Gulch). The Piceance Creek valley is presently being farmed, so there is no natural exposure of the recent alluvial section. However, Holocene alluvial material is exposed in an arroyo approximately 15 feet deep where the graben crosses Ryan Gulch.

The deposits in the Ryan Gulch arroyo were logged across the projections of both graben faults to a depth of 6 feet and found to be continuous (Eckert, 1982). In addition, earlier in 1981, a deposit of charcoal and large rocks in a firepit configuration was found in the Ryan gulch alluvium by members of the Colorado Geological Survey and Bisonhead Geological Services. This firepit lies approximately 50 feet north of where the northern fault of the graben projects through the valley and is about 9 feet below the surface. The location of the firepit is shown in Figure 2. The charcoal was dated by the USGS using the Carbon-14 method as 1230 $\pm$ 60 years before present (USGS-1259). Based on the age of the firepit at 9 feet deep and assuming a constant rate of deposition, the sediments logged at a depth of 6 feet are estimated to be approximately 800 years old. Therefore, there has been no surface rupture on the graben in the Ryan Gulch area for at least 800 years. This precludes rupture as a result of the 1882 earthquake at this location.

Pleistocene Deposits. During the mapping of the graben, a Pleistocene conglomerate was found overlying the southern fault in the gully just east of Piceance Creek (Eckert, 1982). The location of this deposit is shown in Figure 2. The deposit is composed of well-rounded pebbles, cobbles, and boulders deposited in a disorderly fashion and is locally carbonate-cemented.

The conglomerate lies approximately 80 feet above the present Piceance Creek and was traced for at least 200 feet both north and south of the gully. The deposit extends down to an elevation approximately 50 feet above Piceance Creek in the area north of the gully deposit. A swath approximately 5 feet high and 57 feet long was cleared in the gully to expose the bedrock/gravel contact. The cleared area was then examined and logged.

The southern fault of the Dudley Gulch Graben trends N65°W 56°NE in this exposure and juxtaposes the white-yellow to yellow sandstone of the Uinta Formation inside the graben against the light brown, thinly laminated calcareous claystone of the Thirteenmile Creek Tongue of the Green River Formation outside the graben. A 3-foot-thick sequence of unfaulted Pleistocene-cemented conglomerate overlies the fault indicating that surface rupture has not occurred on the fault since the cementation of the Pleistocene deposit. This precludes rupture of the fault as a result of the 1882 earthquake at this location.

Microseismic Monitoring

A vertical-component seismograph was installed for 8 weeks during the summer of 1981 to monitor seismic activity in the Dudley Gulch Graben area. The seismograph location is shown in Figure 2. During that time, 21 possible earthquakes were identified. Of these, nine are most likely to be local earthquakes based on signal shape, time of occurrence, and spacing. The magnitudes of these nine events were roughly estimated to range from 0.7 to 1.7. Based on the S-wave minus P-wave arrival times, these nine events were estimated to have occurred about 10 km from the seismograph and, therefore, could be associated with the graben. However, these data by themselves are inconclusive. Further details of this micro-earthquake survey are discussed in a paper by Clift and Billington in this volume and Eckert (1982).

Fracturing With Respect to Faulting

A stress system responsible for formation of the graben can be postulated, assuming that the two bounding faults of the Dudley Gulch Graben formed at the same time and that the predominantly dip-slip slickensides are an indication of overall movement on the graben. In this proposed system, the maximum compressive stress acts in a vertical direction bisecting the angle between the graben faults and the minimum compressive stress acts horizontally in a N10° to 30°E direction, perpendicular to the strike of the graben faults.

A detailed study of the fracture history in the Piceance Creek Basin has been performed by Verbeek and Grout (1983). Of the five fracture sets identified, one set which has developed regionally in the Piceance Creek Basin is of importance to this study. Set F_{2c} trends west-northwest with an average strike of N65°W dipping subvertically. These extension fractures are commonly calcite-filled. Formation of the F_{2c} fractures occurred in a stress system where the maximum compressive stress direction was oriented subvertically and the minimum compressive stress direction was oriented horizontally north-northeast (Verbeek and Grout, 1983). The formation of these fractures is compatible with the stress system proposed earlier for formation of the graben. Verbeek and Grout (1983) note that the F_{2c} fracture set appears to have formed prior to the major uplift of the Grand Hogback Monocline, which ended in the early Oligocene. Formation of the graben could have occurred contemporaneously with formation of the F_{2c} joints because of the similar stress orientation needed to produce those structures. This would place the time of formation of the graben prior to early Oligocene.

CONCLUSIONS

The Dudley Gulch Graben was studied to evaluate its possible relationship to the Colorado 1882 earthquake. The results of this investigation are as follows:

- There is no geomorphological evidence to indicate that surface rupture has occurred along the Dudley Gulch Graben in historic times.
- Examination of the exposed Holocene sediments that cross the fault traces in Ryan Gulch indicates surface rupture has not occurred in that area for at least the past 800 years.
- Unfaulted Pleistocene deposits which overlie a portion of the southern graben fault near Piceance Creek indicate that rupture has not occurred on the fault in that area since the Pleistocene.
- Twenty-one possible local earthquakes were identified during the microseismic survey in the graben area. Of these, nine are most likely to be local earthquakes, which could be associated with movement on the graben. While these data add to the overall data base, they are inconclusive in terms of evaluating historical movement on the graben.

Based on these results, the Dudley Gulch Graben does not appear to be historically active and, therefore, is not considered to be a source for the November 7, 1882 earthquake. The graben most likely formed in the late Eocene or early Oligocene and has not experienced surface rupture since at least the Pleistocene.

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NEOTECTONICS OF THE UNCOMPAHGRE UPLIFT, EASTERN UTAH AND WESTERN COLORADO

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ABSTRACT

The Uncompahgre uplift is a crustal block of the Colorado Plateau that has experienced significant tectonic activity since the Laramide. On December 6, 1985 a small earthquake of M_L 2.9, followed by three possible aftershocks, occurred on the southwestern flank of the Uncompahgre uplift. The mainshock appears to have been the result of extensional seismic slip on an east-west or west-northwest trending fault associated with the uplift. The epicentral locations of the earthquakes suggest that they occurred on the Ryan Creek fault, one of the bounding faults of the Ute Creek graben. However, uncertainties in both the event locations and the subsurface fault geometry permit other possibilities for the causative fault. These include a concealed, deep-seated, west- to northwest-trending reverse fault zone that now may be undergoing extensional reactivation, or one of the other west- to northwest-trending faults of the Ute Creek graben. The focal mechanism supports any of these interpretations. The mechanism also suggests that the region is being subjected to north-northeast directed tectonic extension rather than the east-west compression postulated for the Colorado Plateau stress province. Quaternary uplift rates, inferred from terrace heights above major rivers, differ greatly along the flanks of the Uncompahgre block; the region to the northeast has a rate 5 to 10 times higher than the salt anticline region to the southwest. The Uncompahgre uplift appears to occupy a transition zone between these two uplift domains, and to be rotating down to the southwest as a rigid block between hinge-lines that approximate the margins of the block. Subsidence along the southwestern flank is consistent with extensional faulting here, and otherwise anomalous geomorphic features in Unaweep Canyon.

INTRODUCTION

The Uncompahgre uplift is a northeast-tilted crustal block of the Colorado Plateau in western Colorado and eastern Utah. The uplift separates the Paradox Basin on the southwest from the Piceance Basin and the Gunnison uplift on the northeast (Figure 1). Unlike much of the rest of the Plateau, the Uncompaghre uplift has experienced significant tectonic activity since the end of Laramide time (40 mya). Although substantial geologic evidence attests to a relatively high level of tectonism during the Pliocene and Pleistocene, the historical seismicity in the vicinity of the uplift appears to be low level,

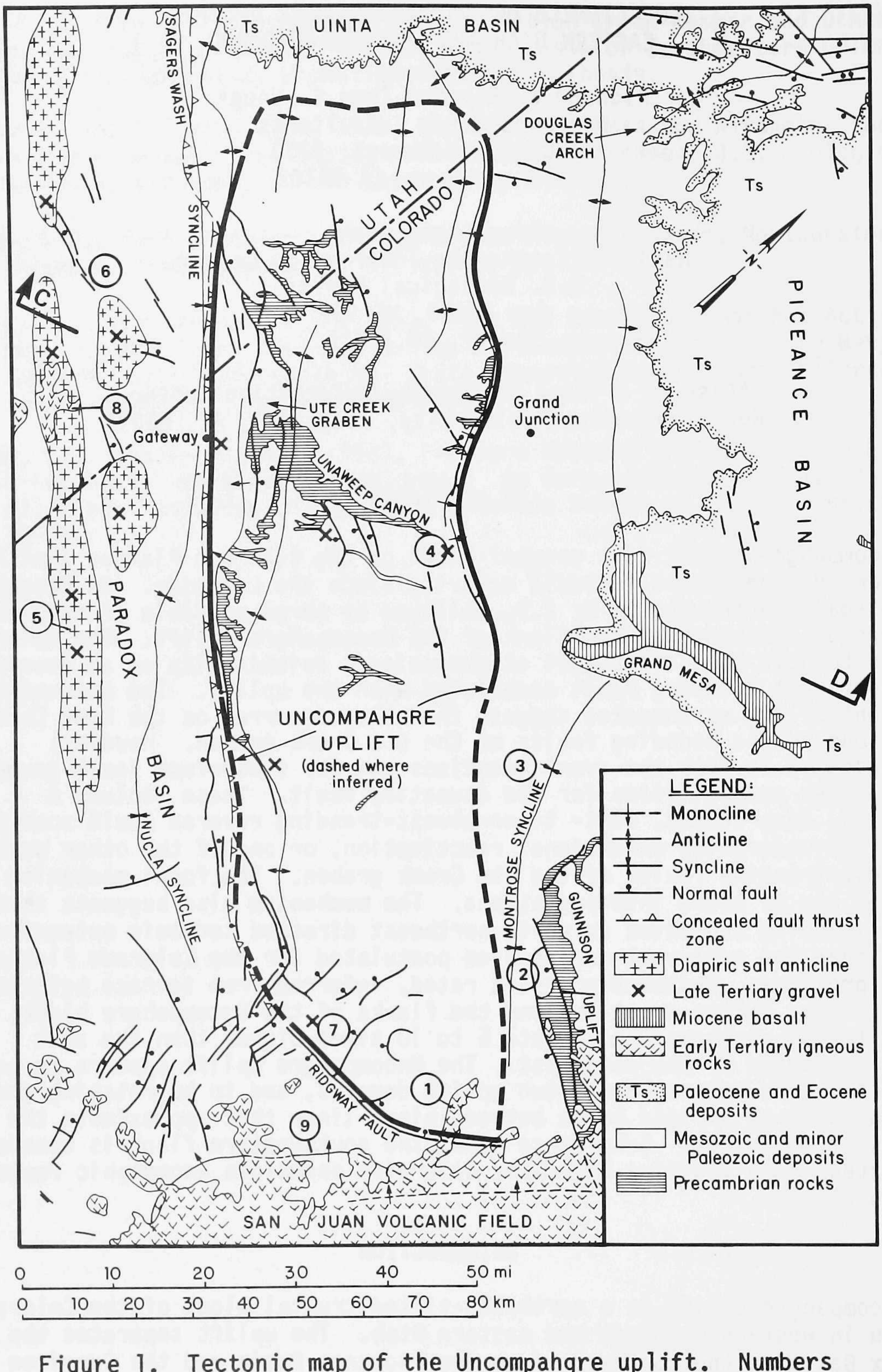

Figure 1. Tectonic map of the Uncompahgre uplift. Numbers refer to the following locations: 1) Cimarron Ridge; 2) Bostwick Park; 3) Delta; 4) Cactus Park; 5) Paradox Valley; 6) Professor Valley; 7) Horsefly Peak; 8) La Sal Mountains; 9) San Juan monocline.

consistent with other observations of Plateau seismicity. However, such observations have been limited by the relatively poor seismographic coverage of the region until recently. The operation of networks in southeastern Utah and southwestern Colorado during the past eight years has allowed the first seismological analysis of an earthquake located in the region, a Richter magnitude (M_L) 2.9 event that occurred on December 6, 1985. The epicenter was located 16 km north of the town of Gateway, Colorado, between the mapped traces of the bounding faults of the Ute Creek graben (Figure 2). Analysis of this event and several other microearthquakes in the vicinity provides an opportunity to evaluate the seismogenic and tectonic characteristics of the southwestern bounding faults of the Uncompahgre uplift. The following is a discussion of the neotectonics of the Uncompahgre uplift with an emphasis on its southwestern flank and an evaluation of the earthquake in the context of its structural setting. The accepted neotectonic history of the uplift involves northeast tilting during the late Cenozoic and diversion of the Gunnison (or Colorado) River away from a route that crossed the uplift at Unaweep Canyon to the present route around the northwest end. However, a number of geologic observations have been made in recent years that do not appear to fit this scheme. We have attempted to develop a late Cenozoic tectonic history that accommodates these observations and is consistent with the vertical tectonic behavior of the areas flanking the uplift.

ACKNOWLEDGMENTS

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GEOLOGIC SETTING

The Uncompahgre uplift is nearly rectangular in map view and measures approximately 50 km wide by 180 km long, with the long axis trending northwest (Figure 1). The uplift is asymmetric in cross section and has a somewhat sinuous structural crest that lies approximately 15 km from the southwestern margin. Mesozoic sedimentary deposits northeast of the crest are part of a regional homocline that dips 1 to 3 degrees northeast and includes part of the Piceance basin (Williams, 1964) (Figure 1). The southwestern flank of the uplift exhibits approximately 600 to 900 m of structural relief on the Cretaceous Dakota Sandstone between the crest of the uplift and the Sagers Wash-Nucla synclines 15 to 25 km to the southwest (Williams, 1964) (Figures 2 and 4). This flank is the most structurally complex part of the uplift and is thought to be underlain by a 5- to 15-km-wide, zone of northeast-dipping reverse faults that have produced several kilometers of structural relief in the crystalline basement (Frahme and Vaughn, 1983; Heyman, 1983; White and Jacobson, 1983) (Figures 3 and 4). The deep-seated basement fault zone apparently underlies much of the region between the crest of the uplift and the synclinal axis to the southwest. These faults were overlapped and buried by sediments during Early Permian time and are inferred from boreholes and geophysical observations. Mesozoic sediments presently exposed at the ground surface along the southwestern flank show considerable variability in dip and are faulted by a crudely right-stepping system of normal faults indicative of

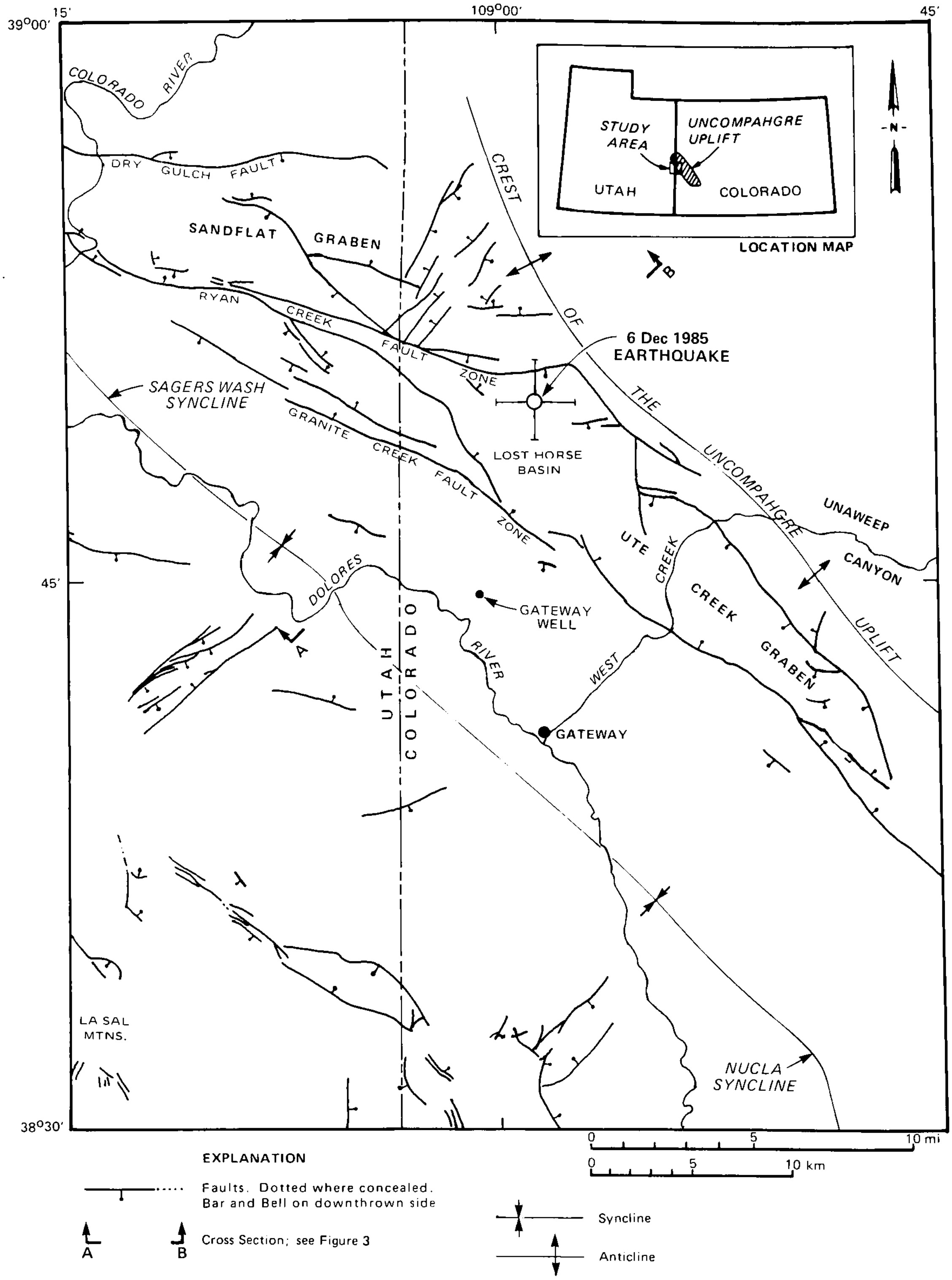
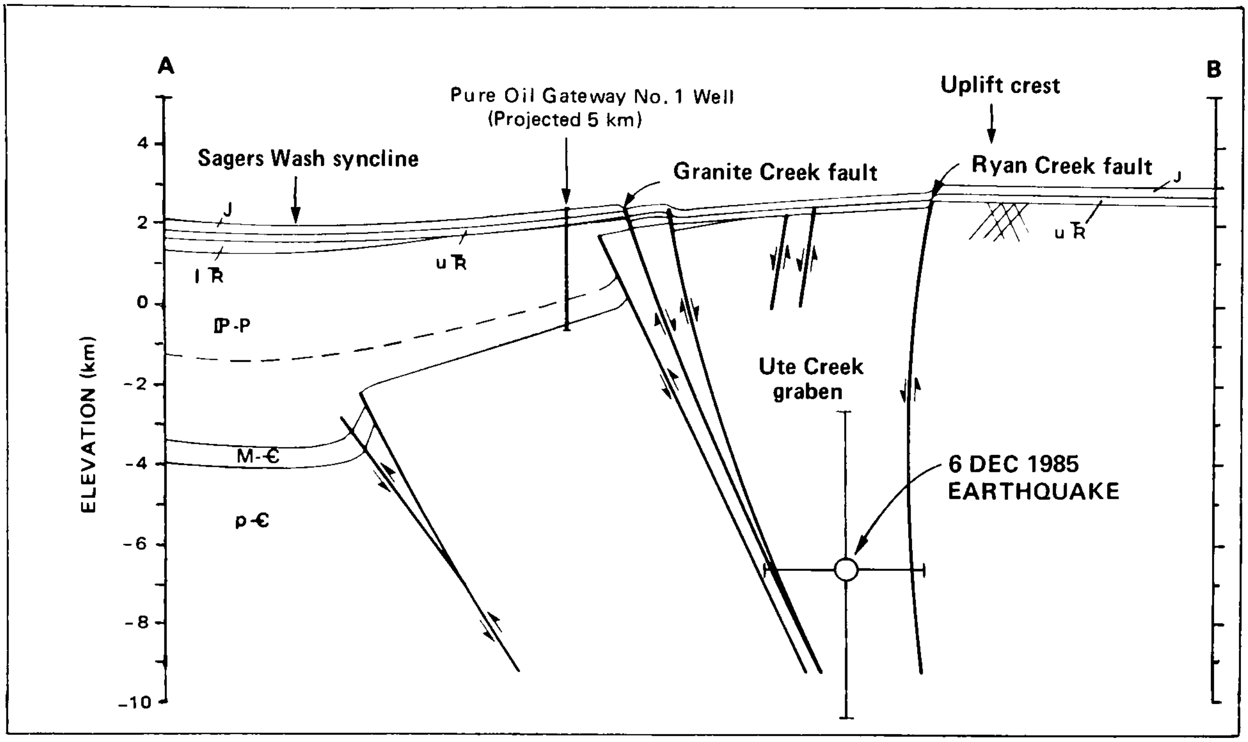


Figure 2. Detailed fault map of the southwestern flank of the Uncompahgre uplift near Gateway, Colorado. Faults taken from Williams (1964) and Heyman (1983). Also shown is the epicenter of the M_L 2.9 Gateway earthquake. Error bars represent estimated epicentral uncertainties of 2 km.

a component of left-slip on the deep seated fault system (Figures 1 and 2). Sparse subsurface control allows only a schematic depiction of the subsurface fault geometry (Figure 3; see also Frahme and Vaughn, 1983; Heyman, 1983; White and Jacobson, 1983). In detail the concealed reverse fault zone probably exhibits great complexity with strands branching and converging along a northwest trend.



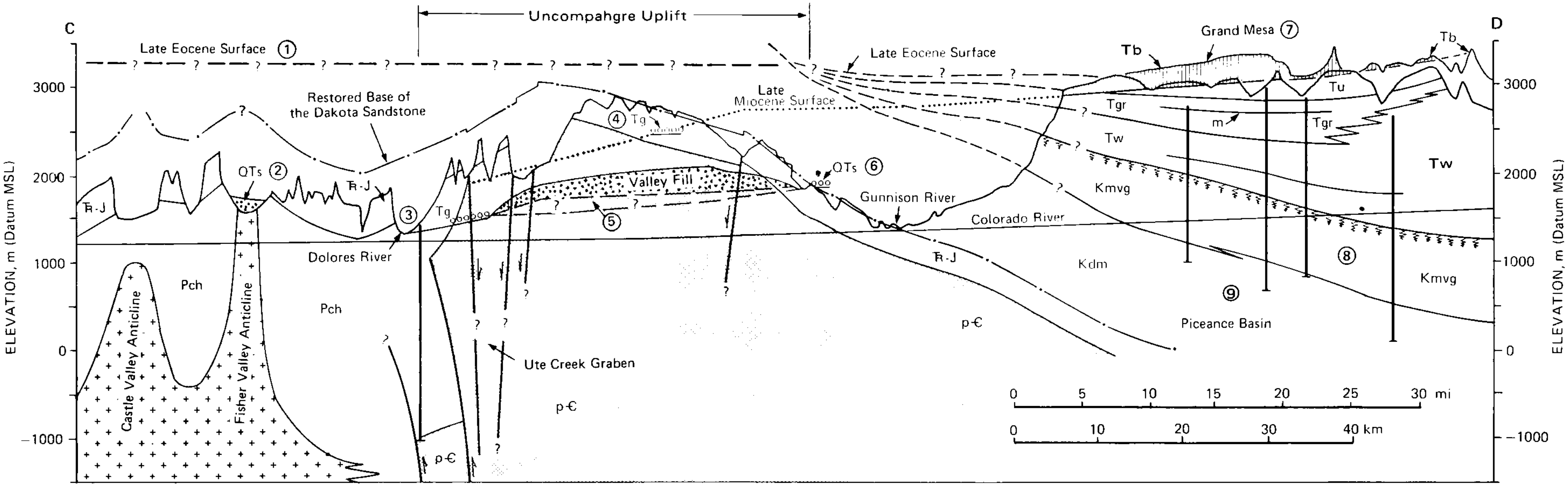
(Modified from Heyman, 1983)

EXPLANATION

J	Jurassic rocks
uTR	Upper Triassic rocks
lTR	Lower Triassic rocks
IP-P	Permian and Pennsylvanian rocks
M-€	Mississippian—Cambrian rocks
p-€	Precambrian rocks
	Contact
	Fault; arrows indicate sense of displacement
	Brittle flexure

NOTE:
Location of cross-section A—B is shown on Figure 2.

Figure 3. Schematic geologic cross-section across the southwestern flank of the Uncompahgre uplift. Also shown is the hypocenter of the Gateway earthquake. Error bars represent estimated uncertainties.



NOTE: Location of cross-section C—D is shown on Figure 1.

Circled numbers refer to the following notes:

1. Late Eocene surface is from Ely (1982). The elevation of the surface is loosely constrained by the occurrence of the Evacuation Creek Member of the Uinta Formation as high as 2,899 m on the Roan Cliffs (Cashion, 1973) and the Late Oligocene - earliest Miocene La Sal Mountains laccoliths as high as 3,877 m. Surface geologic contacts and Dakota structure are from Williams (1964), Cashion (1973), and Tweto and others (1978).

2. Late Pliocene and early Pleistocene deposits in Fisher Valley were trapped behind a salt diapir (Colman and Hawkins, 1985).

3. Late Pliocene gravel deposits near Gateway. Vertical line is Pure Oil Gateway No. 1 well.

4. Gravel deposits near the south rim of Unaweep Canyon contain siliceous pebbles from the Dakota Sandstone and volcanic clasts (Sinnock, 1981b) These deposits are interpreted to lie close to the position of the Late Miocene topographic subenvelope.

5. The two dashed lines delineate the uncertainty in the elevation of the buried thalweg of Unaweep Canyon as determined by Oesleby (1983). Top of the valley fill is the present floor of Unaweep Canyon.

6. Gravel deposits at Cactus Park contain clasts of basalt, granite, and quartzite (Lohman, 1981).

7. Grand Mesa is capped by an approximately 10 my old sequence of basalt flows that overlie Late Eocene fluvial deposits of the Uinta Formation. The position of the Late Miocene subenvelope in this area is very close to the Late Eocene surface.

8. A deep tropical weathering horizon developed on top of the Mesa Verde Group in the early Paleocene. Boreholes in the Piceance Basin are from Johnson and others (1979a, 1979b). Top of the Mesa Verde Group is from Grancia and Johnson (1980).

9. The Mancos Shale-Mesa Verde Group contact at Grand Mesa is approximated by structure contours on the top of the Rollins Sandstone tongue from Johnson (1983).

Figure 4. Cross section of the Uncompahgre uplift. Vertical exaggeration is 10.4X. Crosses are evaporites of the Paradox Formation; p = Precambrian crystalline basement; Pch = Honaker Trail Limestone and Cutler Group; T-J = Triassic and Jurassic sediments; Kdm = Dakota Sandstone and Mancos Shale; Kmvg = Mesa Verde Group; Tw = Wasatch Formation; Tgr = Green River Formation; m = the Mahogany oil shale bed; Tu = Uinta Formation; Tb = Miocene basalt flows; Tg = Late Tertiary gravel deposits; QTs = Pliocene or early Pleistocene sediments.

It is likely that the normal faults exposed at the surface merge at depth with the reverse faults (see Figure 3) and partially compensate for curvature of those faults. Another possibility is that the dips of the normal faults change with depth, and the faults are actually curved reverse faults at deep crustal levels that allow the Uncompahgre uplift to rotate as a rigid block. Some of these faults appear to be reactivated pre-Triassic faults that have a complex history. Exposures of the Granite Creek fault just south of Lost Horse Basin, for example, reveal that late Paleozoic reverse fault separation of the basement surface has been nearly removed by 70 m of post-Triassic normal displacement (Heyman, 1983).

The northeast boundary of the uplift varies in style and extent of deformation observed in the Mesozoic sediments at the ground surface (Figures 1 and 4). In the northwesternmost segment, which is approximately 70 km long, the uplift is separated from the Piceance basin by a southwest-side-up zone of monoclinal folding and basement faulting having up to 300 m of structural relief (Williams, 1964; Cashion, 1973). The middle segment of this side is a homocline that descends from the crest of the uplift to beneath the early Cenozoic deposits of the Piceance basin, with only a gentle dip inflection to mark the uplift boundary (Williams, 1964). Lack of published structure contour data prevents us from precisely delineating the uplift boundary further to the southeast. The general location of the boundary is indicated by the Montrose syncline, which separates the Uncompahgre uplift from the Gunnison uplift (Tweto, 1979).

The uplift is not clearly demarcated on the northwest, although it is bounded in the broad sense by the Uinta basin (Figure 1). The uplift ends in this area in a northwest-dipping homocline, complicated by broad low-amplitude folds that strike and plunge to the northwest (Cashion, 1973). The northern corner of the uplift lies on trend with the crest of the Douglas Creek Arch, a north-trending structure that separates the Uinta and Piceance basins.

The Uncompahgre uplift terminates to the south at the east-west trending Ridgway fault, just north of the San Juan monocline (Dickinson and others, 1968) (Figure 1). The Ridgway fault is considered to be a normal fault having approximately 300 m of south-side-down displacement near the town of Ridgway (White and Jacobson, 1983). The fault terminates to the west in a complexly faulted area at the uplift crest, and disappears to the east under extensive landslides along the western flank of Cimarron Ridge. Dickinson and others (1968) interpret a steeply dipping fault at the crest of Cimarron Ridge with approximately 90 m of north-side-down displacement to be the northeastern continuation of the Ridgway fault. The fault is interpreted by Dickinson and others (1968) to be a scissors fault that accommodates the differential motion between the northeast-tilted Uncompahgre uplift and the San Juan monocline.

HISTORICAL SEISMICITY

The historical seismicity record in the vicinity of the Uncompahgre uplift consists of seven (possibly ten) earthquakes. This small number may be, to a large extent, due to the poor detection capability in the region both prior to and during the operation of seismographic stations in the intermountain U.S. (Wong and Simon, 1981). Only since July 1979, with the installation of the Paradox basin network in southeastern Utah by Woodward-Clyde Consultants (for the Department of Energy), has there been complete detection of earthquakes of M_L 3.0 and greater in the region.

The most significant historical earthquake in the vicinity of the southwestern flank of the uplift was an event of estimated M_L 4.0, which was felt at a Modified Mercalli (MM) intensity III, on November 12, 1971 (Stover and others, 1984). It was located 22 km east-northeast of the 1985 Gateway earthquake and the focal depth was estimated to be 5 km. A pre-instrumental earthquake having a maximum MM III intensity in Grand Junction on February 28, 1915 (Stover and others, 1984) may have occurred along the northeastern flank of the uplift. Several events, including an October 11, 1960 M_L 5.5 earthquake, have been assigned locations between Montrose and the Ridgway fault (Sullivan and others, 1980; Stover and others, 1984; Wong and Humphrey, 1986). However, epicentral uncertainties of at least 10 km for these historical earthquakes prohibit an assignment of the earthquakes to specific faults along the Uncompahgre uplift.

Sullivan and others, 1980 suggest that the Ridgway fault is seismically active based on their observations of seismic activity during a 3-month microearthquake survey conducted in 1979. A total of 13 events located within 6 km south of the surface trace of the fault. However, no focal mechanisms could be determined, and a cross-sectional plot of hypocenters (Sullivan and others, 1980) does not exhibit a planar trend consistent with a dipping fault plane. However, the microearthquakes could be occurring within a zone of complex faulting associated with, and manifested at the surface by, the Ridgway fault. Operation of a permanent seismographic network installed in 1985 by the U.S. Bureau of Reclamation (USBR) around the proposed Ridgway dam should provide data to further assess the seismicity in the vicinity of the fault.

GATEWAY EARTHQUAKE

On December 6, 1985, at 0857 Mountain Standard Time, an earthquake occurred north of Gateway in southwestern Colorado and was recorded by the nearby 17-station Paradox basin network in southeastern Utah, the 10-station Paradox Valley network (operated by the U.S. Geological Survey for the USBR) and the 6-station Ridgway network, both in southwestern Colorado, and by several stations of the University of Utah's regional network (see Wong and Humphrey, 1986 for network locations). Three microearthquakes were also recorded and located near the Gateway earthquake on September 18, (M_L 1.8), September 20, (M_L 1.6), and October 5, (M_L 1.7), prior to the mainshock, followed by at least three possible aftershocks on December 8, 11, and 24, (M_L 1.6, 1.7, and 1.8, respectively). In this study P- and S-wave arrival times read from all available stations were used to determine the epicentral location, focal depth, and origin time of the mainshock (see Wong and Humphrey, 1986 for discussion of data analysis). The magnitude of the event was estimated to be M_L 2.9 based on coda durations measured from the Paradox basin network. Since July 1983 when the Paradox Valley network was established adjacent to the uplift, very few microearthquakes have been recorded in the vicinity of the southwestern flank (Martin and Spence, 1986).

The Gateway earthquakes appear to have occurred beneath Lost Horse Basin, in the northwestern part of the Ute Creek graben, which is bounded on the north by the Ryan Creek fault zone and on the south by the Granite Creek fault zone (Heyman, 1983) (Figure 2). The epicentral uncertainty of the mainshock is estimated at 2 to 3 km. Kirkham and Rogers (1981) have classified the Ryan Creek fault zone, the Granite Creek fault zone, and the other Ute Creek graben faults as potentially active based principally on the studies by Cater (1970). Cater (1970) suggests that the comparable degree of stratigraphic and topographic displacement across the graben-bounding faults indicates that the graben has been active during late Pliocene and Pleistocene time; otherwise the graben flanks would be more deeply eroded than the subsided block.

The focal depth of the Gateway mainshock was determined to be 8 km with a computed standard error of +/- 1.8 km (Figure 3). The nearest seismograph station to the epicenter was at a distance of 40 km, so the depth is not well constrained, although a sensitivity test of the root mean square error with depth suggests that the uncertainty is approximately +/- 4 km. The 8-km depth is quite consistent with the upper-crustal nature of the vast majority of intermountain U.S. earthquakes (Smith, 1978; Wong and Chapman, 1986). Based solely on its epicentral location, the Gateway earthquake appears to have occurred on the south-dipping Ryan Creek fault zone (Figure 2). However, the Ryan Creek fault zone and the other normal faults probably merge at depth with the major reverse faults that control the uplift flank (Figure 3). The 8-km focal depth, even with a +/- 4 km uncertainty, would suggest that the Gateway earthquake could also have been the result of seismic slip on a reactivated portion of the deep-seated reverse faults that are now undergoing northeast-side-down normal displacement. Seismicity possibly associated with extensional reactivation of Laramide basement reverse faults responsible for development of the Waterpocket fold has also been observed near Capitol Reef National Park, Utah (Humphrey and Wong, 1983).

Because of their smaller magnitude, the events preceding and following the mainshock were not as well recorded and thus not as well located. To evaluate any spatial association that might exist between the Gateway earthquakes, a relative location technique was applied to the set of events. A "master event" location of the three microearthquakes preceding the mainshock and the three possible aftershocks was performed, using the mainshock as the master event (see Humphrey and Wong, 1983 for discussion of technique). The results suggest that the source of these events is an approximate northwest-trending fault zone that dips steeply to the northeast (Figure 5). However, a much larger number of events will be required to confirm the geometry of this structure. The orientation and depth of the faulting would be consistent with the deep-seated faults.

A focal mechanism determined for the Gateway mainshock (Figure 6), based on recorded P-wave first motions, exhibits normal faulting very similar to the mechanism for the 1983 Cimarron, Colorado earthquake (Wong and Humphrey, 1986; Wong, 1987). The nodal planes have estimated uncertainties of $\pm$ 10° to 15° in their strikes and $\pm$ 5° to 10° in their dips. Although southern coverage of the focal sphere is sparse, the well-constrained N86°W plane limits the strike of the N67°W plane. The mechanism can support either the surface normal faults or the deep-seated northeast-dipping fault zone as the source of the mainshock. The N67°W nodal plane would be consistent with the average orientation of the Ryan Creek fault zone, north of the epicenter. The uncertainty in the strike of the N86°W plane permits assignment of this plane to the N70°W trending Granite Creek fault, south of the epicenter (Figure 2). The N86°W plane, which dips 48° to the north, would also be consistent with the deep-seated basement fault zone, given the variety of possible fault orientations within this zone. The deep-seated faults may have provided a zone of weakness that is now undergoing reactivation in response to north-northeast trending extensional stress (T-axis), as suggested by the focal mechanism (Figure 6).

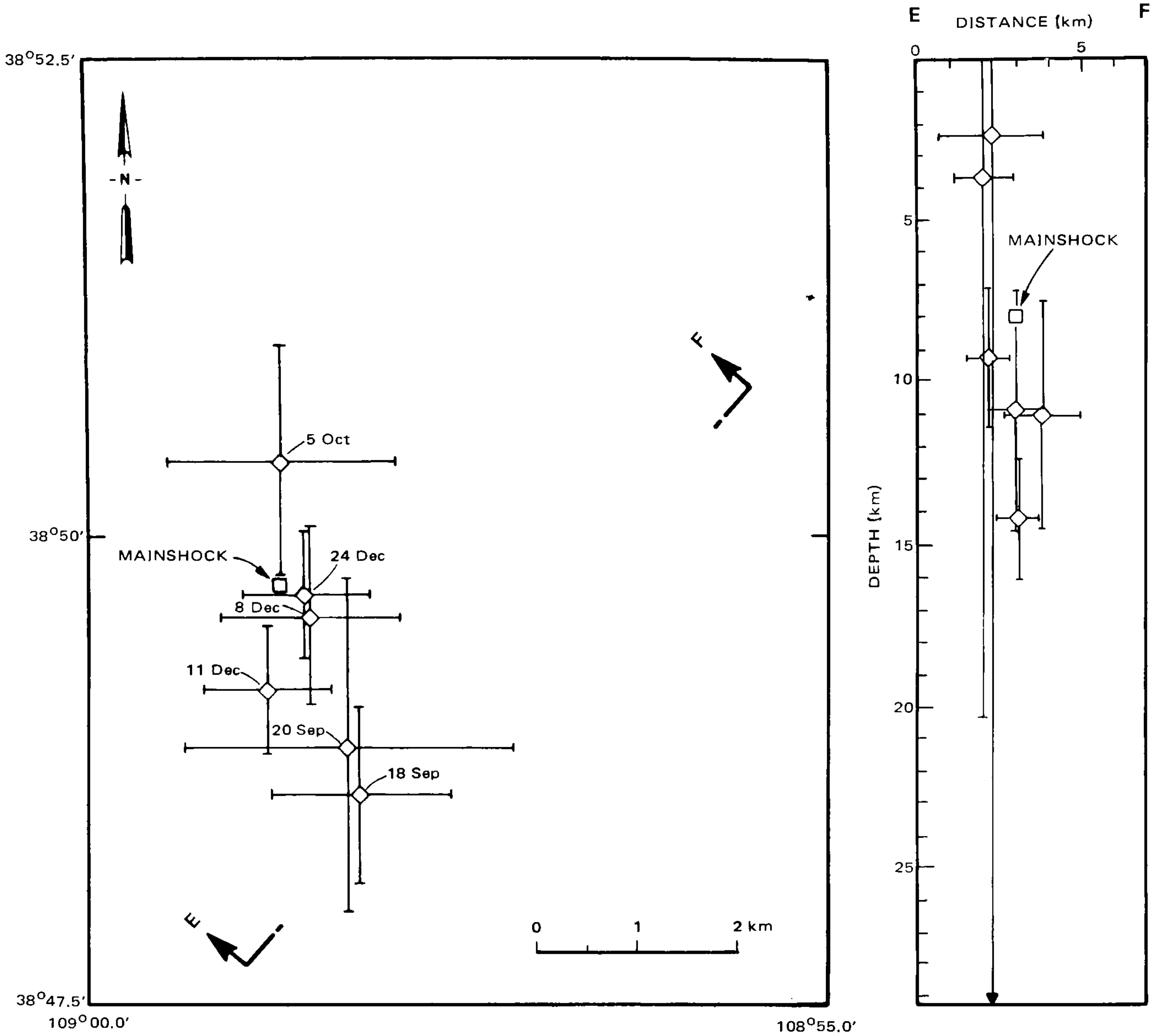


Figure 5. Epicentral plot and cross-section of Gateway earthquakes located by the master event technique. Error bars represent computed relative standard errors.

The extensional nature of the Gateway earthquake is anomalous because the traditional interpretation of the Pliocene and Pleistocene tectonics of the Uncompahgre uplift implies reverse faulting along the southwest flank (see below) and a compressive stress regime. It was previously thought that the Colorado Plateau interior was being subjected to east-west tectonic compressive stress, and that this stress province extended east of the Uncompahgre uplift (Zoback and Zoback, 1980; Wong and Simon, 1981). However recent focal mechanism data now suggests that most of the Colorado Plateau as well as much of the Southern Rocky Mountains (which takes in western and central Colorado) are within stress regimes that can be characterized by NNE to NE- directed tectonic extension (Wong, 1987; Wong et al, 1987).

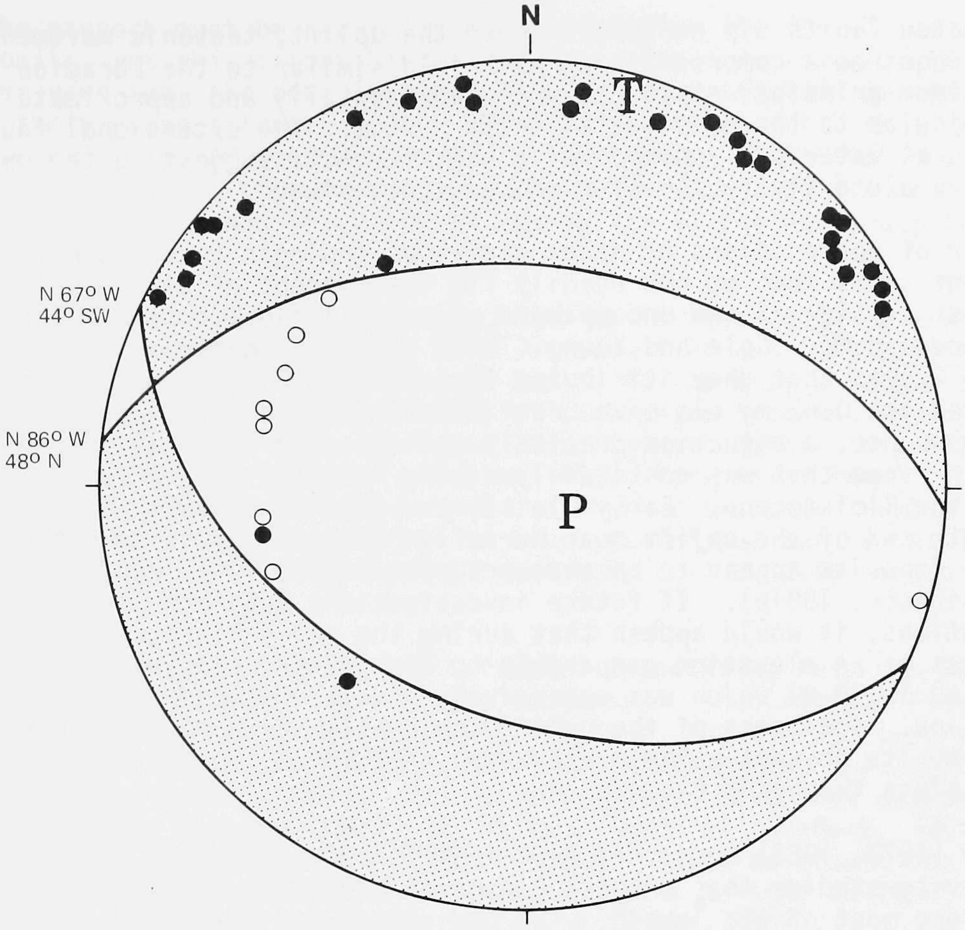


Figure 6. Fault plane solution (lower hemispheric projection) of the December 6, 1985 Gateway earthquake. Solid and open circles represent compressional and dilatational first motions, respectively. P and T represent compression and tension axes, which approximate the axes of the maximum and minimum compressive stresses respectively. Shaded areas are the compressional quadrants.

TECTONIC HISTORY

Three main episodes of deformation along the southwestern flank of the uplift have been identified. The major episode of faulting took place during the Ancestral Rocky Mountains orogeny in Pennsylvanian and Permian time, when 2 to 4 km of northeast-side-up reverse displacement took place (Stone, 1977). During the Laramide orogeny in latest Cretaceous to Eocene time, the Uncompahgre crustal block was homoclinally tilted to the northeast (Cater, 1966) and (Figure 4).

Late Cenozoic uplift of the Uncompahgre block relative to the Paradox Basin has been inferred to be approximately 400 to 600 m, based on the elevation of the floor of Unaweep Canyon above late Pliocene gravel deposits near Gateway (Cater, 1966) (Figures 1 and 4). Most recent discussions of the Pliocene and Pleistocene tectonics of the uplift either imply or explicitly state that the uplift was tilted to the northeast, with the hingeline located along its northeastern flank (Hunt, 1969; Lohman, 1981; Sinnock, 1981b). Because the deep-seated faults dip northeast under the uplift, tectonic movement of this nature requires a compressive stress field similar to the Laramide field, with the maximum principal stress oriented horizontally and approximately perpendicular to the deep-seated fault system. The extensional faulting observed at Gateway is anomalous in this respect, suggesting the uplift is now subsiding along its southwestern margin, not rising.

A number of observations of other anomalous geologic features have been made in recent years that do not readily fit the concept of simple uplift and northeast tilting of the Uncompahgre structural block in the Pliocene and Pleistocene time. Cole and Young (1983) described numerous features in Unaweep Canyon that they attributed to extensive Pleistocene glaciations that pre-dated the 0.62 my old Lava Creek B ash. Evidence for younger glaciations is very sparse, a situation precisely the opposite one would expect for a mountain range that was continually rising into the snow accumulation zone during the Pleistocene. Early Pleistocene glacial deposits are also found at the south end of the uplift near Horsefly Peak, whereas late Pleistocene glacial deposits appear to be absent there (Figure 1) (Atwood and Mather, 1932; Sinnock, 1981b). If future investigations substantiate these observations, it would appear that during the early Pleistocene the uplift crest was at an elevation comparable to the present elevation of Grand Mesa (3,050 to 3,300 m) which was extensively glaciated during the Wisconsin glaciation. The crest of the uplift apparently has subsided 300 or more meters to its present maximum elevation of 2,909 m. in the vicinity of Unaweep Canyon since the Early Pleistocene.

Oesleby (1977, 1983) concluded from seismic refraction and electrical resistivity studies that Unaweep Canyon is underlain by about 300 m of valley fill along most of its length. The buried bedrock thalweg appears to lie in line with pre-Pleistocene gravel deposits northeast of Gateway that are only 60 m above the level of the Dolores River 3 km away, and old gravel deposits near Cactus Park (Figures 1 and 4) (Cater, 1966). The gradient on the buried thalweg is steep, about 8.7 m per km to the southwest, close to the present gradient of the Gunnison River through the Black Canyon. The presence of this buried valley is difficult to reconcile with the traditional interpretation of northeast tilting of the uplift, because northeast tilting would have reduced the gradient on the buried valley, implying an anomalously steep original gradient.

The regional topographic subenvelope (defined by the elevations of large rivers) is an appropriate reference datum to use when comparing differential uplift in regions of persistent high relief, because large rivers will either alluviate their beds or cut deep canyons in relatively short geologic time frames following differential vertical crustal movements. Relict fluvial deposits thus can be used to define the position of the subenvelope at the time they were deposited and to distinguish between areas with different vertical movement histories.

Indurated river gravels and fanglomerates are preserved at many locations in the cores of the salt anticlines elsewhere in the Paradox Basin (Figure 1). The age of these deposits is not well established, but they are considered to be of probable late Pliocene age because in Paradox Valley they are overlain by unconsolidated lacustrine beds that contain the 0.7/my old Bishop Tuff (Cater, 1970). In a number of instances the Pliocene deposits fill paleovalleys that are cut into the residual caprock and are slightly deeper than the modern stream valleys (Cater, 1970). Clearly, salt dissolution beneath the caprock must be partially responsible for the low elevation of these deposits, yet this cannot be the entire explanation, because Cater (1970) concluded that the deposits accumulated "after the valleys had reached virtually their present form." Since the scarps bordering the salt anticline valleys typically are 300 to 600 m high, it appears unlikely that post-gravel fluvial downcutting and concurrent caprock subsidence has been much more than 100 m; otherwise gross modifications of the valley morphology would be apparent.

The highest terraces along the Colorado River in Professor Valley are 25 to 32 m above river level and are thought to be between 0.25 and 0.61 my old (Colman and Hawkins, 1985). These terraces were mapped as the middle member of the Harpole Mesa Formation by Richmond (1962). Downstream from Professor Valley at Negro Bill Canyon near Moab, Richmond (1962) mapped terrace deposits of the older member of the Harpole Mesa Formation 100 m above river level. These deposits have not been studied in detail. Elsewhere the older member of the Harpole Mesa Formation has been shown to have accumulated during the later part of the Matuyama reversed polarity chronozone 0.73 to 2.48 my ago (Biggar and others 1981).

Northeast of the Uncompahgre block the fluvial downcutting rate has been much more rapid in the Quaternary than to the southwest. The Colorado River has downcut approximately 170 m below the highest Bull Lake terrace (approximately 150,000 years old; Biggar and others, 1981) southeast of Grand Junction, Colorado (Cole and Sexton, 1981), and the Uncompahgre River has downcut about 150 m below similar terraces nearby at Delta (Figure 1) (Sinnock, 1981a). The highest pediments in the vicinity of Grand Mesa project to elevations approximately 400 m above nearby base level, and are thought to be of early Pleistocene or possibly Pliocene age (Cole and Sexton, 1981).

The Uncompahgre River apparently has downcut approximately 330 m in the last 0.62 my, because the Lava Creek B ash overlies a 50-m-thick sequence of fluvial deposits of the ancestral Uncompahgre River at Bostwick Park near the Gunnison uplift. The present river is now at an approximate 1,770 m elevation 12 km to the southwest, whereas the top of the alluvial fill of the park is now at about 2,100 m (Hansen, 1971; Izett and Wilcox, 1982). The 1.27/my/old Mesa Falls ash is interpreted to be present near the base of the fluvial deposits underlying Bostwick Park (Hansen, 1971; Izett and Wilcox, 1982). These deposits suggest a local pause in downcutting from 1.3 to 0.6 my ago, perhaps induced or influenced by tectonic movements on the nearby Gunnison uplift.

If it is assumed that the fluvial downcutting rate of the master streams in a region is closely correlated with the regional uplift rate, then it appears from the previous discussion that the salt anticline region has been uplifted on the order of 100 m in the last 2 my, for a rate of about 50 m per million-years (Table 1). The details of how the uplift rate may have varied during this time are not apparent from the available data. The uplift rate northeast of the Uncompahgre uplift during the entire Quaternary, as inferred from fluvial downcutting, appears to be four to ten times larger than the rate in the salt anticline region. The younger deposits listed in Table 1 suggest the late Quaternary uplift rates may differ by about a factor of 10 between the two regions. The uncertainties in the ages of the deposits will have to be lowered before more detailed comparisons are possible.

Table 1. Fluvial downcutting rates.

Location of Deposit	Height (m)	Age (my)	Rate (m/my)	Source
Gateway	60	Late Pliocene (2)	30	Cater, 1966
Salt anticlines	0-100	Late Pliocene (2)	0-50	Cater, 1970
Professor Valley	25-32	Pleistocene 0.25 to 0.61	41-128	Colman and Hawkins, 1985
Moab	100	Pleistocene to Pliocene 0.73 to 2.48	40-137	Richmond, 1962
Grand Junction	170	Pleistocene early Bull Lake 0.1 to 0.2	850-1700	Cole and Sexton, 1981
Delta	150	Pleistocene early Bull Lake 0.1 to 0.2	750-1500	Sinnock, 1981a
Grand Mesa	400	Early Pleistocene to Pliocene (1-2)	200-400	Cole and Sexton, 1981
Bostwick Park	330	Pleistocene 0.62	530	Hansen, 1971; Izett and Wilcox, 1982

The evidence cited obviously lacks the precision to define the detailed structure in space and time of the uplift history, but appears sufficient to draw a distinct contrast in the uplift histories of the regions adjacent to the Uncompahgre uplift on the northeast and southwest. The Uncompahgre uplift therefore seems to occupy the transition zone between the two uplift regimes, with the result that Quaternary uplift has been greatest along the northeastern flank, causing rigid block rotation between hinge-lines located along the northeast and southwest margins of the uplift such that the southwestern flank is now subsiding relative to the Piceance Basin.

Differences in average topographic relief between the southern Piceance basin and the northern Paradox basin support this conclusion. Mesa surfaces near the Colorado River in the northern Paradox basin generally are 600 to 800 m higher than the river, whereas the basalt capped surfaces of Battlement Mesa and Grand Mesa are 1,600 to 1,700 m above the Colorado River. The Tertiary deposits underlying Grand and Battlement Mesas are relatively weak, as evidenced by ubiquitous large landslides around the mesa flanks, compared to the cliff forming Mesozoic sandstones of the Paradox basin. High relief on weak deposits suggests geologically recent uplift of those deposits compared to a region of stronger rocks with much lower relief.

A comprehensive re-evaluation of the geomorphic history of Unaweep Canyon is necessary to substantiate the conclusions arrived at in this paper. In particular it will be essential to accurately determine the depth to bedrock beneath the canyon floor and the composition of the alluvial fill. The old gravels at Gateway are very similar to the gravels of the Dolores River except for the presence of a few basalt pebbles (Cater, 1966). However, basalt pebbles are abundant in the higher terraces in the headwaters of the Dolores River at Glade Mountain (Shawe and others, 1968) suggesting an alternative source for the basalt pebbles at Gateway. We propose as a working hypothesis that Unaweep Canyon may have been cut by the ancestral Dolores River in the Miocene prior to diversion by relative uplift along the northeast flank of the uplift.

CONCLUSIONS

On December 6, 1985, a small earthquake of M_L 2.9 preceded by three microearthquakes and followed by at least three possible aftershocks occurred approximately 16 km north of Gateway, Colorado. Data from three seismographic networks operating in the region provide the first opportunity to evaluate the location and source mechanism of the earthquakes in the vicinity of the Uncompahgre uplift. The analysis revealed that the mainshock occurred within the Ute Creek graben at a depth of approximately 8 km.

The earthquakes may have been due to seismic slip on a reactivated portion of the deep-seated northeast-dipping fault zone beneath the uplift flank or slip on one of the bounding faults of the Ute Creek graben. A focal mechanism displayed normal faulting on either an east-west-trending, north-dipping plane or a west-northwest-trending, southwest-dipping plane, consistent with the above possibilities, respectively. The T-axis exhibited by the Gateway focal mechanism suggests that the region of the Uncompahgre uplift is at present within an extensional regime (north-northeast directed) rather than a compressive stress field in which the Uncompahgre uplift principally developed.

The uplift is now undergoing rigid block rotation between two hinge-lines that lie along its northeastern and southwestern margins. The topographically higher southwestern flank has subsided relative to the northeastern flank, giving rise to slight tectonic adjustments and extensional faulting along the southwestern block boundary.

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SEISMIC DESIGN CONSIDERATIONS IN THE CENTRAL FRONT RANGE IN COLORADO

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INTRODUCTION

Ground shaking from potential earthquake occurrence is a primary consideration in the design of critical facilities such as dams or nuclear reactors. In this report, a methodology for ground acceleration estimation is discussed for critical facility design at sites in central Colorado. The scope and nature of the seismic hazard studies leading to an application of these methodologies is not discussed herein. Studies commensurate with the hazard present, with the risk posed, and with reasonable economic expenditure are necessary. Accelerations and return periods inferred from the potential occurrence of earthquakes can then be estimated.

The following section outlines the rational for the philosophical approach this paper adapts. The first question addressed is definition of the results expected: What type of earthquakes and corresponding acceleration estimates are we looking for? Secondly, how do we arrive at these estimates? The methods available include the deterministic approach and the probabilistic approach. The method recommended in this paper falls between these extremes; it incorporates the input of relevant quantitative facts, professional judgements, and geological inferences into a computationally intensive probabilistic model. Subsequent review and evaluation are necessary to insure that the model chosen is stable and the results are consistent with contemporary geologic knowledge.

The following section gives details on the geologic and seismologic data which are required. Seismic sources and the attenuation relationships are discussed and details of any acceleration-attenuation functions that can be used are also presented. Some additional factors are also discussed.

ACKNOWLEDGMENTS

This paper is the result of several seismic hazard studies undertaken in central Colorado for a number of clients. Their permission to publish this paper is gratefully acknowledged. However, the ideas and concepts given herein are the sole responsibility of the authors.

SEISMIC DESIGN PHILOSOPHY

Much of the following is taken from Seed (1982) and describes the philosophy used by many engineers in California for design earthquake selection. Seed states that design earthquake selection should include the determination of the "Maximum Credible Earthquake, The Seismic Safety Evaluation Earthquake, and the Seismic Engineering Design Earthquake". A portion of his discussion is summarized below. The accelerations for design purposes even in stable areas can be selected on the same philosophical grounds as given by Seed (1982).

Site Safety Evaluation Earthquake (SSEE)

This subsection will explore the relationship between the Maximum Credible Earthquake (MCE) and the Site Safety Evaluation Earthquake (SSEE). Several types of seismic events are used to determine the design acceleration for critical structures. The MCE is defined by Seed (1982) as "the largest rationally conceivable event that could occur in the tectonic environment in which the project is located. Such an event may have a recurrence interval of several hundred years in some regions but many tens of thousands of years in others. It is clearly important to know the order of magnitude of the recurrence interval for the Maximum Credible Earthquake or Earthquakes since this can have an impact on societal concerns, risk analysis, and value judgements concerning its significance."

"The determination of a Maximum Credible Earthquake for a project involves considerable judgement but it only involves experts in the disciplines of seismic geology and seismology."

"The Seismic Safety Evaluation Earthquake. The Seismic Safety Evaluation Earthquake, and its associated motions, is the largest event and the strongest motions which a structure should be designed to withstand. In some cases, the Seismic Safety Evaluation Earthquake may be equal to the Maximum Credible Earthquake. This would probably be the case for example for projects located very close to major faults such as the San Andreas in California, for which the Maximum Credible Earthquake is an event with magnitude about 8 1/4 to 8 1/2 and a recurrence interval of several hundred years. In other cases, the Seismic Safety Evaluation earthquake might well be less than the Maximum Credible Earthquake. This is likely to be so, for example, in cases where the frequency of occurrence of the Maximum Credible Earthquake is extremely long (say tens or hundreds of thousands of years)."

"This involves considerably more judgement than selection of the Maximum Credible Earthquake, and the judgement should desirably be based on the collective wisdom of experts in a larger group of disciplines including, for example, seismology, seismic geology, engineering, risk analysis, social science, economics, public policy, and government."(Seed, 1982).

The Seismic Engineering Design Earthquake is the specific earthquake or earthquakes used by the engineer for design of the structure and thus relies heavily on engineering considerations for its selection. Selection of the Seismic Engineering Design Earthquake and its time histories are beyond the scope of this report.

The recurrence interval for the MCE at many sites in central Colorado is 100 thousand to 500 thousand years. Because these return times are so long, a very conservative choice of 35,000 years as the recurrence time for the SSEE might be used. This level of risk is the same as that used for nuclear power plants and is more conservative than the level of risk assumed for many engineered structures. Note that the selection of a 35,000 year recurrence interval of the design event implies that the structure will not catastrophically fail even if the unlikely event for which the structure is designed occurs immediately. The cost of the additional caution is not inconsequential and the design of many critical structures in California is based on a 5,000 or 10,000 year return time of the SSEE.

Operating Basis Earthquake (OBE)

One other design-related earthquake to be chosen is the Operating Basis Earthquake (OBE). The occurrence of such an earthquake could produce damage to the facility, but would not cause significant operational curtailment.

The OBE evaluation usually includes judgements from similar experts in those disciplines needed for the SSEE previously discussed. However, the evaluation is dominated by consideration of the engineer. The OBE is conservatively evaluated as the earthquake which has a relatively high probability of occurrence within the facility lifetime.

Selection of the SSEE and OBE considers many factors, but prime consideration, following Seed (1982), is given to : 1) "the consequences of underestimating the seismic risk say in terms of the possibility of its leading to catastrophic performance of a structure or structures in the project or to excessive damage," and 2) "the consequences of overestimating the seismic risks, in terms of the possibility that such an overestimate may lead to cancellation of a project, thus depriving the public of a service whose benefits might be enormous, or causing the public to suffer financially because of excessive costs in providing needed facilities and constructing them to withstand geologic events which might never occur" (Seed, 1982).

It should be noted that these events, the SSEE and OBE, are hypothetical with extremely low probabilities of occurrence in the central Front Range. In addition, keep in mind that the primary purpose of the evaluation is to select design accelerations, not design earthquakes. The parameters to be estimated are an Operating Basis Acceleration (OBA) and a Site Safety Acceleration (SSA).

METHODS FOR ACCELERATION DETERMINATION

Two techniques are routinely employed to determine design parameters from known seismicity. These are deterministic and probabilistic analyses. The following discussion considers both of these techniques and some mixing of the two methods. Philosophically, it should be noted that a "pure" deterministic method would involve exact prediction of the expected events and a "pure" probabilistic method would disregard most of the available data.

Deterministic Approach

The deterministic approach involves the selection of the Maximum Credible Earthquake (MCE) from geologic surface mapping and information about the specific tectonic province under consideration. The credibility of the event is derived from an estimation of the return interval. The return interval can be estimated from statistics that might include geologically determined slip rates, an instrumentally measured recurrence curve, or a professional judgement about what percentage of a mapped fault might move in a given time interval. "The Controlling Maximum Credible Earthquake (CMCE) is the most critical of all the MCEs capable of affecting a dam. It is determined after successively assuming that each MCE would occur along its associated fault or within its associated tectonic province at a location closest to the dam with capability of originating the event. The MCE that would result in the most severe consequences for the dam considered represents the CMCE" (USCOLD, 1985).

"It should be noted that, in the case of tectonic provinces with low rates of activity and poorly identified tectonic features, the concept of a CMCE, while being undoubtedly conservative, may result in making the credible occurrence of the MCE within such province tend towards the incredible in the immediate vicinity of the dam. For such conditions, probabilistic seismic hazard evaluations are considered to be more appropriate" (USCOLD, 1985).

The deterministic technique is used when known geologic structures with seismicity (or potential seismicity) are observed at the surface. Recurrence statistics from recorded seismicity or reasonable fault slip-rate estimations are used to determine the recurrence and magnitude of the MCE. Deterministic approaches have rarely been used where seismicity patterns exist at depth with no evidence of surface displacement. Its application to subsurface microseismic zones, the Derby events, and other mapped features is questionable.

The deterministic method often requires specific detailed knowledge of the known geology of the area tempered slightly by the observed seismicity. The relationship between historically, instrumentally, and geologically observed seismic hazards can be summarized as follows.

Seismic Hazard Evaluation

There are usually three main sources of data for a seismic hazard study: 1) geological, 2) historical seismicity, and 3) instrumental seismicity studies. Often, the instrumental and historical record of earthquakes in a given area is short, on the order of tens or hundreds of years.

Geologic investigations yield data extending throughout geologic time, but the incompleteness of the record and the large magnitude of events (greater than 6) usually required for detection by geologic methods often leaves a great deal of latitude for interpretation. Breakage of geologic layers indicates simply that the breakage occurred after deposition. Whether the break occurred immediately after deposition or very recently is usually not determinable.

Geologic investigations, especially of fault-disturbed deposits less than 100,000 years old, are of great importance. The results can confirm that the recognized earth movements are likely to reoccur in the lifetime of a critical facility. On the other hand, the results can also confirm the antiquity and therefore limit the relevance of the fault movement to the critical facility.

The seismological record is often broken into two parts -- historical seismicity taken from historical felt reports and instrumental seismicity taken from actual recordings of events. This historical record typically spans more time than instrumental studies. However, the historical record is limited to relatively large magnitude events (greater than 3.0), is subject to influence by early population distributions and their interest in record preservation, and is quite imprecise with respect to location. Despite these limitations, the historical record is quite valuable in determining seismic hazard in an area.

The instrumental record is short, usually months to years in length and quite precise and quantitative with respect to location and magnitude. The instrumental investigation often produces negative evidence for site safety; it neither condemns or confirms safety. The most cogent objection to the instrumental record is it brevity. However, the comparison of six months of microearthquake data to a million years of geologic history is not a foolish comparison. The basis of the instrumental studies is the recurrence curve. Small earthquakes occur more often than large ones. Sets of earthquake data exhibit a remarkably straight-line relationship between the log of the number of events and the magnitude of the events. The slope of this straight line is also remarkably constant at a value near -0.89 (Richter, 1958, p. 359). Thus, for each event of a given magnitude, about 10 events of one magnitude smaller will occur.

It is not unusual for a sensitive seismic network to push the detection threshold down three or four magnitudes below the threshold of the historical record and six to seven magnitudes below the threshold of the geologic record. Thus, if the events occur uniformly in time, the instrumental record is equivalent to inspection of a historical record 1,000 to 10,000 times as long as the instrumental recording period and is equivalent to a geologic study investigating one to ten million times as long as period as the instrumental study has investigated.

The uniformitarianism concept mentioned above is important. The potential for statistical fluctuations in seismicity must certainly be incorporated into each method of investigation: instrumental, historical, and geologic.

The results expected from an instrumental-seismic study of an area include identification of active faults, seismicity estimates, return periods for each size of event on the active structure, and uncertainty estimates for each fact reported.

Probabilistic Approach

A probabilistic approach to seismicity-related design considerations is discussed in the following sections. The following discussion is taken from USCOLD (1985). "A probabilistic seismic hazard evaluation (also called a seismic exposure evaluation) involves obtaining, through mathematical and statistical processes, the relationship between a ground motion parameter and its probability of exceedance at the dam site during a specified interval of time (such as the operating life of the reservoir). The value of the ground motion parameter to be used for the seismic safety evaluation of the dam is then selected after defining an acceptable level of probability for the structure and site considered. Recognized active, or potentially active, faults and seismic provinces are referred to as seismic sources. The spatial relationship between the dam site and the seismic source(s) of concern to the site, and the rates of activity assigned to each seismic source, form the basic elements of the seismic hazard model of the site considered."

The probability analysis (Cornell, 1968; Cornell and Van Marcke, 1969) establishes a relationship between each site and all the individual seismic sources. The recurrence statistics of each source are incorporated to obtain the contribution of each source to each site. The result is an acceleration versus return time curve for each site. Judgemental estimates must be made for the following input parameters:

1. The parameters of each source: location, depth, b-slope, and recurrence statistics.

2. The form and parameters of the attenuation of acceleration with distance from source to site.

In the probabilistic analysis all sources make a contribution to the evaluation. That is, there are all degrees of "activity". A fault with a very low but real degree of seismic activity used in the probability analysis might well have been defined as "inactive" or "non-capable" on a geologic, semantic, or regulatory basis by others. The requirement for judging a source capable or non-capable is removed and the relative contribution of all sources is incorporated. It should be recognized that for low-activity sources, a substantial extrapolation of the known data is sometimes necessary.

The method combines the contribution of all the sources and produces an acceleration versus return time for the site. Thus, a nearby, low-activity source is put into proper perspective with a distant, active, and possibly dangerous source. Note that all identified sources contribute to the final design value.

Selection of Method

Without a history of significant seismic events and with the geologic provenance of potentially active faults in doubt in many low seismicity areas such as central Colorado, the deterministic method is difficult to apply. Do a multitude of "inactive" faults very near the site constitute a hazard (disregarding the definition of inactive) or do you select an MCE based on the one clearly identified macroseismic source such as the Derby area? Certainly the exclusive use of the deterministic approach is not appropriate.

Regardless of any positive arguments for a deterministic approach in low seismicity areas, the final results are often less conservative (lower design acceleration) than those from other techniques. Thus, deterministic methods have minor input to the design acceleration selection at many sites.

The probabilistic method relies on quantitative data. However, in a seismically inactive area, critical data are often incomplete. Statistical inferences and judgemental decisions are as critical to the probabilistic approach as to any other. The probabilistic approach has two principal strengths. First, the quality of the number can be evaluated by careful selection of conservative inputs and by variational techniques once the model is selected. Secondly, all sources are considered, and in fact, additional ones can be added as new data become available.

The probabilistic study, as used below, incorporates a great deal of deterministic and judgemental geologic data. Often the evidence for seismicity estimates is a geological study concluding that there has been no movement in a specified period before the present. To incorporate such evidence, the conservative assumption was made of ground breakage (geologically detectable) actually occurring just before the specified interval of quiescence. Generally this use of geological data gives higher estimates of seismicity rate than the observed rate by one or two orders of magnitude.

PROBABILISTIC ANALYSIS

The Cornell (1968) method requires two major sets of parameters - the source parameters and the acceleration-attenuation parameters. The following two sections discuss the selection of these parameters.

Seismic Sources

Seismic sources are defined by recorded seismicity, by mention in the literature as potentially active faults, by virtue of being selected as controlling structures for other critical facilities, or by proximity to a site.

Geographical contiguity of a microseismic source and a surface fault trace can be used to assign events to a fault, even where substantial geologic evidence may indicate the fault is not active. Faults not identified with a specific microseismic source are often assigned a low seismicity rate. This low rate also can account for the "background" level of seismicity not otherwise assigned.

Seismic Source Parameters

Source parameters needed for the Cornell (1968) method are:

1. Dimensions and location of feature

2. b-slope

3. Seismicity rate (incorporated as an annual probability of an earthquake greater than 4.0 per unit dimension)

4. A maximum upper-bound earthquake, an estimate of the largest magnitude (M_L) earthquake the source can support. The extremely long recurrence intervals for some of these events reduce their credibility to a negligible level. This earthquake will be termed the Cornell UBE throughout the rest of this report.

A discussion of the selection of these parameters for each source follows:

For parameter 1, the dimensions are taken from published maps or interpreted micro- and macroseismic zones.

For parameter 2, where sufficient data have been recorded, a b-slope can be determined. Where no information is available, the regional b-slope is often reduced slightly, partially to be more conservative but also due to the ambiguities perceived by some in relating regional b-slopes to specific structures.

For parameter 3 a seismicity rate is estimated for each structure. The probabilities are input in the form of annual probability of an event greater than magnitude 4.0 per unit length. Where no clear evidence exists for activity on a structure, the background seismicity rate can estimated.

For parameter 4, it should be noted that the Cornell UBE is generally determined from fault length versus magnitude considerations following Slemmons (1977) in low seismicity areas. Where segmented, the length of the whole fault is used to estimate the Cornell UBE. However, the extremely long return time estimated for such events removes them for consideration as the SSEE (see quote by Seed, above).

Acceleration Attenuation Parameters

The form of the acceleration formula given by several authors (see McGuire, 1976 for an exhaustive set of references) is:

$$A = b_1 e^{b_2 M} R^{-b_3}$$

Where A = the acceleration in cm/sec^2

M = earthquake magnitude

$R = (h^2 + d^2 + k^2)^{1/2}$ or

$R = (h^2 + d^2)^{1/2} + k_2$

h = depth

d = epicentral distance

b_1, b_2, b_3, k, k_2 = constants to be determined from the literature or empirically

Many values have been used for these constants as additional data have been recorded from major earthquakes. It is important to note that until the 1979 Imperial Valley earthquake, the acceleration data for distances of 1 to 15 km were very sparse. Such distances are most important in many studies. An empirical fit to the data in the nearfield region of present concern (1 to 40 km) has been made and the following three sets of constants are determined for the formulas given above.

Formula 1	Formula 2	Formula 3
$b_1 = 95.5$	$b_1 = 18.5$	$b_1 = 15.9$
$b_2 = 0.573$	$b_2 = 1.28$	$b_2 = 0.868$
$b_3 = 1.0$	$b_3 = 1.75$	$b_3 = 1.09$
$k = 7.3$	$k = 0.0$	$k = 0.0$
$k_2 = 0.0$	$k_2 = 5.5$	$k_2 = 1.0$

The formulas are based on Joyner and Boore (1981) (Formula 1) and Campbell (1981). Formula 2 is the constrained version of Campbell's formulas, and Formula 3, unconstrained. These formulas incorporate the 1979 Imperial Valley earthquake data. Discussion of the relative merits of each is beyond the scope of this report. The data sets given below incorporate observed data compiled by Seed and Idriss (1982) (Data Set 1) and Joyner and Boore (1981) (Data Set 2).

Table 1 summarizes the data and the calculated results. Each of the formulas gives values greater than Joyner and Boore's data (Data Set 2) but less than Seed and Idriss (Data Set 1).

These three formulas were selected after consideration of several hundred different versions (McGuire, 1976). Conservatively, the high values for each calculation are generally given maximum weight in compiling the final results.

Table 1. Acceleration data and calculations.

	Distance (km)			
	5.0	10.0	16.0	25.0
Data Set 1	390	280	190	120
Data Set 2	190	130	70	52
Formula 1	291	208	146	98
Formula 2	346	211	127	70
Formula 3	240	153	101	66

Accelerations in cm/sec^2
Distances in kilometers
Event = 5.75 magnitude   Depth = 5.0 km

Additional Factors

Numerous factors exist which could increase or decrease the estimated design acceleration. Each of these factors is characterized by a lack of theoretical or observational basis which would allow the quantitative application of the given factor to the design estimate. In each case, one must say that while any one factor may increase the site accelerations, the factor may also decrease the value given. Such factors include.

1. Directivity and source radiation effects
2. Specific site effects
3. Variation of the attenuation along the source-site path
4. The possibility of a single, exceptionally high, acceleration peak in the ground motion at one site
5. The statistical uncertainty in the ground motion predictors used
6. The overall geologic setting with respect to interplate and intraplate tectonics
7. The possibility of a seismic source not now recognized being the source of the significant event
8. The possibility of a characteristic earthquake pattern of recurrence

To the extent feasible each of these factors can be evaluated. Usually, the lack of a useful basis for their application and the fact that any one factor may either increase or decrease the hazard, leads to the incorporation of a small safety factor (design acceleration increase) in the estimated made.

CONCLUSIONS--PROBABILISTIC METHOD

The analysis is a set of complex mathematical operations applied to statistical inferences and professional judgements. The uncertainties in this analysis are relatively large. However, the guiding philosophy of the analysis is to confine these uncertainties by selecting parameters which will give very conservative (high) design accelerations. Another type of analysis which simplifies the above considerations is to assume that the recorded seismicity does not indicate the activity of any specific structure.

As a relaxation model of the stress fields in central Colorado would be consistent with a pattern of random locations of events and a lack of correlation with mapped geologic structures, a probabilistic model of the random seismicity can be used to evaluate the hazard. If the possible location of the event is unknown, it is no more likely to occur at the critical structure than on the periphery of the area involved. The annulus model with an assigned probability per unit area produces an accurate measure of the seismic hazard in terms of an acceleration versus return time curve.

Cornell (1968, equations 27 and 34) gives a straightforward technique for calculating this curve. A more sophisticated approach is available (Cornell and Van Marcke, 1969) which allows the incorporation of the vital geologic knowledge about an upper bound.

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SEISMIC EVALUATION OF SPINNEY MOUNTAIN DAM

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ABSTRACT

The Spinney Mountain Dam, in South Park, central Colorado, is a zoned earth embankment with a maximum height of 95 feet (29 m) above foundation. Detailed geologic investigations revealed nearby faults which have probably undergone tectonic movement within the past 13,000 to 30,000 years and hence are considered capable. Studies indicate the largest earthquake expected on the controlling fault would have a Richter Magnitude of about 6.2, implying peak ground accelerations at the site of about 0.6g and a 15-second duration of strong motion. Displacement on a branch of the main capable fault during such an event is estimated at 4 to 6 inches (10 to 15 cm). Slope deformation analyses estimate a movement at the crest of dam of not more than 2 inches (5 cm) horizontally and considerably less vertically, which would not result in a significant decrease in strength of the compacted soils. Reservoir-induced seismicity is not considered to be a hazard.

INTRODUCTION

The Spinney Mountain Project, constructed in 1980-81 for the City of Aurora, Colorado, consists of a dam and reservoir for the City's water supply. It is located on the South Platte River in South Park, about 130 miles (210 km) by highway southwest of Denver and about 3 miles (4 km) upstream of Denver Water Board's Elevenmile Canyon Reservoir (Figure 1). Its purposes are to store waters originating west of the Continental Divide and diverted to the east slope via the Homestake Project, to allow full utilization of water available in the South Park tributary area, and to provide reserve storage for periods of extreme drought and during emergency outages of conveyance facilities of the Homestake Project.

The major features of the Spinney Mountain Project are shown in Figure 2. They include a reservoir with an active storage capacity of 48,000 acre-feet (59 hm^3) and surface of 2,252 acres (1,020 hectares); a 4,100-foot-long (1,250-m) earthfill dam with a 25-foot-wide (7.6-m) crest and maximum height of 95 feet (29 m); service and auxiliary spillways; dam outlet works; Homestake diversion structure and conveyance channel; and waterfowl and recreation facilities.

The dam site is underlain by sedimentary rocks comprising interbedded sandstones, siltstones, claystones, and conglomerates. Geologic characteristics of the dam foundation were delineated by normal methods of geotechnical exploration and analysis. These investigations revealed no

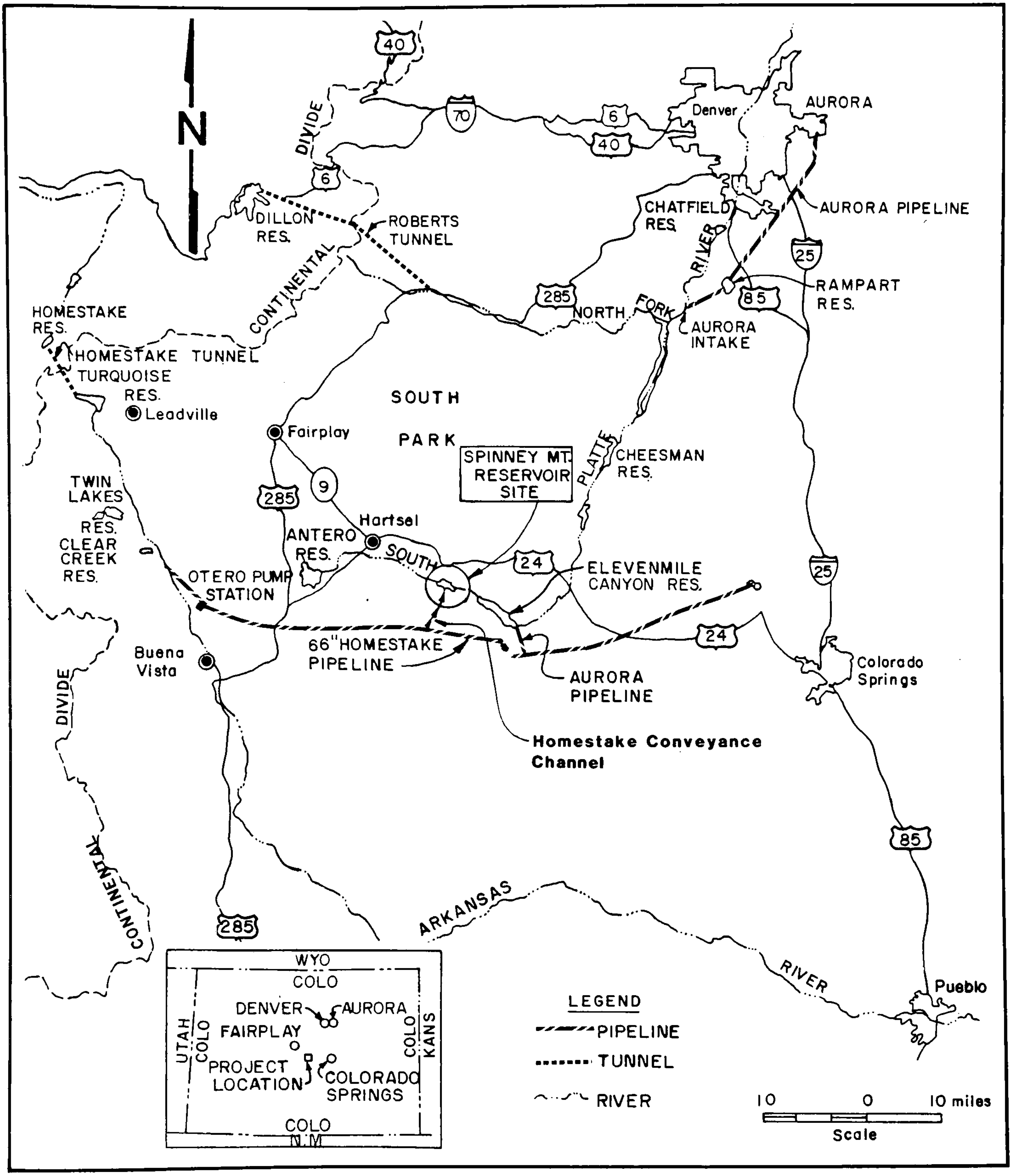


Figure 1. Location map of Spinney Mountain Reservoir site.

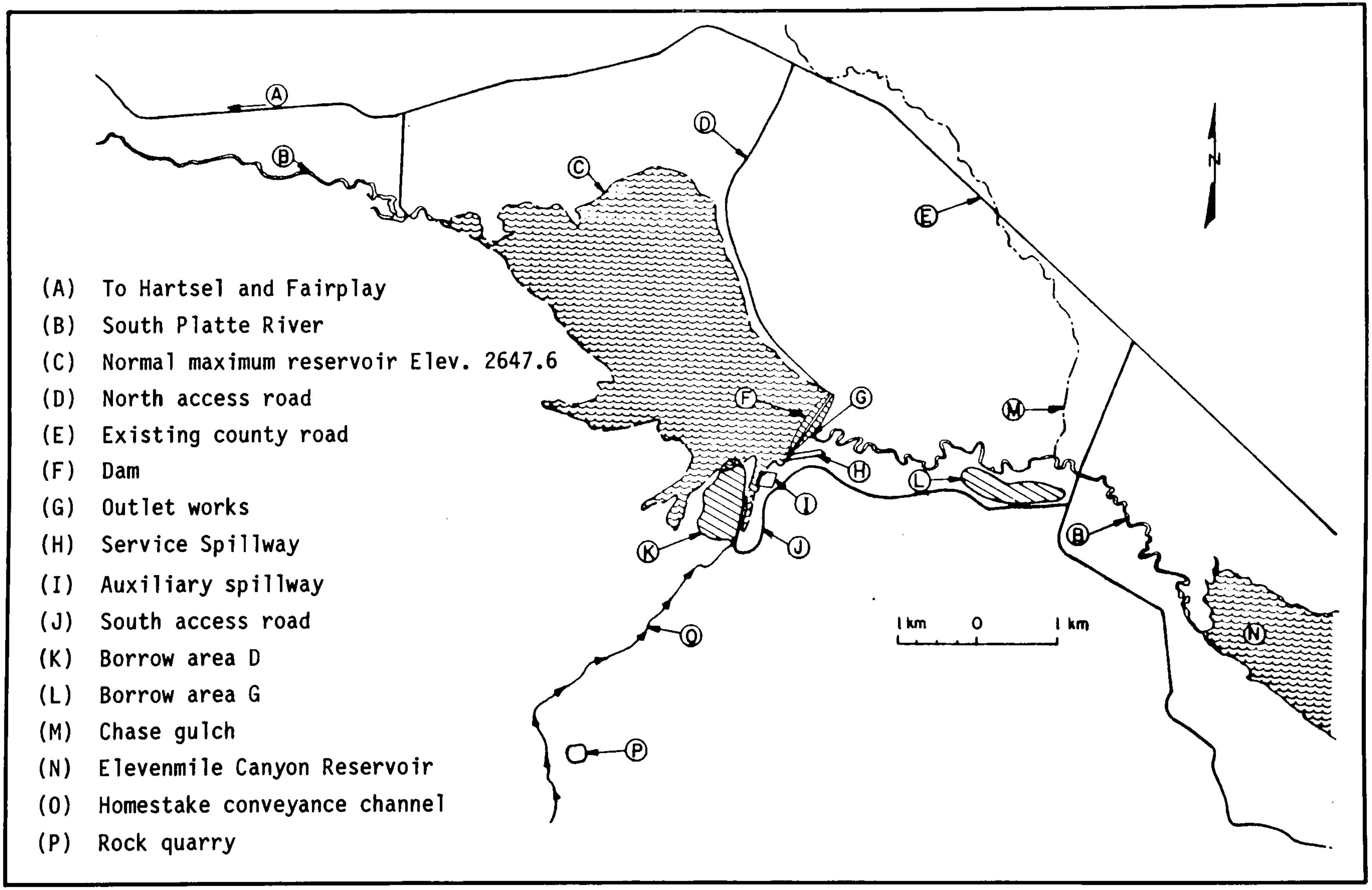


Figure 2. Major features of Spinney Mountain Project.

unusual engineering problems. However, additional geologic and geophysical investigations, unparalleled in Colorado at the time, were performed near the site to determine the potential for capable faults which could affect the design and construction of the dam. This paper presents the findings of those investigations.

ACKNOWLEDGMENTS

This paper is a slightly expanded version of one published in the Proceedings of the International Commission on Large Dams (1982). Permission of the City of Aurora to publish these results is gratefully acknowledged.

The investigation summarized here owed its success to the assistance and cooperation of a great many people and organizations, who are cited in the unpublished technical report (Shaffer, 1980). Copies of the report were sent to a number of state and federal agencies, including the Colorado Geological Survey and State Engineer. Supplies of the original report are now exhausted, but copies of the text, maps, and logs and of aerial and trench photographs can be obtained from the senior author for the cost of reproduction and mailing.

ASSESSMENT OF EARTHQUAKE RISK

General

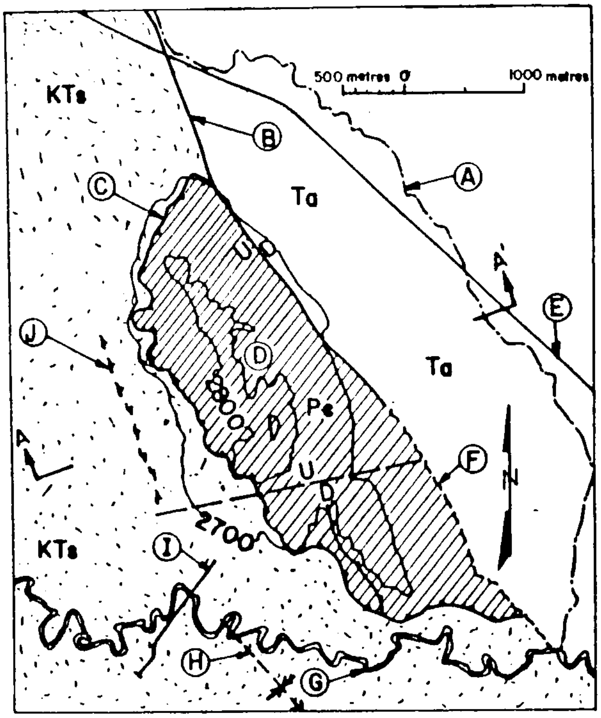
The Spinney Mountain Dam is located in the southeast corner of a 40- by 60-mile (65- by 95-km) topographic and geologic basin known as South Park. Historical earthquake reports over about the past century and reasonably complete regional seismographic data recorded since the mid-1960's, suggest the South Park Basin constitutes a nearly aseismic area within a broader zone of low-level seismicity. A seismograph, capable of detecting tremors as small as about magnitude 1.8 at the dam site, operated at Fairplay for an aggregate period of about one year without detecting seismic activity anywhere in South Park (Dr. Maurice Major, written communication).

Ordinarily, structures in a historically aseismic region would be designed for minimal ground motion. However, a combination of increased regulatory awareness of seismic hazards, local concern, and a desire by the projet owner and engineer to properly assess all factors related to dam safety, led to performance of a reconnaissance-level geologic assessment of seismic risk at Spinney Mountain. The results of this preliminary study were surprising. Geologic evidence, compiled originally by Dr. Keenan Lee of the Colorado School of Mines and further evaluated by the project geologist, indicated a possibility of active faults in the project area. This unforeseen discovery prompted detailed study of the fault systems involved, and ultimately resulted in a more sophisticated seismic analysis and design of the dam.

Geologic Setting

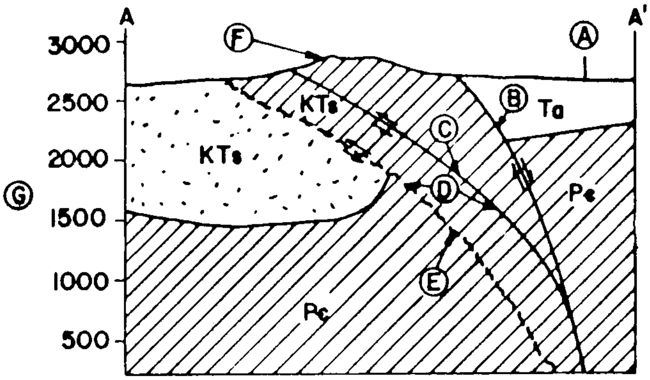
A generalized geologic map and cross section of the dam area are shown in Figure 3. The dam foundation is underlain by interbedded Paleocene (about 55 to 65 million years old) sandstones, conglomerates, siltstones, and claystones of the South Park Formation (formerly considered part of the Denver Formation). These rocks are of terrestrial origin and are moderately to well indurated. Somewhat older (Cretaceous) marine sediments crop out upstream of the dam. These older sediments are primarily well indurated shales that

Generalized Bedrock Geological Map



A) Chase Gulch
B) Chase Gulch Fault
C) Elkhorn Fault
D) Spinney Mountain
E) Existing County Road
F) Eastside Fault
G) South Platte River
H) Axis of Spinney Syncline
I) Dam Axis
J) Westside Fault

Cross Section A-A'



A) Chase Gulch
B) Chase Gulch Fault
C) Plane B
D) Elkhorn Thrust
E) Plane A - Westside Fault
F) Spinney Mountain
G) Elevation in Meters

LEGEND

- Ta — Tertiary Valley Fill
- KTs — Mesozoic (mainly Cretaceous) and Tertiary Sedimentary Rocks
- Pє — Precambrian Crystalline Rocks
- U/D — Non-capable Fault w/direction of movement
- Non-capable Fault, sawteeth on upthrown side
- Capable Normal and Thrust Faults
- Location of Cross Section

Figure 3. Generalized bedrock-geologic map and cross section A-A' of Spinney Mountain Dam area.

underlie the South Park Formation with a slight erosional disconformity. A thick Cretaceous section presumably underlies the South Park Formation in the dam foundation, but was not encountered in exploratory borings as deep as 170 feet along the dam axis.

Sedimentary units in the foundation area generally strike parallel to the dam axis and dip 20 to 50 degrees downstream. This orientation of bedding is part of a larger structure, the Spinney Syncline, which is visible in outcrops and particularly well displayed on aerial photographs of an area extending 2 to 3 miles (3 to 4 km) south of the right abutment. There the South Park Formation has been folded into a symmetrical, closed synclinal basin, with a northwest-southeast axial trend. The dam axis straddles the synclinal axis near the northwest terminus of the fold. The detailed character of this termination was not known until the core trench was excavated, because younger, non-indurated sediments mask bedrock north of the right abutment.

Significant faulting is not present anywhere in the South Park Formation south of the dam site. This fact is readily discernible in the absence of major shearing or offset of conspicuous sandstone and conglomerate beds that delineate the Spinney Syncline. However, the synclinal axis parallels the trend of two major fault systems each 20 to 25 miles (30 to 40 km) long and passing within 1 mile (2 km) of the site. These faults were known prior to dam exploration from regional geologic and geophysical evidence.

The better known of the two faults in the project area is the Elkhorn Thrust, which forms the eastern geologic boundary of the South Park Basin. Precambrian basement rocks were pushed up and westward along this break, overriding Tertiary and Cretaceous sedimentary rocks by at least 4,000 feet and probably considerably more in some locations (Bryant and Naeser, 1980). Spinney Mountain, directly north of the dam left abutment, is an erosional remnant of this overthrust block.

Subsequent to Elkhorn deformation, down-dropping of rocks to the east occurred along the Chase Gulch Fault, which locally cuts the Elkhorn Fault, but is generally parallel and east of it. The Chase Gulch Fault has little visible expression and is known primarily from geophysical data and deep exploratory drilling for uranium. Although inferred surface traces of the two fault systems appear parallel and distinct, geologic evidence suggests they may merge into the same major crustal discontinuity at depth. The reversal in relative displacement indicates that a transition from compressive to extensional crustal stresses occurred between Elkhorn and Chase Gulch Fault movements. This change in stress regime coupled with the geometry of the basin resulted in the differing surface traces of the two faults. Abundant regional evidence indicates major displacement of the Chase Gulch Fault occurred between about 30 and 40 million years ago, and that activity of the Elkhorn Fault ceased 45 to 50 million years ago.

Fault Investigations

Non-seismologic investigation of active faults involves a search for geomorphic evidence of geologically young displacement. One part of a general standard promulgated by the U.S. Nuclear Regulatory Commission (1975) and presented in several Corps of Engineers publications (e.g., Slemmons, 1977) classifies faults as "capable", that is, potentially earthquake-generating, if they have undergone tectonic movement in the past 35,000 years. This standard was acceptable to the regulatory agencies involved in the Spinney Mountain Project and was adopted in the seismic hazard analysis.

Attention to seismic hazards in Colorado was focused by open-file reports of the U.S. Geological Survey (Witkind, 1976) and Colorado Geological Survey (Kirkham and Rogers, 1978). Several faults less prominent or more distant from the dam site than the Elkhorn or Chase Gulch were characterized in these reports as "potentially active", because they were known to displace Miocene or younger geologic strata (less than about 25 million years old).

Initial field investigation consisting of a field reconnaissance and study of aerial photographs indicated the major post-Miocene faults were not capable; however, it did confirm the existence of two very subtle, linear topographic scarps situated between 1 to 2 miles (1.5 to 3 km) from the dam site, that were cited as possible faults in previous unpublished work by Dr. Lee unrelated to the dam. The scarps were located on the east and west sides of Spinney Mountain, generally parallel to the ridge crest and to the traces of the Elkhorn and Chase Gulch Faults. Average topographic relief was about 6 feet (1.8 m), but erosion had so smoothed the scarps that they were virtually indiscernible on the ground. However, both features showed clearly on aerial photographs taken at a low sun-angle to accentuate shadows. Shallow trenching revealed that both features were in fact slip planes along which bedrock was thrusted over unconsolidated alluvial deposits of relatively recent geologic origin. This wholly unexpected discovery prompted more detailed geologic investigation designed to document the age and character of displacement.

The absence of known active faults in South Park and the aseismic nature of the area suggested strongly that the slip planes had a source other than earthquake-producing crustal stress. Thus, initial efforts concentrated on finding the cause of these features. With both scarps, reverse movement was observed on planes that dipped toward Spinney Mountain. This mode of displacement seemed most consistent with landsliding or gravitational spreading of the adjacent slopes of Spinney Mountain. However, detailed geologic mapping of the scarps and upper slopes of Spinney Mountain revealed evidence contradictory with mass gravitational movement. This included continuity of bedrock features, uniformity of scarp height, absence of tension cracking upslope, and lack of a well defined slide scarp or slide mass. None of these data gave direct evidence of a tectonic origin of the scarps, but neither did they support the mass-movement hypotheses. It then was decided to drill in an effort to delineate the slope plane geometry. If the planes curved upward beneath the flanks of Spinney Mountain landsliding was probable, but a downward curvature would suggest faulting.

A fortuitous choice for the drill was a Becker air rotary-percussion drill. With this drill, cutting samples are recovered by a cyclone attached to the return air line. When the drill bit encountered the west-side fault plane, this unit disgorged large chunks of relatively intact, highly sheared clay gouge that contrasted vividly with the alluvial gravels and chips of shale bedrock. Drilling indicated beyond any doubt that the west-side topographic scarp was continuous with a major fault in the bedrock. The fault plane steepened with depth, but remained a reverse fault of moderate (about 45° $\pm$) dip.

Drilling and a refraction seismic survey of the east-side scarp revealed a steeper fault plane with normal displacement beneath the rolled-over surficial zone. Both faults, now recognized as such, cut geomorphic features that obviously were not of great geologic age. The actual age, frequency, and magnitude of displacements and the lateral extent of the faults remained unknown. Of particular concern was that the trend of the west-side fault carried it directly toward the center of the dam axis. This caused concern over the possible need for redesign of the project.

For formulation of seismic design criteria, research was required to 1) determine whether the faults were young enough to be considered capable and 2) if capable, determine the characteristics of fault displacement and the lateral extent of surface rupture. Three main lines of inquiry were pursued. First, the fault planes were excavated further and meticulously examined for clues as to their mode of displacement. In all, 1,300 lineal feet (400 m) of trench were logged, and almost 300 feet (86 m) of trench walls 10 to 15 feet (3 to 5 m) in height were mapped at a scale of 1:12. In a few cases, carbonate cement in the fault zone or in strata cut by the fault was retrieved for radiometric dating.

Radiometric dating of carbonates is subject to a number of uncertainties. Accordingly, those data were supplemented by a second major research effort, the geologic age-dating of geomorphic surfaces and alluvial deposits cut by the fault. This was accomplished by field mapping and stratigraphic correlations of river terraces and other unconsolidated units with upland pediment surfaces cut by the faults. Mapping was conducted on aerial photographs at a scale of 1:12,000. Age relationships were established by comparison with known periods of alpine glaciation. These relationships were corroborated by pedologic (soil genesis) analyses of the various geomorphic surfaces and deposits performed under direction of Dr. Pete Birkeland of the University of Colorado.

These first two areas of research established that both faults were technically "capable", the last movement having displaced glacial outwash of Pinedale age. Pinedale displacement (about 13,000 to 35,000 years ago) was on the order of 6 feet (2.5 m), but evidence as to the number and magnitude of individual displacements during that interval was ambiguous. If, as appears likely, the original bedrock pediment surface was Bull Lake in age, the average rejuvenated strain rate between the Pinedale and Bull Lake Glaciations (some 13,000 to 140,000 years before the present) was about 0.014 cm/year. Datable deposits and surfaces were lacking to evaluate pre-Bull Lake fault displacement.

The third thrust of research was to determine the lateral extent of faulting. This assumed major importance when it became apparent that the faults would be classed as capable. Preliminary efforts to trace the fault planes employed additional drilling, electrical resistivity surveys, and seismic refraction surveys. These were generally unsuccessful. In areas of most distinct surface expressions of faulting, these techniques confirmed the obvious. Where the fault traces faded out on low sun-angle photography, their geophysical expression likewise diminished. Geophysics failed to detect the west-side fault in a few areas where trenching had confirmed its presence. Overriding landslide deposits made further trenching impractical, and random drilling would have been inordinately expensive and of doubtful utility. This was because while positive delineation of the fault planes was useful, negative results left open the possibility that a fault plane had been missed or gone unrecognized in the samples.

Geologic data compiled and analyzed to this point strongly indicated that predecessors of the west-side and east-side faults were planes of the ancient Elkhorn and Chase Gulch fault systems, respectively. Stresses required to initially form these fractures tens of millions of years earlier were necessarily much greater than those required to renew movement on the established planes of weakness. It was felt that all the observed movement could be readily absorbed by pre-existing fractures, and that propagation of new fault planes was unlikely.

Mapping of the Elkhorn and Chase Gulch fault systems then proceeded on the basis that delineation of these pre-existing fracture patterns would establish limits on the extent of capable faults. This research entailed relatively detailed field mapping (at 1:12,000) of about 16 square miles of bedrock terrain in the Spinney Mountain vicinity, and additional low sun-angle photography and reconnaissance geology along slightly over 100 miles of inferred fault traces. This mapping eventually enabled unraveling of a very complex deformational history beginning about 65 million years ago and extending to the present. It was established that the controlling tectonic structure was the east-side fault, whose surface rupture was conservatively estimated to occur along a 10-mile (16-km) trace roughly coincident with a segment of the old Chase Gulch Fault. The west-side fault, originally a secondary plane of the Elkhorn Thrust, was interpreted to branch at depth from the plane of the east-side fault (Figure 3a). Displacement of the west-side fault is believed to have occurred sympathetically to east-side fault movement.

The west-side fault was interpreted to terminate against a tear-type cross-fault having a complex, but explicable relationship to the overall overthrust movement of the Elkhorn Fault. However, despite indirect geologic evidence for termination of the west-side fault 1/2 mile (1 km) or more from the dam site, it was felt that the possibility of an undiscovered capable fault occurring in the dam foundation could not be eliminated entirely. Excavation of the core trench eventually exposed drag folding that confirmed presence of the terminating cross-fault. No indication of the west-side fault was found. Deformation in the South Park sediments underlying the dam foundation was almost wholly absorbed in a relatively plastic siltstone and no significant faults were observed.

Overall the successful conclusion of the seismic hazard study can be attributed to thorough geologic investigations and, equally important, to frequent communication with and field presentations for regulatory agencies. Throughout the fault investigations, results ran counter to expectations. A part of one of the minor "potentially active" faults identified by the Colorado Geological Survey appears capable, possibly connecting with the system delineated near the dam site. However, major regional faults suggested as "potentially active" by the Colorado and U.S. Geological Surveys showed no evidence of young displacement while older faults, unsuspected of Quaternary activity, proved capable according to the criteria applied.

A major uncertainty regarding the capable faults is the timing, number, and magnitude of individual displacements. An immense effort would be required to resolve this question. These are, nevertheless, important considerations in that if movements on capable faults have ceased or if movements occurred as gradual, semi-continuous tectonic creep, damaging earthquakes would presumably not occur. In this case, it was more practical to design for ground shaking than to attempt assessment of dates and magnitudes of individual fault displacements.

Epilogue -- Earthquake Assessment

Since the Spinney Mountain fault investigations were completed in 1979, much new information has become available on Rocky Mountain tectonics, and methods for evaluating seismicity have progressed. In South Park, extensive reflection seismic data were reprocessed by Durrani (1980). Re-interpretation of those profiles using state-of-the-art structural concepts (e.g., Harding, 1985) could provide important information on the Elkhorn/Chase Gulch fault system and its possible relationships to Rio Grande rift tectonism (Tweto, 1979; Knepper, 1976). Theoretical considerations (Glazner and Bartley, 1985) as well as experience in the Wasatch Fault zone (e.g., Sprinkel, 1979) and Rocky Mountain Trench (e.g., Bally and others, 1966) indicate younger, rift-type normal faulting may be a usual overprint of earlier thrusting. Given the evidence of Quaternary normal faulting (this paper; Kirkham and Rogers, 1981), these considerations could apply to many locations in and adjacent to the Colorado Front Range as well as in the Rio Grande rift zone itself.

The methodology applied to earthquake hazard assessment as of 1985 varies widely among state and federal regulatory agencies (National Academy of Sciences, 1985). In many instances, deterministic (capable fault) and probabilistic (historic seismicity) approaches are still debated as alternative approaches instead of being appropriately integrated. In our experience since 1979 in the western United States and Canada, probabilistic methods provide reasonable seismic design criteria in most areas away from known capable faults. The probabilistic approach requires accurate geologic and geophysical definition of seismotectonic provinces, as well as compilation and, in some cases, fault-mechanical classification of historic and instrumental seismicity. The general methodology enunciated by Atkinson and Charlwood (1983) has proven to be a highly practical and mathematically robust technique for application of the probabilistic approach.

As the Spinney Mountain project clearly shows, however, probabilistic methods alone cannot be depended upon to completely evaluate seismic hazards. In our opinion, detailed lineament studies should always be paired with a probabilistic analysis in the first phase of seismic hazard evaluation. Preliminary regional geologic and geophysical data compilation provides the basis for seismotectonic province definition as well as a focus for lineament analysis. The geographic range of lineament studies is defined by the results of the probabilistic assessment. This is accomplished by deriving the capable-fault lengths which imply potential ground motions that exceed probabilistic estimates for a range of distances from the site. The capable-fault-length versus distance-from-site relationship is then used to establish the types of remote-sensing imagery required to resolve lineaments at various distances, ranging from low-altitude, high resolution aerial photography within a few miles of the site to progressively higher altitude photography, SLAR, and satellite imagery at increasing distances.

ESTIMATE OF GROUND MOTION FOR DESIGN

In the regulatory view delineation of a capable fault using geologic criteria established the need for seismic design. However, geologic conditions cannot of themselves indicate the specific ground motions appropriate to such design. At Spinney Mountain indirect geologic evidence suggested that capable faults did not extend into the dam foundation. However, that possibility could not be entirely discounted, and provisions were formulated to accommodate up to 6 inches (15 cm) of vertical or overthrust displacement in the event that capable faults were found in the foundation excavation. This figure was based on statistical correlations (Krinitzsky, 1974) of branch fault displacement with main (east-side) fault surface-rupture length. This is similar to the method employed to arrive at intensity of ground shaking, as discussed below.

Probable earthquake magnitudes can be assigned to capable faults based on statistical relations between magnitude and fault length for earthquakes of record. Various relationships are available, depending on geographic groups and fault characteristics. While the correlation relationships could be better, this was the only practical technique for assigning ground motion parameters to a capable, but historically inactive fault for design purposes. For this project statistical relationships and methodologies formulated by Slemmons (1977) were used.

The 10-mile (16-km) surface-rupture length of the main capable fault at Spinney Mountain correlated statistically to a Richter Magnitude of 6.2. Standard attenuation curves (Schnabel and Seed, 1973) extrapolated on the basis of other experience to distances as close as 2 km from the causative fault, indicate a probable peak horizontal acceleration at the dam of about 0.6g. Duration of strong ground motion for such a tremor is expected to be about 15 seconds (Bolt, 1975).

While these values do not represent extreme limits of probability for the combinations of rupture length and distance from the causative fault used, the conservatism of assumptions and analyses leading to the fault characteristics themselves make the overall seismic design quite conservative. Major considerations leading to this conclusion include 1) the capable faults appear to have been dormant for close to 13,000 years, contrasted with a relatively uniform prior strain rate, 2) continuity was assumed between fault traces separated by present-day floodplains and reservoir, and 3) the area is historically and instrumentally aseismic.

SEISMIC EVALUATION OF DAM

General Method of Stability Analysis

The embankment stability was analyzed by the slip circle method (modified Bishop) using the computer program STABL. Stability against earthquake forces was initially analyzed using a conventional pseudo-static analysis with a seismic coefficient of 0.1g. Determination of this seismic acceleration was based on the faults along the upper Arkansas Valley, some 50 km from the site, which for a Richter Magnitude of 6.0 would require a design horizontal acceleration of 0.08g to 0.1g, according to Schnabel and Seed (1972). There have been several examples, however, of dams which have failed which were considered to be safe based on a satisfactory pseudo-static analysis. Impetus to research and development to improve dynamic analysis of embankments was given particularly by the failure of the lower San Fernando Dam during the 1971 earthquake in southern California.

The state-of-the-art in 1979 of earthquake resistant design of earth dams was presented in the Rankine Lecture by H. Bolton Seed (1979). The two predominant current methods of stability analysis of earth embankments under seismic loading were the complex dynamic-response method and the slope-deformation solution. The former is described by Seed and others (1975, 1978). Although there are variations of the dynamic analysis method, the more rigorous solution consists of determination of stresses by finite element analysis, dynamic laboratory tests, and field tests, both geophysical and standard penetration, followed by the evaluation of probable performance. The slope deformation concept is based on the mechanics of a sliding block on a plane which was advocated by Newmark in the fifth Rankine Lecture in 1965. Newmark's method is based on a rigid body and is therefore considered conservative in determining estimated movements. Makdisi and Seed (1978) introduced a method which reduces the base or crest accelerations to effective average values for the full height of the dam, and in essence reflects some plasticity in the dam and results in considerably less deformation than the Newmark approach.

Considering the type and height of Spinney Mountain Dam and the nature of the foundation, the slope deformation method was selected for seismic analysis of this dam using both the Newmark and Makdisi and Seed procedures, to bracket the potential movement. The method is also considered particularly applicable here since the embankment is constructed of clayey soils founded on a rock foundation, anu no cohesionless materials are present in the embankment or its foundation which could be subject to liquefaction and would therefore warrant the more complex analysis.

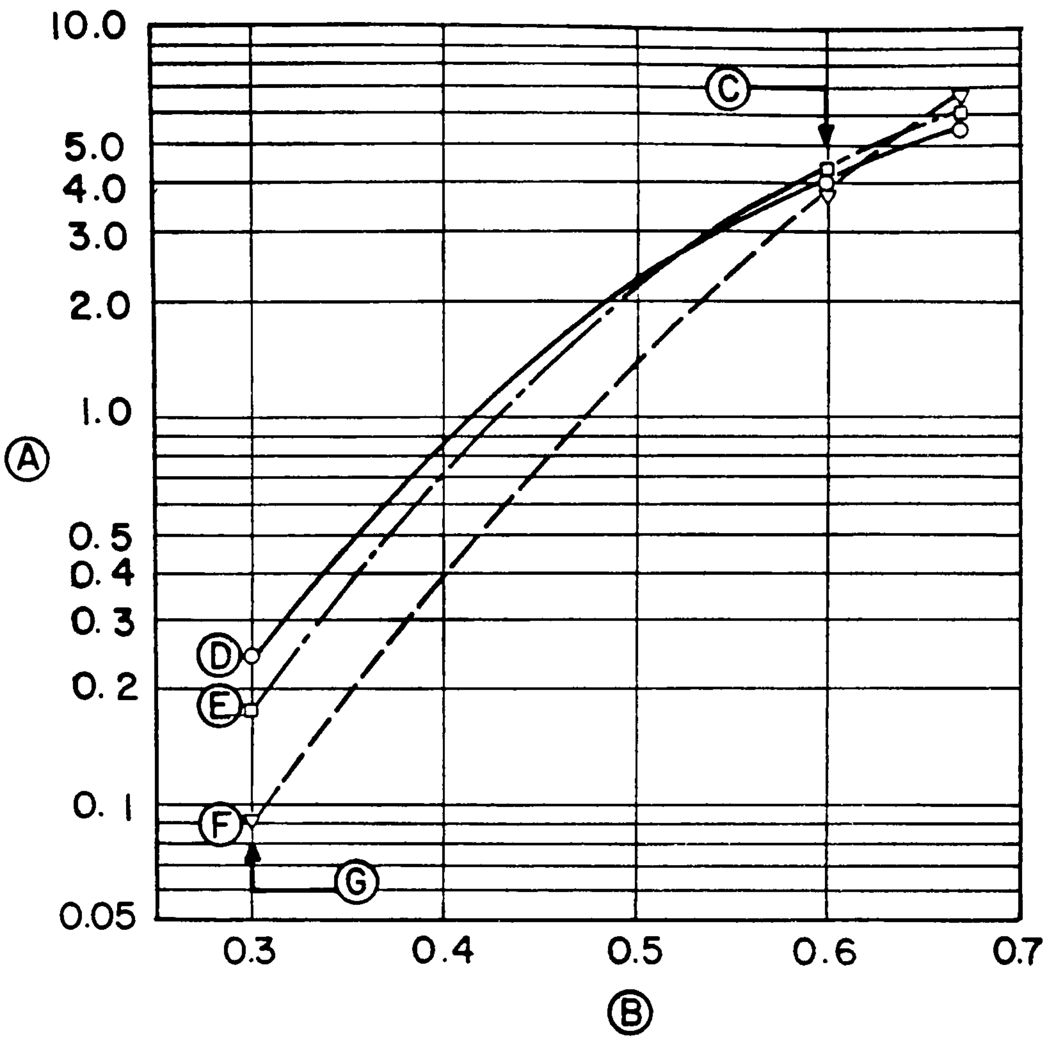
Time History of Design Earthquake

Three recorded ground motions were selected as representative of the geological conditions at this site. Two of these records, Pacoima and Castaic, were obtained during the 1971 San Fernando magnitude 6.6 earthquake. The third record, Temblor, was obtained during the 1966 Parkfield magnitude 5.6 earthquake. The records were obtained on a computer tape from the Cal-Tech Earthquake Engineering Research Laboratory. Each horizontal accelerogram was scaled to three levels of peak acceleration (0.3g, 0.6g, and 0.67g) for the subsequent slope deformation analysis.

Slope Deformation Analysis

Newmark advanced the concept of permanent slope deformation as a rational alternative for evaluating embankment performance. In this method the net resultant horizontal force on the sliding block considered in the analysis at any time is the difference between the actuating dynamic force and the contact resistance on the plane surface within the embankment. Relative motion (sliding) will occur if and when the dynamic actuating force exceeds the internal resistance of the sliding plane. This internal resistance is based on a pseudo-static stability analysis which determines the horizontal yield acceleration based on the physical properties of the embankment zones. A horizontal yield acceleration of 0.16g was calculated for the Spinney Mountain Dam.

Slope deformation analyses were then carried out using both Newmark and also Makdisi and Seed methods. The results, shown in Figure 4, indicate that based on Newmark the crest of the dam would have a horizontal movement of less than 5 cm, while on the more realistic Makdisi and Seed method it would be about 0.25 cm. Based on the results it is the opinion of the designers that the proposed dam would spread horizontally less than 5 cm at each slope face. Some vertical movement would accompany this lateral deformation, but is expected to be a fraction of the horizontal values.



A) Permanent Horizontal Seismic Displacement (centimeters)

B) Effective Average Horizontal Acceleration (g)

C) Newmark (1965)

D) Temblor

E) Castaic

F) Pacoima

G) Makdisi - Seed (1978)

Figure 4. Results of slope deformation analyses.

DESIGN AND CONSTRUCTION OF DAM

Design Section

A typical embankment section for the dam is shown in Figure 5. The embankment is a multi-zone type with a chimney filter-drain leading to a horizontal blanket drain downstream. Sources of materials were chosen carefully so that each succeeding downstream zone acts as a filter to resist migration of fines from the adjacent upstream zone. Zone 1 consists of impervious clays and Zone 2 also has low permeability. Zone 3 consists of silty and clayey sands which transition into the free-draining sands and gravels of the Zone 5 filter drain.

In the design of the dam it was planned that if a capable fault was discovered in the foundation, a Zone 6 of cohesionless "crack-stopper" materials would be located across the fault and extend 30 m either side of the fault along the dam axis. It would be 3 m thick and would extend horizontally upstream of, and 6 m vertically along, the upstream face of Zone 1. In the event of a vertical displacement (which could be as much as 15 cm) along a foundation fault, the fines in the "crack-stopper" material would migrate to the core and fill the void; thus any leakage caused by displacement would be stopped or significantly reduced. Subsequent piping would thus be eliminated. However, no evidence of a fault was found during construction of the dam and, hence, the Zone 6 material was not produced. There was also a concern that the fine-grained Zone 1 and 2 materials might have dispersive characteristics. In the event of cracking of the fill due to an earthquake, piping of these materials would be more critical if they were dispersive and special sand filters would probably be required. Tests of these materials established that they were not of a dispersive nature.

Features Providing Improved Earthquake Resistance

The dam embankment has characteristics generally recognized as providing inherently strong earthquake resistance, and the dam section was adjusted to improve this resistance ability. Several of the factors in this respect are:

1) It will have 7.2 m of freeboard above normal highwater level.

2) The strength characteristics of Zone 1 clays plus the ample freeboard should prevent an open crack forming below the reservoir normal highwater level.

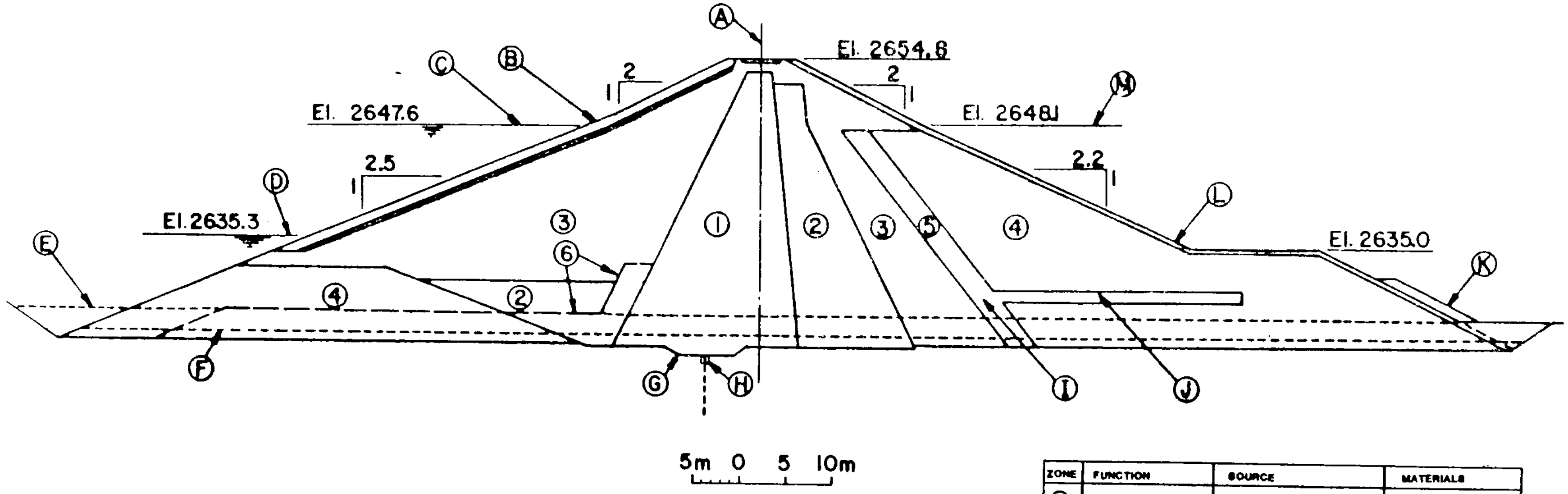
3) The section is a multi-zoned type with wide transition zones.

4) It has a positive drainage system with a chimney drain in the downstream portion of the dam. This chimney drain will ensure that the downstream Zone 4 shell is not saturated.

5) It has a wide plastic central core.

6) In case a capable fault was encountered in the foundation of the dam, a granular "crack-stopper" would have been added in case of movement due to a major earthquake.

7) The topography of the reservoir basin is relatively flat, obviating problems with large landslides.



ZONE	FUNCTION	SOURCE	MATERIALS
1	Impervious	Borrow Area D-lower units-soils and weathered shales	Silty clays (ML, CL, CH)
2	Transition	Approved excavation material from spillways	Silty sands and clays (SM, ML, CL)
3	Upper shell	Borrow Area D-upper soil units	Silty and clayey sands (GM, SW-SM, SM-SC, SM, ML)
4	Lower shell	Approved excavation material from dam foundation	Sands and gravels (GP, SP-GP, SM, ML, ML-CL)
5	Chimney drain	Processed from Borrow Area G	Well graded sands and gravels
6	Crack stopper	Processed from Borrow Area G, 1 1/2" max.	Well graded sands and gravels

A) Axis of Dam
B) Rock Riprap and Bedding
C) Normal Maximum Reservoir
D) Minimum Reservoir
E) Original Ground Line
F) Assumed Top of Rock
G) Core Trench
H) Grout Cap
I) Chimney Drain
J) Blanket Drain
K) Riprap
L) Stone Protection
M) Slope Change

Figure 5. Typical embankment section of Spinney Mountain Dam.

Construction Control

The entire embankment is founded on rock of the South Park (Denver) Formation. Construction control parameters are shown in Table 1. An engineering geologist inspected the dam foundation excavations as they were being made and the grout cap in the Zone 1 core trench was mapped geologically for its entire length. The purpose of this was to determine if any unusual features, particularly any faults, were encountered in the excavations.

Table 1. Summary of compaction specifications.

Material	Compaction Moisture (% from optimum*)		Lift Thickness Compacted (cm)	Passes Roller
Zone 1	+1	-3	15	12 (Sheepsfoot)
Zone 2	+1	-2.5	15	12 (Sheepsfoot)
Zone 3	+1	-2	23	12 (Sheepsfoot)
Zone 4	+1	-2.5	30.5	6 (9 Tonne Vibratory)
Zone 5	as necessary		30.5	4 (9 Tonne Vibratory)
Zone 6	as necessary			

Minimum Density Requirements

Zone 1, Zone 2, Zone 3	Average	100%
	Not more 20%	98%
	None	96%
Zone 4	None	100%
Zone 5, Zone 6	None	2,909 kg/m^3 dry density (70% relative density)

*Optimum moisture and maximum density determined by ASTM D-698

CONCLUSIONS

Seismic investigations disclosed a fault considered to be capable and having an estimated length of 10 miles (16 km) that approached within about 1 mile (2 km) of the Spinney Mountain Dam. This inferred fault length was statistically correlated to a maximum earthquake of Richter Magnitude 6.2. The maximum estimated horizontal rock acceleration from this earthquake would be 0.6g at the proposed dam site. The estimated duration of the shaking is 15 seconds for this event.

Seismic analysis of the dam embankment was performed using the slope deformation analysis methods of Newmark and also of Makdisi and Seed. These results indicated the dam would spread out horizontally in the range of 0.25 to 5.0 cm at each slope face for the design earthquake. Vertical displacement would be a fraction of the horizontal values. Even a 5-cm slope deformation will not significantly decrease the strength of the compacted embankment soils; therefore the integrity of the earthfill dam would not be altered significantly by strong ground shaking from the magnitude 6.2 earthquake.

The dam embankment section has characteristics generally recognized as providing inherently strong earthquake resistance. Further, if a capable fault had been encountered in the dam foundation, it was planned to provide a granular "crack'stopper" to accommodate movement (which could be as much as 15 cm vertically) due to a major earthquake. However, no such fault was encountered during construction. Reservoir-induced seismicity is not considered to pose significant risk to the project because of the relatively low hydrostatic head and generally non-permissive geology and site conditions.

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AN INTERPRETATION OF THE NOVEMBER 7, 1882 COLORADO EARTHQUAKE

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ABSTRACT

On November 7, 1882 an earthquake rocked parts of Colorado, Wyoming, Utah, and Kansas. It was felt over 470,000 km^2, with a maximum reported Modified Mercalli intensity of VII. An isoseismal map for the main event and the felt area of an aftershock on November 8th, along with historic wave path and focusing considerations, suggest the epicenter was probably in north-central Colorado, perhaps in the northern Front Range or possibly southern Laramie Mountains. The felt area for the aftershock is in our opinion the most significant factor for defining the general epicentral location for the main earthquake. Earthquake magnitude is estimated at 6.2 $\pm$ 0.3 ML, based on felt area size. Similarities with the 1984 Laramie Mountains earthquake support an interpretation that the 1882 event probably occurred at a fairly great depth, perhaps 20 km or more. The possibility of there having been two earthquakes closely spaced in time at different locations was specificially addressed and no data supporting this theory was found.

INTRODUCTION

On November 7, 1882 at about 6:30 p.m. Denver time a relatively large earthquake occurred which was felt strongly in Colorado and Wyoming, at less intensity in Utah, and at one known location in Kansas. Numerous previous investigators have studied this earthquake. Heck (1938) suggested the tremor was felt over 28,000 km^2. Hadsell (1968) proposed the earthquake was centered just north of Denver, was felt over 1,200,000 km^2, and had a Richter magnitude of 5.0 $\pm$ 0.6 based on the maximum observed Modified Mercalli intensity (MMI) of VII and 6.7 $\pm$ 0.6 based on its felt area size. Coffman, von Hake, and Stover (1982) estimated the felt area size at 28,500 km^2 with a maximum intensity of V. According to Docekal (1970), the felt area was 285,000 km^2, while the maximum intensity was VII.

Dames & Moore (1981) collected and interpreted additional felt reports and estimated the felt area at 500,000 km^2, the magnitude (ML) at 6 1/2, and the maximum intensity at VIII. They placed the epicenter in northwest Colorado and suggested the Dudley Gulch graben as a possible causative fault. A summary of the Dames & Moore study was published by McGuire and others (1982). Oaks and others (1985) compared the 1882 quake with the 1984 Laramie Mountains earthquake and noted similarities in their felt areas and intensity distribution.

This earthquake was probably the largest to occur in Colorado during the period of historic record. A similar-sized event today could have significant impact on modern structures, possibly causing serious property damage and perhaps injury or death. Because of the potential effects of such an earthquake, and the varied interpretations regarding the magnitude, maximum intensity, epicentral location, and felt area size of this earthquake, the Colorado Geological Survey (CGS) undertook this investigation to clarify some of the mysteries surrounding this century-old earthquake.

Additional felt reports have been located by Oaks and Kirkham (1986) as part of the CGS investigation. These reports were discovered in newspapers, in unpublished local diaries, through interviews with knowledgeable individuals, and in manuscripts held by the National Archives in Washington, D.C.. MMI assignments are herein proposed for these newly discovered felt reports, and intensity ratings for previously known accounts are re-examined and revised in some cases. An isoseismal map for this earthquake is presented based on our intensity assignments, along with descriptions of our interpretation as to the magnitude, maximum intensity, felt area size, and most probable epicentral location.

ACKNOWLEDGMENTS

This investigation was supported in part by U.S. Geological Survey Grant No. 14-08-001-G975 and Requisition No. 1-9500-7130/Project 1-9500-01301. Carbon-14 dating of the charcoal sample from Ryan Gulch was arranged by S.M. Colman and D.A. Trimble of the U.S. Geological Survey. We thank the U.S. Geological Survey for their cooperation.

FELT REPORTS AND INTENSITY ASSIGNMENTS

Table one lists all currently known felt reports and the MMI rating assigned to each report. Also included in Table 1 is the source or reference for each felt report. Verbatim transcriptions of selected original accounts are contained in Appendix A. Only those original accounts which have not previously been assigned a MMI (i.e. new accounts from Oaks and Kirkham, 1986) or those which our assigned MMI differs from intensity ratings previously reported in earlier studies are included in Appendix A.

Please refer to Dames & Moore (1981) and Oaks and Kirkham (1986) for all other felt reports. All felt reports are plotted on Figure 1, along with their assigned MMI.

Table two Describes locations and newspapers examined by Dames & Moore (1981) or Oaks and Kirkham (1986) in which no local effects were reported. These locations are herein considered "not reported" localities. In many instances these newspapers carried accounts of the earthquake effects in other towns, but did not describe any local manifestations. "Not reported" localities cannot be definitively categorized as "not felt" locations. "Not reported" localities are designated on Figure 1 by the symbol "X".

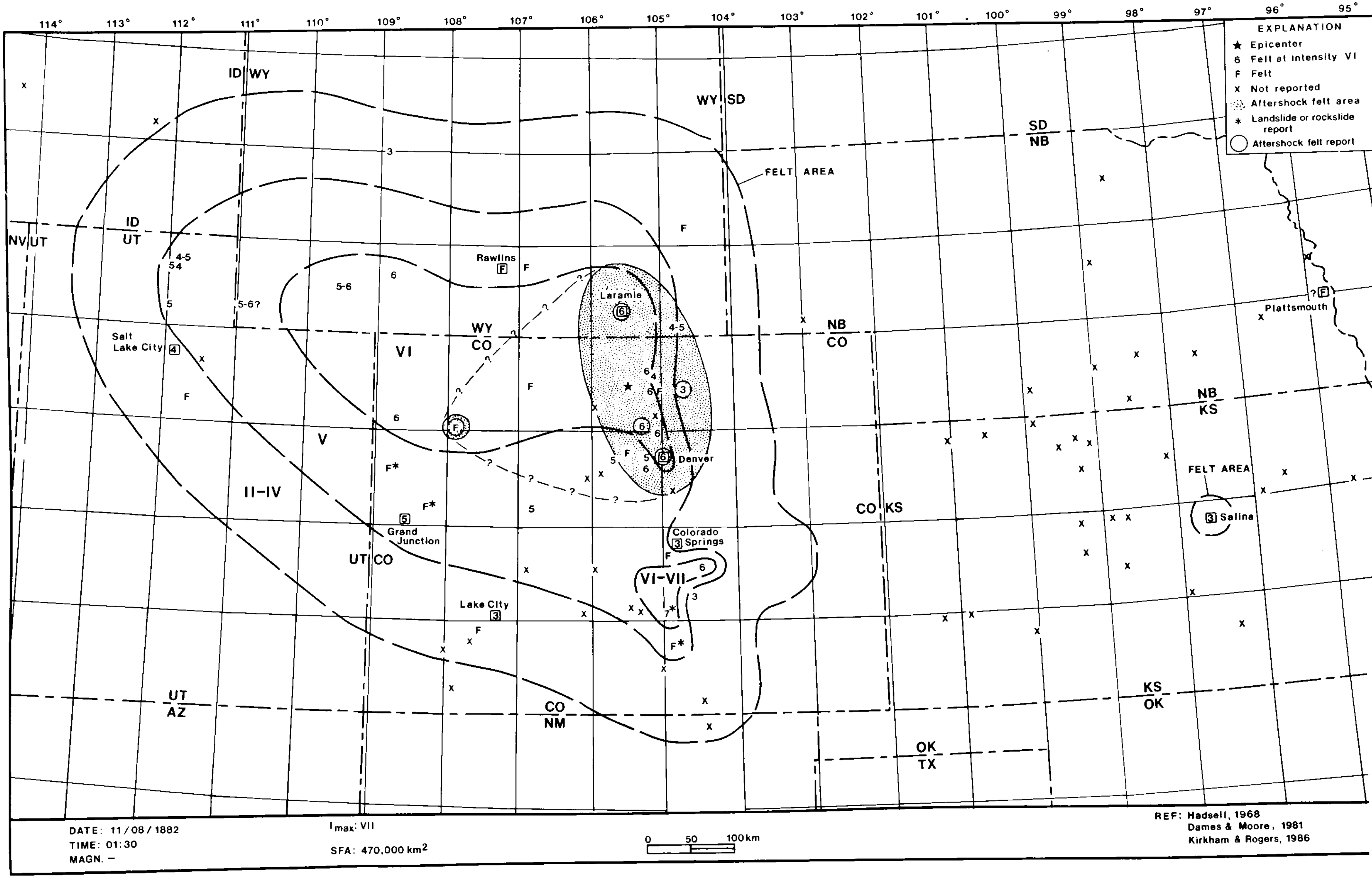

Figure 1. Isoseismal map for the 1882 Colorado earthquake. Stippled pattern is felt area of aftershock the next day. Date and time shown on the map is in Coordinated Universal Time.

Table 1. Intensity assignments for the November 7, 1882 earthquake (modified from Dames & Moore (1981) and Oaks and Kirkham (1986).

Location	Reference and Date	Intensity
COLORADO		
Animas Forks	Animas Forks Pioneer - 11/18 & 12/9	F
Aspen	The Aspen Times - 11/11	V
Boulder	Boulder County Herald - 11/8	VI,AS
	University Portfolio - December,1882	
Central City	The Post - 11/18	F
Chico Creek	The Pueblo Daily Chieftain - 11/11	VI
Colorado Springs	The Weekly Gazette - 11/11	III
DeBeque Canyon	The Daily Sentinel (Grand Junction) - 7/11/1976 (see Oaks and Kirkham, 1986)	F *
Denver	The Daily Denver Times - 11/9	VI,AS
	The Denver Republican - 11/8	(ranges from IV-VII)
	The Denver Tribune - 11/8	
	The Queen Bee - 11/8	
	Rocky Mountain News - 11/8	
	War Dept., U.S. Signal Office, Monthly Meterological Report - November, 1882	
	Abstracts of Daily Journals - 11/7	
Fort Collins	Daily Evening Courier - 11/8	IV
	The Daily Express - 11/8	
	War Dept., U.S. Signal Service, Voluntary Observers's Meteorological Report - November, 1882	
Georgetown	The Colorado Miner - 11/11	V
	Georgetown Courier - 11/9	
	Rocky Mountain News - 11/8 & 11/11	
Golden	The Golden Globe - 11/11	V
	Colorado Transcript - 11/8	
Greeley	The Colorado Sun - 11/11	III,AS
Greenhorn Mtn. foothills	The Pueblo Daily Chieftan - 11/11	VII *
Grand Junction	Grand Junction News - 11/11	V
	Haskell (1886)	
La Porte	Daily Evening Courier (Ft. Collins) - 11/10	VI
Lake City	Silver World - 11/11	III
Louisville	The Daily Denver Times - 11/9	VI
	The Daily Express (Ft. Collins) - 11/11	
	Rocky Mountain News - 11/8	
Loveland	The Daily Express (Ft. Collins) - 11/11	F
Pueblo	The Pueblo Daily Chieftain - 11/11	III
Rangely	Diary of Charles Porter Hill - 11/7 (see Oaks and Kirkham, 1986)	VI
Steamboat Springs	Diary of Perry A. Burgess -11/7 (see Oaks and Kirkham, 1986)	F
Thompson	Daily Evening Courier (Ft. Collins) - 11/24	VI (VII?)
Turkey and Beaver Creeks	The Pueblo Daily Chieftain - 11/11	F

AS indicates aftershock reported on 11/8/1882
* indicates landslide or rockslide reported

Table 1. Continued.

Location	Reference and Date	Intensity
White River Agency (near Meeker)	Carbon County Journal (Rawlins, WY) - 11/18	F,AS
30 or 40 miles south of Pueblo Walsenburg area)	The Pueblo Daily Chieftain - 11/11	F *
Douglas Pass area	Grand Junction News - 11/18	F *
UTAH		
Hyrum	Salt Lake Daily Tribune - 11/11	IV
Logan	Cache Coin in Ogden Daily Herald - 11/9	IV-V
	Journal (Logan) in The Deseret Evening News (Salt Lake City) - 11/11	
Ogden	Ogden Daily Herald - 11/8	V
Provo City	The Territorial Enquirer - 11/8	F
Salt Lake City	The Deseret Evening News - 11/8	IV
	Salt Lake Daily Herald - 11/8	
	The Salt Lake Daily Tribune -11/9	
	Abstracts of Daily Journals - 11/7	
Wellsville	Cache Coin in Ogden Daily Herald - 11/9	V
	Ogden Daily Herald 11/10	
WYOMING		
Cheyenne	The Cheyenne Daily Leader - 11/8	IV-V
	War Dept., U.S. Signal Office, Monthly Meteorological Report - November, 1882	
	Abstracts of Daily Journals - 11/7	
Evanston	The Uinta Chieftain - 11/11	V-VI?
Fort Fred Steele	Letter from A. Morton, Captain, U.S. Army to Assistant Adjutant General in Omaha, NE	F
Fort Laramie	U.S. Army, Records of Medical History of Post-November, 1882	F
Fort Washakie	The Cheyenne Daily Leader - 11/12	III
	Fort Washakie Meteorological Register - November, 1882	
	Abstracts of Daily Journals - 11/17	
Green River	Green River Gazette in Cheyenne Daily Sun - 11/15	V-VI
Laramie	Laramie Weekly Sentinel - 11/11	VI,AS
Point-of-Rocks	The Cheyenne Daily Leader - 11/8	VI
Rawlins	Carbon County Journal - 11/11	F
	The Cheyenne Daily Leader - 11/8	
KANSAS		
Salina	War Dept., U.S. Signal Service, Voluntary Observer's Meteorological Record - November, 1882 (also noted by Rockwood, 1883)	III
NEBRASKA		
Plattsmouth	The Omaha Bee - 11/11	F ?
	Plattsmouth Weekly Herald - 11/16	

AS indicates aftershock reported on 11/8/1882
* indicates landslide or rockslide reported

Table 2. "Not reported" locations for the November 7, 1882 earthquake (from Dames & Moore, 1981 and Oaks and Kirkham, 1986).

Location	Newspaper
COLORADO	
Breckenridge	Daily Journal
Castle Rock	The Castle Rock Journal
Durango	Durango Herald
Grand Lake	Grand Lake Prospector
Gunnison	Gunnison Daily Review Press
La Veta	The Huerfano Herald
Leadville	Leadville Daily Herald (note: several non-local newspapers reported that the earthquake was felt in Leadville)
Longmont	Longmont Ledger (note: non-local newspapers reported that the earthquake was felt in Longmont)
Montezuma	Montezuma Millrun
Rico	Dolores News
Rosita	The Sierra Journal
Saguache	Saguache Advance; Saguache Chronicle
Salida	Mountain Mail
Silver Cliff	The Daily Herald; The Weekly Herald
Trinidad	Trinidad Daily News; The Trinidad Democrat; Trinidad Weekly News
UTAH	
Park City	The Park City Mining Record
WYOMING	
NONE	
KANSAS	
Atwood	Republican Citizen
Beloit	The Beloit Gazette
Bunker Hill	Bunker Hill Banner
Dodge City	Ford Country Globe; Dodge City Times
Garden City	The Irrigator
Great Bend	Arkansas Valley Democrat
Hays	The Star Sentinel
Hutchinson	Hutchinson Herald; Hutchinson News
Junction City	The Junction City Tribune
Kirwin	The Independent; The Kirwin Chief
La Crosse	La Crosse Chieftan
Lakin	Lakin Herald
Logan	Logan Enterprise
Manhattan	The Nationalist
Norton	Norton County Advance
Oberlin	Oberlin Herald
Phillipsburg	Phillipsburg Herald
Russell	The Russell Hawkeye
Stockton	The News; The Rooks County Record
Topeka	Daily Kansas State Journal
Wichita	Weekly Leader; The Wichita City Eagle; Wichita Daily Times; The Wichita Weekly Beacon

Table 2. Continued

Location	Newspaper
NEBRASKA	
Arapahoe	Arapahoe Pioneer
Geneva	Filmore County Review
Hastings	The Gazette Journal
Lincoln	The Lincoln Daily News
Minden	Kearney County Gazette
Omaha	The Omaha Bee; The Omaha Daily Bee; The Omaha Weekly Herald
O'Neill	The Frontier
Ord	Valley County Journal
Sidney	Plainsleader-Telegraph
Red Cloud	Webster County Argus
St. Paul	The Phonograph
IDAHO	
Blackfoot	The Blackfoot Register
Boise City	Idaho Tri-Weekly Statesman
Hailey	Wood River Times
Lewiston	The Lewiston Teller
Silver City	The Idaho Avalanche
NEW MEXICO	
Albuquerque	Daily Democrat; The Albuquerque Review
Raton	The Raton Comet
Santa Fe	Santa Fe Daily New Mexican

The primary problem related to the study of older earthquakes is the lack of historical records to document the effects of an earthquake. In 1880 there were less than 200,000 people in Colorado, most of whom were in rural areas (Dames & Moore, 1981). Only Denver, Colorado Springs, Leadville, and Silver Cliff had populations over 4,000. The population of the probable epicentral area, north-central Colorado or southeast Wyoming was especially low. Relatively few newspapers were published daily in Colorado. Some of the weekly newspapers may have ignored the earthquake due to the time lag between the earthquake date and publication date.

Other problems that complicate the understanding of the November 7, 1882 earthquake have been described by Dames & Moore (1981). They include the following factors:

1) The earthquake occurred on a national election day just as the polls closed. The Democratic victory added to the excitement of the day and some editors cleverly related the two news items. Many people were in the streets near telegraph offices and may not have noticed the earthquake effects as readily as those in buildings. The telegraph offices rapidly passed on news of the earthquake, allowing for possible confusion due to association of reported effects with perhaps a wrong locality.

2) Exaggeration in the newspapers also presents difficulties in accurately defining this event. A clear example of this is the numerous accounts of damaged plaster at the University of Colorado at Boulder. Some newspapers state that "plaster fell" or "plaster was shaken down" at the University. Others report "a large quantity of plaster...was thrown to the floor" or " the ceilings of the university were stripped of plaster". The record is set straight in the University Portfolio in December of 1882, when it reported "There is still some plastering on the ceiling of the University"... "The fact is that the building was shaken considerably, and some bits of plastering fell in the third story". Another probable example of exaggeration is illustrated by the account from near Douglas Pass in the Grand Junction News.

3) Some towns in the area were "booster oriented" and their newspapers tended to avoid subjects considered undesirable, such as earthquakes.

4) Hearsay reports consist of newspaper accounts in one town that describe the effects in another town. We utilize the technique of Dames & Moore (1981) to evaluate hearsay reports. If a hearsay report suggests a particular town felt the earthquake, but local newspapers from that town do not report the earthquake, then the location is considered to be a "not reported" locality. Such a situation exists for Leadville and Longmont.

   If local newspapers were not published or if copies have not survived in archive repositories, then the town is assigned a MMI based on the reported effects in the non-local newspaper. Several felt reports fall into this category, and uncertainties in interpreting the earthquake may result from this aspect. An example of this is from Point-of-Rocks, Wyoming where no local report has been discovered because a newspaper was not published there in 1882. Non-local newspapers state that plaster fell at this location.

The remainder of this section describes selected felt reports and our rationale for assigning the MMI for that location. The description is organized by state and alphabetically by location.

BOULDER, CO: A small amount of plaster fell from the third floor of the University. The newspaper accounts suggest the quake was felt by a large number of residents. Previous investigators have rated Boulder at MMI V. We believe even a small amount of fallen plaster justifies a rating of VI.

DEBEQUE CANYON, CO: According to Mr. Al Looks (in Oaks and Kirkham 1986), a rockfall occurred in DeBeque Canyon during the earthquake. No intensity rating is assigned to this report. Rockfalls can develop at relatively low intensities, particularly in an area with unstable slopes like those in DeBeque Canyon.

Denver, CO: Felt reports from the Denver area vary with respect to location and the type of structure. The strongest shaking was reported in the downtown, northern, and western parts of the city. Most of this area is underlain by water-saturated alluvial deposits.

At the electric light plant a bolt nearly 2.5 cm in diameter was snapped and another was bent, causing the lights to go off in Denver. This is the most significant reported damage in Denver, and could justify a MMI rating of VII. Other reports suggest intensities of IV to V. Rather than assign an intensity rating of IV-VII for Denver, we chose to rate it at VI.

GRAND JUNCTION, CO: A brief account of the earthquake was reported in the Grand Junction News. It states that "the buildings [which were log structures] moved and quaked as if they were being torn down and that hanging objects were put into motion at a lively rate", suggestive of intensity V shaking. The article also indicates that "our people were frightened by the shock". Previous investigators have assigned a MMI of VI to this report because of this statement, although no other evidence of intensity VI damage was reported. It is unclear whether this statement means all, many, or a few of "our people" were frightened by the earthquake. We rate the Grand Junction report at intensity V.

LA PORTE, CO: A house in La Porte shook until the timbers cracked. Although previous investigators assigned only an intensity of IV to this report, we believe the damage justifies an intensity VI rating.

LOUISVILLE, CO: The walls of the railroad depot were cracked in Louisville, indicative of intensity VI damage.

RANGELY, CO: An excerpt from the diary of C.P. Hill states "heard the roaring and thundering of some great noise. The ground shook and the trees bent. They said it was an earth tremor." We assign an intensity of VI to this account. The exact location of this report is uncertain. It is thought to have come from just east of Rangely along the White River.

STEAMBOAT SPRINGS, CO: An excerpt from the diary of Perry A. Burgess (in Oaks and Kirkham, 1986) describes a distinct earthquake in Steamboat Springs. No mention is made of any local damage. Unfortunately, no other accounts have been located for Steamboat Springs. Various descriptions of other earthquakes in northwest Colorado are included in Fitzpatrick (1974), but the 1882 quake is not mentioned. We do not assign a numerical intensity to the diary account.

THOMPSON, CO: The walls of a residence near Thompson were badly cracked during the earthquake and some walls were stripped of plastering. This account justifies at least an intensity VI rating and may, perhaps, indicate intensity VII damage.

DOUGLAS PASS AREA, CO **(north of Grand Junction)**: An intriguing account of severe shaking was reported by a party of travelers at the head of Douglas Creek near Douglas Pass. They describe landsliding and rockfalls, and indicate the quake broke off trees and that it was difficult to stand.

Hadsell (1968) discounted this report because the only account of it that he uncovered was a second-hand version in a Denver newspaper. Dames & Moore (1981) discovered an original, eyewitness account in a Grand Junction newspaper and give considerable credence to this particular report.

We question the reliability of this account. There is little supporting evidence for the descriptions provided by these travelers. Their geographic knowledge as described in the article is limited or incorrect. They state that their horses ran away during the night and that they were lost for nearly four days before finding their way out. If they were lost, they may well have been prone to exaggerate their recollections considerably. Their statement that this was not a "trumped up" story leads one to suspect that it may well be questionable.

Kirkham and Rogers (1985) have demonstrated that Grand Junction is an area sensitive to earthquake shaking. Well documented tremors have been felt more strongly or equally strong in Grand Junction than at their fairly distant epicentral locations. We believe that if the strong shaking described near Douglas Pass had occurred, Grand Junction should have reported equally strong or greater intensities. This very clearly did not happen during the 1882 earthquake.

Likewise, the report from near Rangely does not support an interpretation of there having been high intensity shaking at Douglas Pass. The Rangely report was only about 30 km north of Douglas Pass and was located on saturated alluvial deposits, yet it was only rated at intensity VI.

If the travelers were where they claimed to be and did feel the earthquake, much of the phenomenon they described could be a result of earthquake-induced landsliding. The Douglas Pass area is well known for its numerous large, highly active landslides that do not need seismic shaking for activation. It is widely recognized that landslides can be activated at relatively low intensities, suggesting the Douglas Pass report, if it is authentic, may indicate only MMI IV-V at this location.

B. K. Stover (1985) has studied slope stability problems in the Douglas Pass area and discovered abundant evidence of landsliding, much of which is extremely active. He describes large "landslide bowls" that serve as source areas for earth flows. This type of feature is probably the "immense crater or chasm, from which great volumes of smoke came pouring forth" referred to by the traveler's on Douglas Pass.

Our interpretation is supported by the fact that the travelers did not report the aftershock. If they were in or near the epicentral region or area of highest intensities, they should have felt the aftershock and would likely have reported it. Because of the various discrepancies, we believe the Douglas Pass report should be rated only as a "felt" location. It is equally plausible to totally discount this report.

<u>EVANSTON, WY</u>: The accounts from Evanston, Wyoming were rated at MMI V-VI by previous investigators. An intensity V rating certainly is justifiable, but an assignment as high as VI is probably not reasonable. No definitive evidence of intensity VI shaking has yet been uncovered.

<u>FORT LARAMIE, WY</u>: Oaks and Kirkham (1986) discovered a felt report in the medical records of Fort Laramie, Wyoming. Although no precise intensity assignment can be made based on the brief description, it is an important account because of its geographic location in eastern Wyoming.

<u>LARAMIE, WY</u>: Numerous newspapers carried descriptions of the effects of the earthquake in Laramie, Wyoming. Plaster was cracked and glass windows were broken. A MMI of VI is assigned to this location.

<u>POINT-OF-ROCKS, WY</u>: Only hearsay reports are available for Point-of-Rocks, Wyoming. These indicate plastering fell off in buildings. A MMI of VI is assigned to this location, but it is recognized that these hearsay accounts may be misleading or exaggerated.

WELLSVILLE, UT: A few felt reports have been discovered for towns in Utah. All accounts have been rated at MMI IV or V, with the exception of the brief report from Wellsville. Dames & Moore (1981) assigned Wellsville an intensity V-VI based on a correspondent's report from the Cache Coin reprinted in an Ogden newspaper which indicates that people were frightened and ran from their houses. The original copy of the Cache Coin has not been located. This article fails to explain whether all, many, or only a few people were frightened and ran into the streets, and accordingly, we believe an intensity V rating is probably more valid.

SALINA, KS: Rockwood (1883) briefly mentioned that the earthquake was felt as far east as Salina, Kansas. The original reference to the Salina felt report was located in the National Archives by Oaks and Kirkham (1986). In that no other towns in Kansas are known to have reported the earthquake, the shaking in Salina was probably only very light (MMI III)and may represent an isolated felt area.

PLATTSMOUTH, NB: A confusing exchange of reports developed in Nebraska. The Omaha Bee stated "Plattsmouth felt an earthquake shock on Tuesday morning". The Plattsmouth Weekly Herald came back with a reply stating that "Plattsmouth felt it much more perceptibly, however, Tuesday night when the election returns began to roll in on us". The initial article placed the quake at the wrong time, while the second account is unclear. An earthquake may actually have been felt in Plattsmouth, or it may have been an attempt at satire. Because of this, we rate this report as a questionable "felt" locality.

FELT REPORTS FOR THE NOVEMBER 8, 1882 AFTERSHOCK

A critical aspect in the understanding of this earthquake is the aftershock on the morning of November 8th. The most reliable and numerous felt reports of the aftershock are clustered along the Denver-Laramie corridor. The towns of Boulder, Denver, Greeley, and Laramie all reported the aftershock. Persons in Laramie awake at the time of the aftershock claimed "it was quite as distinct as the first". The Carbon County Journal contains a one sentence summation of a letter from a resident at the White River Agency near Meeker stating that the aftershock was also felt at that location. Unfortunately, the original letter or a copy of it has not been discovered.

If the report from the White River Agency and the reports from Denver to Laramie are included in a single felt area, then the aftershock would have been felt over about 61,000 km^2. Another reasonable interpretation might contour the Denver, Boulder, Greeley, and Laramie felt reports in one area, while showing the report from near Meeker as an isolated felt report (see Figure 1), in a manner similar to the Salina, Kansas report for the main shock.

INTERPRETATION OF INTENSITY DATA

Preparation of a detailed isoseismal map for most pre-instrumental seismic events for which felt data are available is generally a rather difficult task. The available felt reports for the November 7, 1882 earthquake are no exception in that they also present a complex and confusing picture. Moderate intensities in the V,VI, and VII range are reported from a large area, while no clear area of higher intensity damage is apparent. This may be due to an absence of population or felt reports in maximum intensity areas, or it may result from another phenomenon. It is also possible that higher intensity shaking did not occur during the earthquake.

Another difficult aspect of the interpretation is the occurrence of highly varied intensities in close geographic proximity with no obvious explanation. A vivid example of this developed in the Pueblo area. The town of Pueblo reported only MMI III, while surrounding locations ranged up to intensity VII. Another example has been noted in the Fort Collins area. The town of Fort Collins has been assigned intensity IV, yet the nearby towns of Thompson and La Porte experienced MMI VI or possibly even VII.

No matter how the data are contoured, a clearly defined area with high MMI cannot be distinguished. Figure 1 presents our most reasonable version of an isoseismal map for this earthquake. An epicentral area could be selected almost anywhere in north-central Colorado, northwest Colorado, or possibly even southeast Wyoming, if only the isoseismal map for the main shock is considered. However, we believe that data from the aftershock on November 8th provides the most incisive information for constraining the location of the major event.

An intriguing aspect of the felt data is that existing accounts could fit a pattern of there having been two or even three nearly simultaneous earthquakes. One event could have centered in the north Denver or north-central Colorado area, a second in northwest Colorado or northeast Utah, while a third might have been centered in the Wet Mountains. In that there is no known historical precedent for such a phenomenon, we believe the preferred interpretation is that we are dealing with only a single earthquake. In addition, during the historical research for this report a special effort was made to ascertain if there was any confirmation of the multiple earthquake theory. None was found.

A number of factors help to narrow the probable epicentral area. The felt area for the November 8th aftershock is indicated by the screen pattern on Figure 1. It is reasonable to assume that the epicenter of the main quake must be within this region. Therefore, the epicenter seems most likely to have been in north-central Colorado or possibly southeast Wyoming. The northern Front Range or southern Laramie Mountains should be considered as possible epicentral locations. Oaks and others (1985) agree with this interpretation. If the brief account from the White River Agency is considered an outlying felt report, the main aftershock felt area is restricted to an even narrower region. The aftershock reports from Laramie suggest it was nearly as strong at those localities as the main shock. It is perhaps significant to note that neither Grand Junction, any Utah cities, the travelers near Douglas Pass, nor the Hill family near Rangely mention an aftershock.

Another phenomenon to consider when analyzing the 1882 earthquake is the reported occurrence of earthquake lights described in reports by Dames & Moore (1981) and Oaks and Kirkham (1986). In Cheyenne, Wyoming an electrical disturbance or flash lit up the sky. An account from Colorado states "they saw jets of flame rushing from Long's Peak". Such phenomena are thought to occur near the epicentral area and may be due to fault movement (Richter, 1958; Lockner and others, 1983).

As previously mentioned, the Grand Junction area has been shown to be especially sensitive to seismic shaking (Kirkham and Rogers, 1985). If an earthquake felt over 470,000 km^2 was centered in northwestern Colorado and severe shaking occurred in the Douglas Pass area, it is reasonable to anticipate that Grand Junction would report effects at least as strong as the

Douglas Pass area. It is well documented that Grand Junction did not experience high intensities during the 1882 quake (Oaks and Kirkham, 1986). An article in the Daily Sentinel on 11/14/01, which states that the November 13, 1901 earthquake centered in Utah was felt more distinctly in Grand Junction than any previous event, supports this interpretation. The 1901 Utah earthquake generated only intensity V shaking in Grand Junction.

Another factor to consider is the felt effects reported during more recent earthquakes (Kirkham and Rogers, 1985). None of the historic western slope earthquakes have been felt in the Front Range urban corridor from Pueblo to as far north as Cheyenne or Laramie, nor in Kansas. Two of the Rocky Mountain Arsenal events on August 9 and November 27, 1967, however, were felt throughout the area from Pueblo to Cheyenne and Laramie, and as far west as Glenwood Springs. If one would modify these more recent events by slightly increasing the magnitude, moving the epicentral location to the northwest about 90 km, and increasing the hypocentral depth, it is fairly easy to visualize an earthquake that could generate the general intensity pattern of the 1882 earthquake.

Insight into this difficult to understand earthquake is also provided by the October 18, 1984 Laramie Mountains, Wyoming earthquake. This event was magnitude 5.3 mb, 5.1 MS, and 5.5 ML, was felt over 287,000 km^2, and probably occurred at a depth of around 20 km (Stover, 1985; Langer and others, 1985). An isoseismal map for this event is similar in certain aspects to isoseismal map for the 1882 quake (Figure 2). The earthquake was felt over a relatively large area and the epicentral area did not report high intensities. It was felt as far west as Salt Lake City and eastward into Nebraska, South Dakota, and Kansas. The greatest damage reported from this earthquake occurred in Golden, Colorado, although the damage there may have been due in part to poor construction practices and were accentuated by the ground motion. Comparative analyses by Oaks and others (1985) reveal marked similarities in the intensity patterns of the two quakes. The anamolous reports in the Pueblo vicinity during the 1882 earthquake are not readily explained by the 1984 Laramie Mountains earthquake. However, Kirkham and Rogers (1985) describe apparent wave path and focusing effects associated with the Rocky Mountain Arsenal earthquakes that result in somewhat higher intensity reports in the Pueblo area than would be anticipated.

We believe the previously cited factors point to a probable epicentral location for the 1882 earthquake in north-central Colorado, possibly in the northern Front Range or southern Laramie Mountains. We assign a geographic location of 40 1/2° N and 105 1/2° W for the event, but recognize that this may be in error by one-half degree or more. The hypocentral depth of this event was probably about 20 km or more.

All existing data relating magnitude to felt area size for Colorado and other Rocky Mountain region earthquakes is presented in Kirkham and Rogers (1985). Based on a felt area of 470,00 km^2 and the data presented by Kirkham and Rogers (1985), the magnitude of the 1882 earthquake is estimated at 6.2 $\pm$ 0.3 ML.

POSSIBLE CAUSATIVE STRUCTURE

Dames & Moore (1981) suggested the Dudley Gulch graben as a possible causative structure for the 1882 earthquake. The authors of this paper, along with Mr. Rahe Junge, made a field inspection of the Dudley Gulch graben and found no geologic or geomorphic evidence of Holocene or late Quaternary movement on the

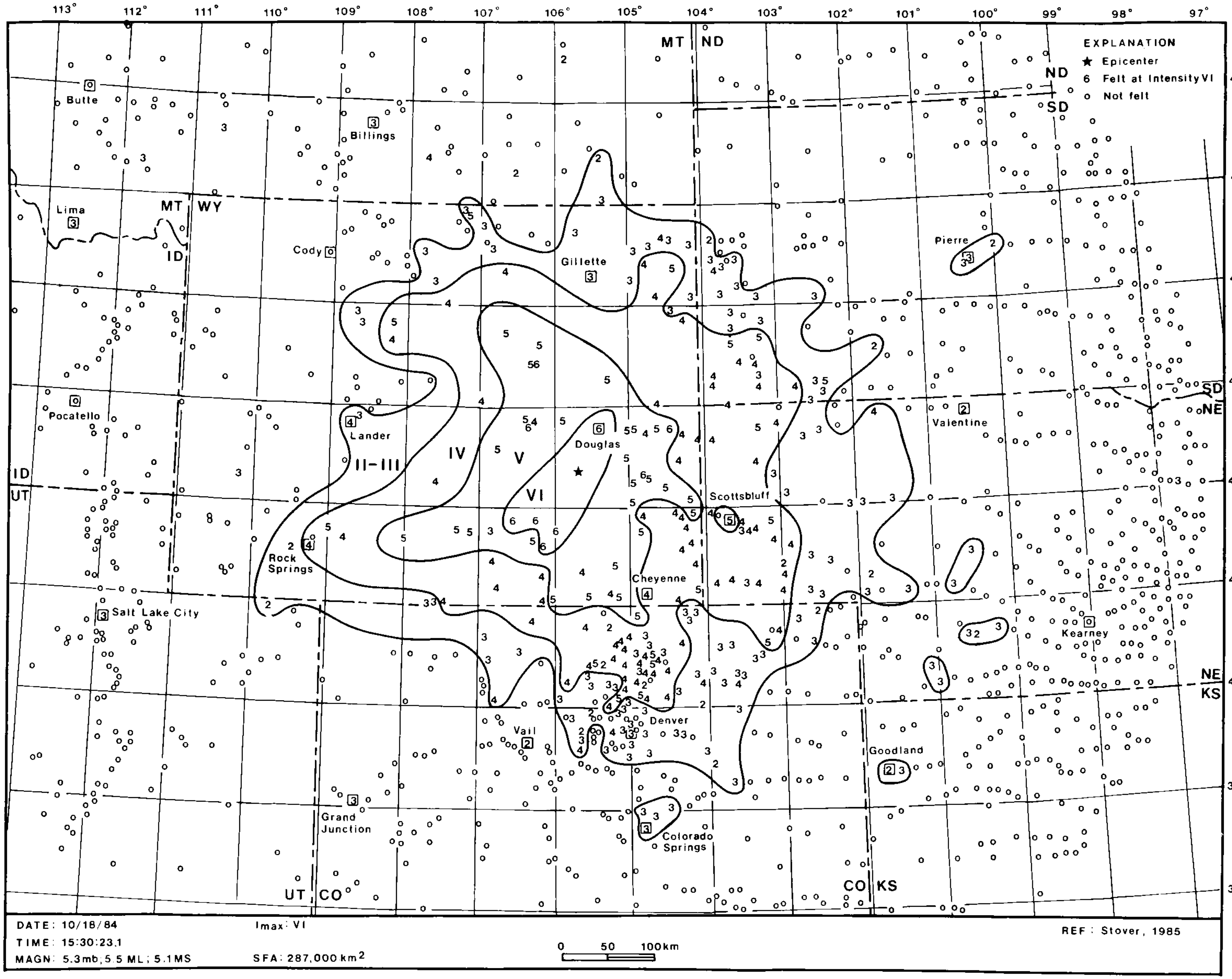

Figure 2. Isoseismal map for the 1984 Laramie Mountains, Wyoming earthquake.

graben. A bison skull and a charcoal-filled fire pit were discovered in unfaulted alluvial deposits in Ryan Gulch approximately 2.7 m below the land surface along the trend of the fault. The charcoal yielded a carbon-14 date of 1,230 ± 60 years before present, as determined by the U.S. Geological Survey. In that the alluvial deposits are not displaced by the Dudley Gulch graben, it is certain that surface rupture did not occur on this part of the graben on November 7, 1882. Furthermore, the Dudley Gulch graben was thoroughly studied by Eckert (1982), who found no evidence of historic or recent movement of the graben. These elements make it very unlikely that the Dudley Gulch graben was the causative structure for the 1882 earthquake.

The authors have not yet identified the causative structure for the November 7, 1882 earthquake. In that the earthquake may have been fairly deep, it is possible that no surface displacement occurred during the earthquake, in which case it will be very difficult or impossible to precisely define the causative structure. It is perhaps significant that the causative structure for the 1984 Laramie Mountains earthquake has not yet been located, even though a concerted effort was made by USGS personnel (G. L. Snyder, pers. comm., 1986).

CONCLUSIONS

The November 7, 1882 earthquake was felt over 470,000 km^2 in Colorado, Wyoming, and Utah, at a single known locality in Kansas, and possibly at one location in Nebraska. It is probably the largest earthquake to affect Colorado during the 118-year period of record. A maximum MMI rating of VII has been assigned to this event based on known felt reports. Earthquake magnitude is estimated at 6.2 ± 0.3 ML. An area somewhere in north-central Colorado or southeast Wyoming, perhaps in the northern Front Range or southern Laramie Range, is hypothesized as the probable epicentral location, based primarily on the concentration of higher intensities of the main quake and the distribution of felt reports for the aftershock. It is probable that the earthquake occurred at a depth greater than most Rocky Mountain events, possibly at a depth of 20 to 25 km, and that no or only very minor surface faulting may have resulted. The causative fault or source of the 1882 earthquake has not yet been determined, but will be the topic of continuing interest and future investigation by the Colorado Geological Survey and others.

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Stover, C.W., 1985, Preliminary isoseismal map and intensity distribution for the Laramie Mountains, Wyoming, earthquake of October 18, 1984: U.S. Geological Survey, Open-File Report 85-137, 9 p.

APPENDIX A

SELECTED REPORTS OF THE NOVEMBER 7, 1882 EARTHQUAKE

Only those reports that are herein published for the first time or those for which our intensity assignments differ from previously published assignments are listed. Please refer to Hadsell (1968), Dames & Moore (1981), Oaks and Kirkham (1986), and McGuire and others (1982) for descriptions of all other reports.

Boulder, Colorado
BOULDER COUNTY HERALD
November 8, 1882
Vol. 3, No. 222

Erratic Earthquake--Two Distinct Shocks Felt in Boulder.

Mother earth seemed to rejoice last evening at the grand political revolution and for joy shook with laughter. At about 6:30 o'clock, when but a few votes were left uncast, the gods knew what the results would be and communicated the news to earth when the earthquake shock took place. A large number of Boulderites felt it. The waves seemed to go from east to west. Houses swayed and rocked, dishes rattled, and many people were startled. No damage, as far as is heard from, was done near Boulder except at the University where a large quantity of plastering in the third story was thrown to the floor. Another shock was felt this morning at about five o'clock. The shock last night was felt in Denver, Golden and Longmont.

Boulder, Colorado
UNIVERSITY PORTFOLIO
December, 1882
Vol. 4, No. 2

We rise to make a correction. There is still some plastering on the ceiling of the University. Now earthquakes do not occur very often in this region, and we believe in making the most of such rare phenomena, but when people begin tumbling plastering about our ears, we object.

The fact is that the building was shaken considerably, and some bits of plastering fell in the third story. This was telephoned downtown and from there to Denver, appearing in the papers next morning. From these the story growing at every step, was copied throughout the State until at last we read the ceilings at the University were stripped of plaster! In Boulder, two or three weeks after the earthquake, we heard the statement that only about forty yards had fallen.

It is any wonder that the rising generation is inclined to be skeptical? Why, people have formed such a habit of exaggeration-to put it mildly-that they cannot trust themselves. In repeating a story they cannot tell whether they draw it mostly from fact, memory or imagination.

Denver, Colorado
THE DENVER TRIBUNE
November 8, 1882
Vol. XVI, No. 312

DAMAGING EFFECTS OF THE EARTHQUAKE

The earthquake Tuesday evening not only created a sensation but did some damage. It was observed by a few pedestrians who were not particularly interested in the election returns that the electric lights were suddenly extinguished at half past 6. Among the observers was Superintendent Runkle. He went immediately to the electric light building at the foot of Twenty-first street and found that an accident had occurred to the machinery. From the driving pulley of engine there is a connection of shafting five inches in diameter and divided into sections of 12 feet. These sections are connected by large iron bolt screws nearly an inch in diameter. At the instant of the earthquake shock one of those bolts was snapped in twain and the other bent out of shape. The whole machinery was thrown out of gear, and it became necessary to stop the machinery at once. Mr. Runkle is of the opinion that the upheaval which caused the earthquake ran east and west and centered about his establishment and the residency of Mr. Birke Cornforth. It was ascertained yesterday that the shock was so severe in the northern portion of the city that many families ran from their houses.

Fort Collins, Colorado
War Department, U.S. Signal Service
VOLUNTARY OBSERVER'S METEOROLOGICAL RECORD (described in Oaks and Kirkham, 1986)
November, 1882

-CASUAL PHENOMENON-

7th earthquake 6:28 p.m.[sic]
Lasting only a few seconds.
Was felt all over town.
Shook books from wall shelves in our house.

Observer-Agricultural College

Grand Junction, Colorado
HISTORY OF MESA COUNTY, by C.W. Haskell (1886)

The election passed off quietly, with a majority in favor of the local Republican ticket. It was on this day of election that a perceptible earthquake shock was felt through the valley, and, indeed, through the entire State. A party camped on Douglas Creek, stated that they saw huge rocks tumble down the mountain side during this shock, and afterwards saw large volumes of smoke, with a sulphurious smell, emerge from crevices newly opened in the ground.

Grand Junction, Colorado
THE SUNDAY MAGAZINE OF THE DAILY SENTINEL, Grand Junction
July 11, 1976
(same information in Oaks and Kirkham (1986) based on an interview with Al Looks).

A "perceptible" earthquake shock was felt through the valley on the first general election day. The 1882 shock dumped large rocks down canyon walls and was said to be felt as far distant as Denver. Highway I-70 [now] cuts across the bottom of an escarpment made by this quake in DeBeque Canyon. It was called Hogback Canon in 1882. Minor quakes have been felt on a few occasions since.

Grand Junction, Colorado
GRAND JUNCTION NEWS
November 11, 1882
Vol. 1, No. 3

On Tuesday night, about seven o'clock, our people were frightened by the shock of an earthquake, those who were in their houses experienced the shock the most, the buildings moved and quaked as if they were being torn down, and things that were hanging up any where, were put in motion at a lively rate.

Grand Junction, Colorado
GRAND JUNCTION NEWS
November 18, 1882
Vol. 1, No. 4

THE EARTHQUAKE

No one in Grand Junction who felt the shock of the earthquake on Tuesday night, the 7th of this month, would have thought that the crater or opening that was made in the earth, was as near to us as fifty miles, but it is a fact, as the following account will show. Mr. J.W. Yard, one of the men who saw the crater, immediately after the shock, gives us the following:

"You see there were three of us in the party, Allen Rice, Thomas Charleston and myself, on our way from the Ouray Indian agency, going to Leadville; we had gone along the range of what is called Crest of Roan, or Book Plateau mountains, until we got to the head of Vaccination creek, or the North Fork of Douglass creek. It was getting late and feeling tired, we began to look around for a camping ground. We found a suitable place in a small gulch, and turned our horses loose, made a fire and got our supper. It was about 7 o'clock, and we were all sitting around the fire, talking and smoking. We had noticed a very strong smell of sulphur when we entered the gulch-just as if it was being burned-and could not account for it.

All of a sudden the earth began to shake and roll. I looked over to Tom and said: "What's the matter?" At the same time I started to get on my feet, but could not stand.

Tom called to me and said: "Let's go on top of the hill."

"This is the best place for us!" I said. "We might as well die here as anywhere."

In the mean time, great rocks, came rolling down the mountain side, and trees were broken off by the shock.

The feelings that came over us while the earth was trembling and pulling was like that of sea-sickness.

After the shock had subsided I ran on the mountain, and there, about a mile and a half to the north, gaping wide open, was an immense crater or chasm, from which great volumes of smoke came pouring forth. I immediately called Tom and Al to witness it, and we resolved to go over and look at it more throughly in the morning.

Next morning it was snowing, and our horses having ran away during the night, in our search for them we got lost, and wandered nearly four days, before we found our way out.

This is not a 'trumped up' story but a fact, and anyone who will take the trouble to ride over there, will see the crater, just as we saw it."

LaPorte, Colorado
DAILY EVENING COURIER(Fort Collins)
November 10, 1882
Vol. 1, No. 142

OUR LAPORTE LETTER

Last Tuesday evening, about six o'clock, Mr. Jacob Flowers felt the shock of an earthquake, which shook his house until the timbers cracked. LOCAL.

Rangely, Colorado
FROM THE DIARY OF CHARLES PORTER HILL (reprinted in local history by the Meeker History Book Committee of the Rio Blanco Historical Society, 1978, This is What I Remember, Rio Blanco Historical Society, Meeker, CO; also described in Eckert, 1982 and Oaks and Kirkham, 1986; location thought to be a few kilometers east of Rangely along the White River.)
November 7, 1882

They finally made it to the river and it took them three days to get from Wolf Creek to the place they wanted to stop. When they got there, it was late in the day, so they made camp and heard the roaring and thundering of some great noise. The ground shook and the trees bent. They said it was an earth tremor. This was November 7, 1882. Next day the three men started to build a cabin.

Steamboat Springs, Colorado
<u>FROM THE DIARY OF PERRY A. BURGESS</u> (Buddy Werner Memorial Library, Local History Collection, Steamboat Springs, CO; also described in Oaks and Kirkham, 1986)
November 7, 1882

Am sick nearly all day. Went to election in afternoon. At 7 p.m. we had a distinct shock of an earthquake which lasted several seconds.

Thompson, Colorado
<u>DAILY EVENING COURIER</u> (Fort Collins)
November 24, 1882
Vol. 1, No. 154

THOMPSON TALK from the REPORTER

We learn from Theo. Chubbuck that the walls of his residence on the farm were badly cracked, and in several places the plastering was entirely stripped from the walls by the late earthquake shock. This is the only instance where any damage was sustained through that cause in this section of country, so far as heard from.

Logan, Utah
<u>OGDEN DAILY HERALD</u>
November 9, 1882
Vol. 11, No. 163
Page 3, Column 4

CACHE COIN - A Distinct shock of earthquake was felt here and at Wellsville, about 6 o'clock, last evening. It appeared to be much more severe at the latter place than the former, as it is reported that people were so badly frightened as to run from their houses into the street.

Peter Spike, Logan, Nov. 8th.

Salt Lake City, Utah
<u>THE DESERET EVENING NEWS</u>
November 11, 1882
Vol. XV, No. 300

<u>The Earthquake In Cache</u>--The late earthquake shock was quite strong through Cache Valley. The JOURNAL (Logan) says, about its effects in that town:

"The earthquake shock of last Tuesday evening was felt by a number of citizens. It occurred at a few minutes past six o'clock, and frightened several persons. One lady was seated at a table writing, but for some seconds was compelled to pause; another lady living on Third Street not far from Z.C.M.I. was playing the organ, when the instrument was so violently shaken that she thought some one was behind it. The chandeliers in the upper story of

Cardon and Thatcher's building swung at least a foot from their normal position by the rocking of the building. In another case an aged lady was quite frightened by the tremor."

Fort Laramie, Wyoming
<u>U.S. ARMY, RECORDS OF MEDICAL HISTORY OF POST</u> (described in Oaks and Kirkham, 1986)
November, 1882

Earthquake--a slight shock of earthquake felt November 7th 6:30 p.m. lasting about a minute shaking lamps and loose articles and rocking buildings without doing any damage. The shock was reported from numerous points in the territory and further south and east by H.V. Paulding, Asst. Surgeon, Post Surgeon.

Fort Washakie, Wyoming
<u>FORT WASHAKIE METEOROLOGICAL REGISTER</u> (described in Oaks and Kirkham, 1986)
November 7, 1882

Light earthquake at 6:12 p.m. lasted about 1/2 a minute
Wm. H. Arthur (?)
Asst. Army Surgeon

Fort Washakie, Wyoming
<u>ABSTRACTS OF DAILY JOURNALS</u> (described in Oaks and Kirkham, 1986)
November 7, 1882

Three distinct shocks of an earthquake were experienced at 6:12 p.m. Each shock hardly continued more than two or three seconds and the entire noise ceased almost as soon as it began. The motion seemed to pass from West to East. The lamps and other small articles vibrated from west to east. No damage was done though the walls of nearly every building in the Post were more or less disturbed. No aurora. Observer- A.M. [or F.M.?] Ambler.

Salina, Kansas
War Department, U.S. Signal Service (described in Oaks and Kirkham, 1986)
<u>VOLUNTARY OBSERVERS METEOROLOGICAL RECORD</u>
November, 1882

- CASUAL PHENOMENA-

7TH. Earthquake 6:55 p.m. SE to NW waves 3-time not to exceed 6 seconds. Same feeling noted by 6 persons - in second story of Brick [sic] building... , perceptible rolling motion to a long table at which was seated Board of Election - swing Chandelier same as if started by same person. Observer - Ino. H. Gibson.

Plattsmouth, Nebraska
<u>THE OMAHA BEE</u> (Omaha)
November 11, 1882
Twelfth Year, No. 125

<u>State Jottings</u>

Plattsmouth felt an earthquake shock on Tuesday morning.

Plattsmouth, Nebraska
<u>PLATTSMOUTH WEEKLY HERALD</u>
November 16, 1882
Volume XVIII

WE FELT IT

Plattsmouth felt an earthquake shock on Tuesday morning - OMAHA BEE.

Plattsmouth felt it much more perceptibly, however, Tuesday night when the election returns began to roll in on us.

THE CONIFER, COLORADO EARTHQUAKE OF NOVEMBER 2, 1981

David Butler and John J. Nicholl, Jr.
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10900 West 44th Avenue
Wheat Ridge, CO 80033

ABSTRACT

The Conifer earthquake of November 2, 1981, provides a guide for seismicity estimation along the Front Range of Colorado. New and additional data indicate that the Conifer epicenter should be moved north and east of the preliminary location at 39.519°N, 105.299°W, and that an uncertainty of 10 km in plan should accompany any location given. Intensity measurements indicate a felt area of about 1000 km^2. Focal mechanism results from microearthquake data recorded several years before and after the event define a microseismic zone striking N20°W with a steep NE dip in an area between the Kennedy Gulch fault and Floyd Hill fault. The zone is one of three possible loci for the Conifer event. A preliminary maximum credible event (MCE) of magnitude 5.5 with a return time of more than 35,000 years is extrapolated from this data.

INTRODUCTION

At 0303 UCT on November 2, 1981 (8:03 pm, November 1, Mountain Standard Time) a small earthquake (M_L=2.8, USGS) was felt near Conifer, Colorado. This earthquake occurred in an area of high population growth within the greater Denver metropolitan area and near potential sites of critical energy and water-storage facilities. Though not a significant event itself, this earthquake merits study as a guide for seismicity estimates along the Front Range of Colorado. This paper summarizes the instrumental and intensity information provided by the earthquake and contains a preliminary interpretation of those data.

Additional data on the main shock have been obtained which supplement the arrival times used for the previous locations. In addition to the earthquake and aftershock data, twelve months of seismic investigations from a nearby microearthquake network are available for periods both before and after the main event. Unfortunately, the network was not operating during the main shock. More than 200 intensity reports from the event are also analyzed.

The seismological data are sufficient to generate a preliminary return time and maximum credible earthquake for the Conifer area. The following sections summarize the instrumental data from the main shock and aftershock sequence, the intensity information, and the pre- and post-earthquake monitoring. A discussion section then provides an interpretation of these data.

ACKNOWLEDGMENTS

The intensity data and PDE were obtained from John Minsch and Carl Stover of the Golden, Colorado office of NEIS. Additional data is courtesy of Dr. Don Steeples, Kansas State Geological Survey; Dr. Ken Olsen and Joyce Wolf, Los Alamos Scientific Lab. Opinions and extrapolations contained herein remain the sole responsibility of the authors.

EARTHQUAKE AND AFTERSHOCK DATA

Table 1 summarizes the National Earthquake Information Service (NEIS) data on the events in this area during late 1981.

Table 1. **Conifer earthquake events.**

Date (UCT)	Time (UCT)	Latitude (PDE)	Longitude (PDE)	Magnitude	S-P Time
Nov. 2, 1981	03h03m0.2s	39.519° N	105.299° W	2.8	(clipped)
Nov. 2, 1981	03h21m	---------	----------	---	2.00sec
Nov. 2, 1981	04h22m	---------	----------	---	1.95sec
Nov. 2, 1981	07h13m	---------	----------	---	2.05sec
Dec. 9, 1981	02h45m	---------	----------	---	2.10sec

The column labeled S-P Time was recorded at the 3 component station labeled M3C on Figure 1. Using an S-P velocity of 7.0 km/sec for the near surface crust (if Poisson's ratio = 0.25, S-P velocity = 7.9 km/sec) shallow aftershocks would fall near the arcs shown on Figure 1. The NEIS epicenter of the main shock is also indicated. Note that the locus of the aftershocks is consistent with the main shock epicenter.

The main shock was assigned a magnitude of 2.8 M_L and a depth of 1.0 km (arbitrary). The depth assignment is reasonable based on reports of audible noise (see intensity section below). No magnitudes were assigned to the aftershocks.

Figure 1 includes for reference several fault zones which have been observed in the Conifer area. The traces given are interpreted from Bryant and others (1973), Peterson (1964), and Kirkham and Rogers (1981). Kirkham and Rogers transfer the "potentially active" trace of the Floyd Hill fault to the Ken Caryl fault at the point where the Floyd Hill fault crosses US-285. The North Mill Gulch fault (Harza, 1985), first described by Peterson (1964), is shown because of its juxtaposition with the microearthquake results given below.

MAIN SHOCK RELOCATION

Table 2 contains information about the solution taken from the PDE listing of NEIS. Note the large errors at regional stations (not used in the solution) and that many of the stations are more than 300 km from the epicenter.

Table 2. **Summary of NEIS data.**

STATION*	LATITUDE	LONGITUDE	DISTANCE IN KM	TIME MIN-SEC	RESIDUAL OF FIT
GLD	39 45.04	105 13.28	26.6	03 05.00	0.0
GOL	39 42.02	105 22.20	21.1	03 03.60	-0.4
DEN	39 47.50	105 01.99	32.8	03 07.00	0.0
MSA	36 51.55	106 01.07	300.2	03 46.20	0.0
BDW	42 46.57	109 34.10	508.8	04 13.00	0.6
ALQ	34 56.71	106 27.45	517.8	04 26.50	12.9x
RMU	37 04.56	110 58.20	564.4	04 19.30	-0.2
TUL	35 38.00	095 47.55	927.8	05 00.00	-5.3x

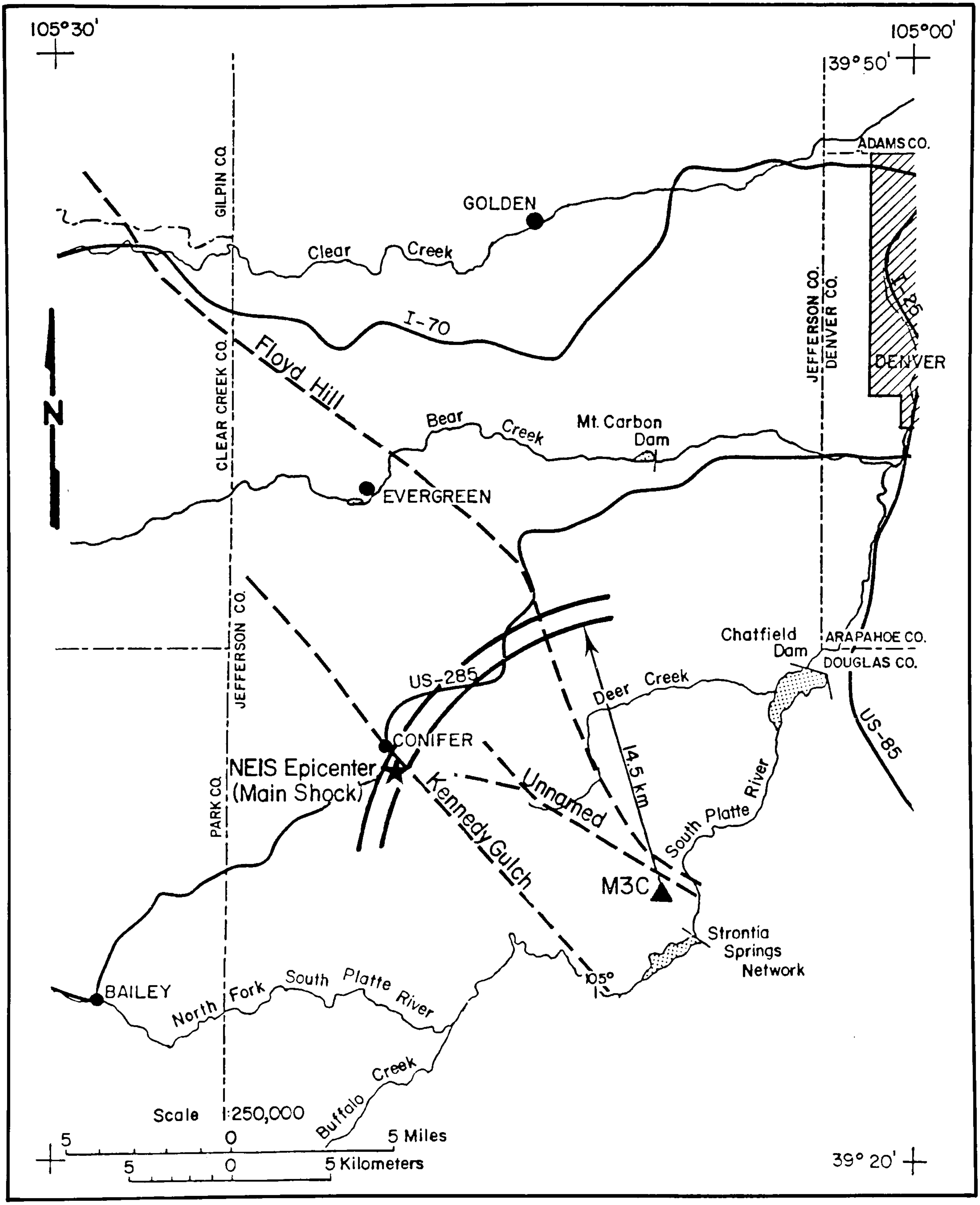

Figure 1. Map showing location of fault zones in the Conifer area.

*Golden, Colorado; Bergen Park, Colorado; Denver, Colorado; Mount San Antonio, New Mexico; Boulder, Wyoming; Albuquerque, New Mexico; Rainbow Monument, Utah; Tulsa, Oklahoma.
x - not used in fit

The PDE report lists +/-1.7 km N-S and +/-2.6 km E-W as uncertainties for this solution. However, most seismologists would doubt such optimism, even though the azimuthal coverage is reasonable. The location is calculated with a standard velocity model based on the Jeffery-Bullen travel-time curves incorporated in the "quick-look" program used at NEIS. The Jeffery-Bullen curves imply a general crustal model which is very adequate worldwide at distances from several hundred to several thousand kilometers. The velocity model for the Front Range developed over several years of observation is more accurate at distances of 10 to 100 km (MicroGeophysics, 1983).

To ascertain if the PDE location and the small uncertainties given by NEIS are reasonable, a new solution was attempted incorporating additional data. Data from the 3-component station shown on Figure 1 and other regional stations were used, some of which were not available to NEIS in 1981. These data are shown in Table 3. Note that significantly more data is available than was used in the original hypocentral determination.

Table 3. Additional seismic data.

STATION*	LATITUDE (North)	LONGITUDE (West)	DISTANCE IN KM	P-TIME (MIN-SEC)	S-TIME (MIN-SEC)
NNKA	39 53.13	100 02.22	451.10	04 02.80	--------
TCK	39 23.09	96 43.35	737.77	04 40.55	--------
SPD	35 45.47	106 22.16	427.80	04 12.60	05 22.00
TTP	35 36.56	106 12.38	441.10	04 17.80	05 06.90
JOAQ	35 46.25	106 22.16	427.80	04 11.40	05 01.80
CZL	36 17.00	105 54.62	363.30	04 00.00	04 42.30
DMPK	36 25.58	106 46.54	336.70	04 00.30	04 44.30
M3C	39 27.24	105 08.46	15.60	03 03.20	--------

*These stations, except for M3C, are in western Kansas and northern New Mexico and are not necessarily near a city or town.

A crustal velocity model similar to that used by NEIS but including a high velocity near-surface layer of 5.1 km/sec was used for relocation. The model combined the general features of the NEIS velocity model along with the detailed results provided by MicroGeophysics (1978). The close-in stations were weighted about twice as heavily as the regional stations. The most probable epicenter is at 39° 33.0N, 105° 17.0W, or about 4 km north and 2 km east of the published location. In addition, rather than the near surface location published, a depth of 4 to 5 km is indicated. The uncertainty is about 10 km in plan and 5 km in depth. In other words, hypocenters within 10 km in plan and 4 km in depth of this solutiion will not have significantly greater time residuals than this solution.

INTENSITY DATA

Over 200 intensity reports for the main event were kindly supplied to the authors by NEIS. One hundred and fifty-eight reports were complete enough for the NEIS scientists to assign an intensity at a particular address. The intensities varied on the Modified Mercalli Scale from I (not felt) to V (sleepers awakened, small unstable objects displaced). After location of the individual reports, the data were gridded by computer to resolve the normal variations typical of intensity reports.

A common problem with intensity data is the tendency to reflect population density. In areas of high population, the inevitable "sensitives" bias the data to a higher intensity value. The bias effect is present in these data though reliable values were fairly uniformly distributed. The contoured intensity data (Figure 2) are consistent with the epicentral locations given above. Two reports judged to be intensity V are shown as point values. Areas of intensity IV typically coincide with the river drainages (Bear Creek, etc.) indicating either ground-motion amplification and/or bias. Bias is thought the less likely explanation for almost as many houses within the area are located on ridgetops as in river valleys. Several reliable reports by professional seismologists on the fringes of the felt area suggest that the estimate of 1000 km^2 in total felt area is a reliable estimate.

One interesting fact about this earthquake was the associated audible noise. Some of the respondents who were out-of-doors at the time of the event reported rumbling or thundering sounds.

The Denver Post (Nov. 2, 1981) also quoted a government scientist as stating, "The quake was very unusual because it never happened there before (sic)." Other local investigators (Waverly Person, M.W. Major, personal communication) have confirmed that this event was a unique occurrence in their experience.

MONITORING NEAR STRONTIA SPRINGS RESERVOIR

A program of seismic monitoring at the Strontia Springs Reservoir and Dam Site (SSR) was conducted between 1977 and 1983. This program consisted of two months of reconnaissance monitoring, six months of baseline studies, 50 months of single-station monitoring, and a final six months of monitoring during the filling period (MicroGeophysics, 1977, 1978, 1983; Butler and others, 1983). Data collected through February of 1983 are considered in this paper. The Conifer earthquake occurred during the 50 months of single-station monitoring.

During the 375 days of network monitoring, 22 events in or near the epicentral zone were located (see Figure 3). These were extremely small events varying magnitude from -0.4 to +1.9. The 22 events define a microseismic zone located near the North Mill Gulch fault zone of Figure 1. This zone can be directly differentiated from the Floyd Hill and the Kennedy Gulch fault zones, and from the other areas monitored by this network. In other words, this zone is anomalous in exhibiting more activity than other areas similarly monitored. Two important qualifications concern the detection and location of these events. One is cultural contamination and the other location accuracy.

Despite an intensive program of blast verification, the numerous quarries and mines in the Front Range contaminate the seismic record with industrial blasts. A Colorado Highway Department quarry on US-285 shoots periodically, but could not be verified as the source of these events. Even though known blasts were eliminated, the majority of the located events are suspected to be quarry shots because they occurred during working hours. Inadvertent inclusion of blasts in the record would cause the seismicity to be overestimated in this study.

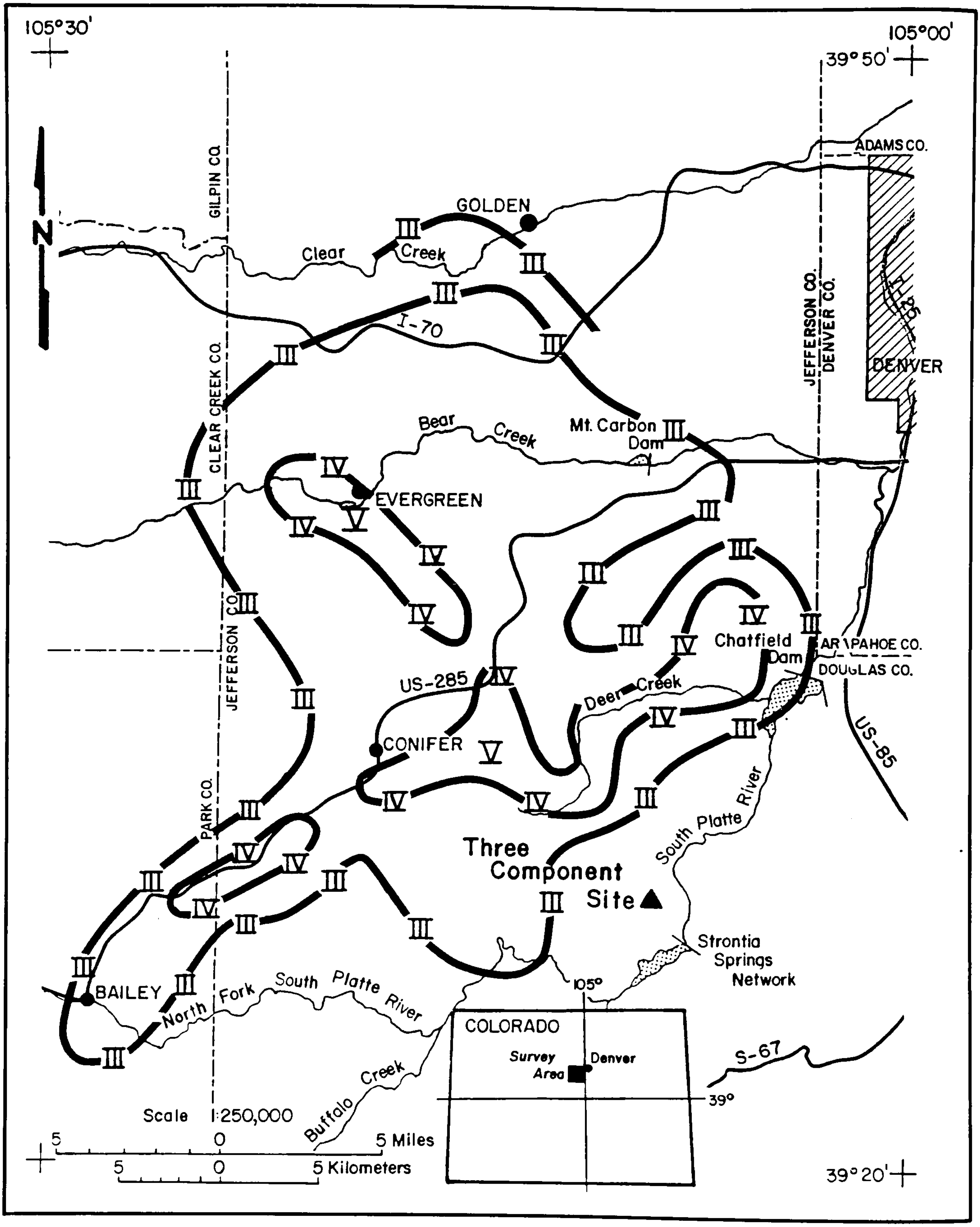

Figure 2. Intensity data of the November 2, 1981 Conifer earthquake.

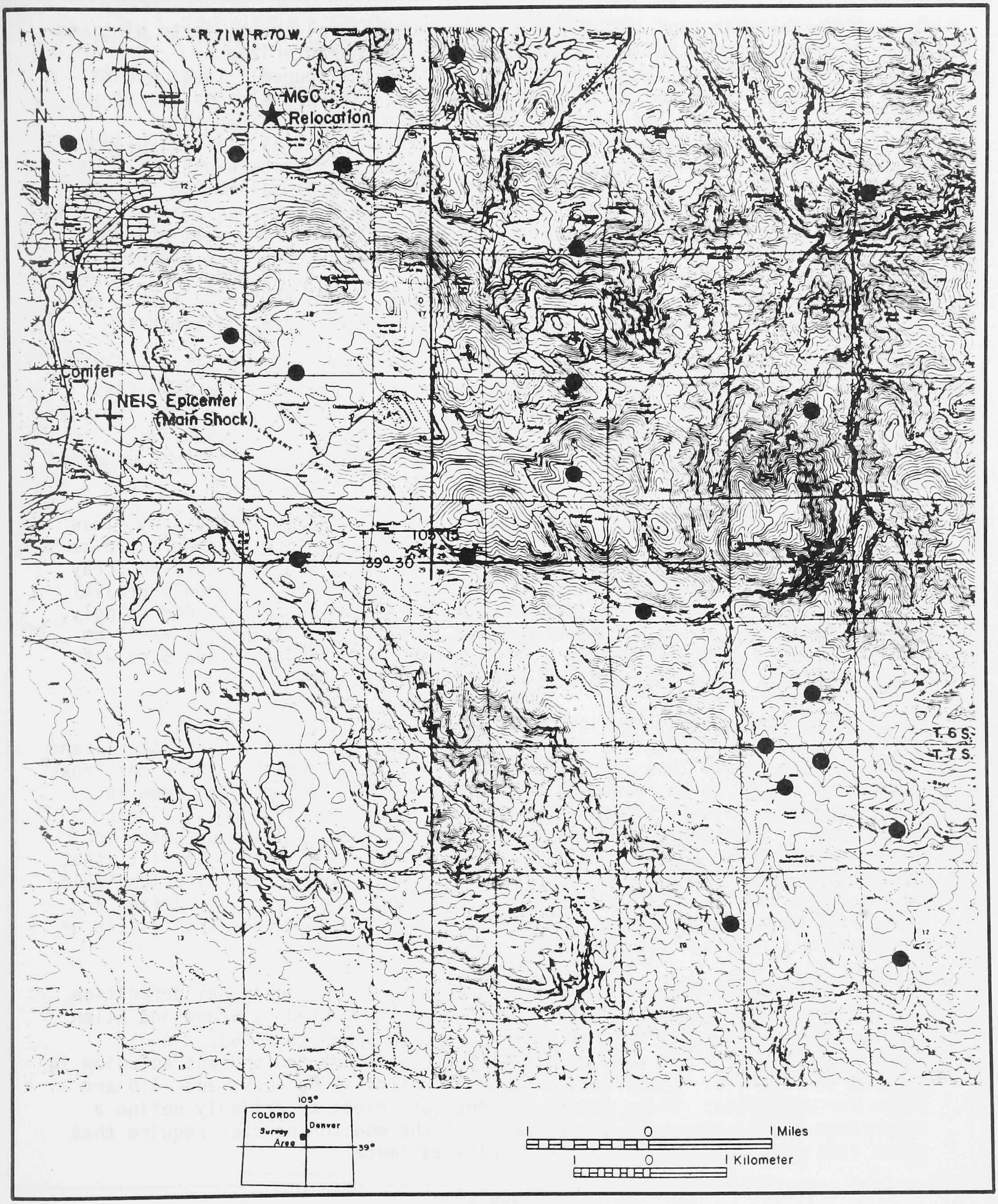

Figure 3. Map showing location of events in or near the epicentral zone of the November 2, 1981 Conifer earthquake.

One additional method of separating blasts from natural events is to plot and compare fault-plane solutions. Blast events are characterized by compressional first motion in any direction from the source. Thus, events with compressional motion in more than two focal-sphere quadrants are very likely blasts. Several of the located shallow events exhibited this multi-quadrant compressional motion and were interpreted as blasts. Using all of the above techniques, many events that located at shallow depths (0-2 km), that occurred along US-285, and that displayed compressional motion in three or four focal-sphere quadrants were eliminated from further analysis. A good composite fault-plane solution (shown in the upper hemisphere plot of Figure 5) is obtained for a preferred fault plane striking N20°W with a steep NE dip. Strike-slip motion with a slight reverse component is observed. A weak NW-SE epicentral trend is noted in the locations. Nine of the 22 events are consistent with the composite fault-plane solution and shown in Figure 4.

All available data were used to ascertain if the Conifer event had a similar focal mechanism. Only seven stations (out of seventeen) had pickable first motions for the Conifer event. This lack of data is primarily due to the size of the event coupled with source-receiver distances. Of the seven first motions picked, five had upper hemisphere plots consistent with the composite solution of Figure 5.

In addressing location accuracy, the detecting array near SSR was very close to the reservoir as shown on Figure 1 and the events in question were two to three apertures away from the center of the network. However, such an array usually produces a good azimuth for events (+/-5°). A fairly good S-arrival on the records provides an acceptable estimate of the distance. Accordingly, the locations have a +/- 1.5 km transverse location uncertainty, a +/- 3 km radial (to SSR) uncertainty, and a depth uncertainty between 0 and 5 km with some functional dependence between these parameters.

Correlating these event locations with surface geologic features is difficult. Other discussions of monitoring along the Front Range (Nicholl and Butler, 1985) report "the low microseismic activity rates throughout the Front Range area appear to be relatively uniform. Hypocenter locations seem to occur randomly, with little or no relation to observed and known geologic structures." With this in mind, contributing these events to one specific surface feature is dubious. Considering all these data, the probability that the Conifer event and microearthquakes are located on the Kennedy Gulch fault or the Floyd Hill fault is extremely low. Rather, the events may define a subsurface zone of fracturing midway between the two features, with little or no relation to the surface geology.

Magnitudes were assigned to these events using Richter's original definition (Richter, 1958) of magnitude with modifications suggested by Brune and Allen (1967). The exact equations are given in MicroGeophysics (1983). A recurrence curve for the nine events with a consistent fault plane solution is plotted in Figure 6. Lines with b-slope values of -0.8, -0.9, and -1.0 are shown for reference. These events are not sufficient to reliably define a recurrence curve. However, the duration of the monitoring does require that these data be considered in any seismicity estimate.

Discussion

A preliminary seismicity estimate of any area often includes a determination of the return time and the magnitude of a maximum credible earthquake. Each

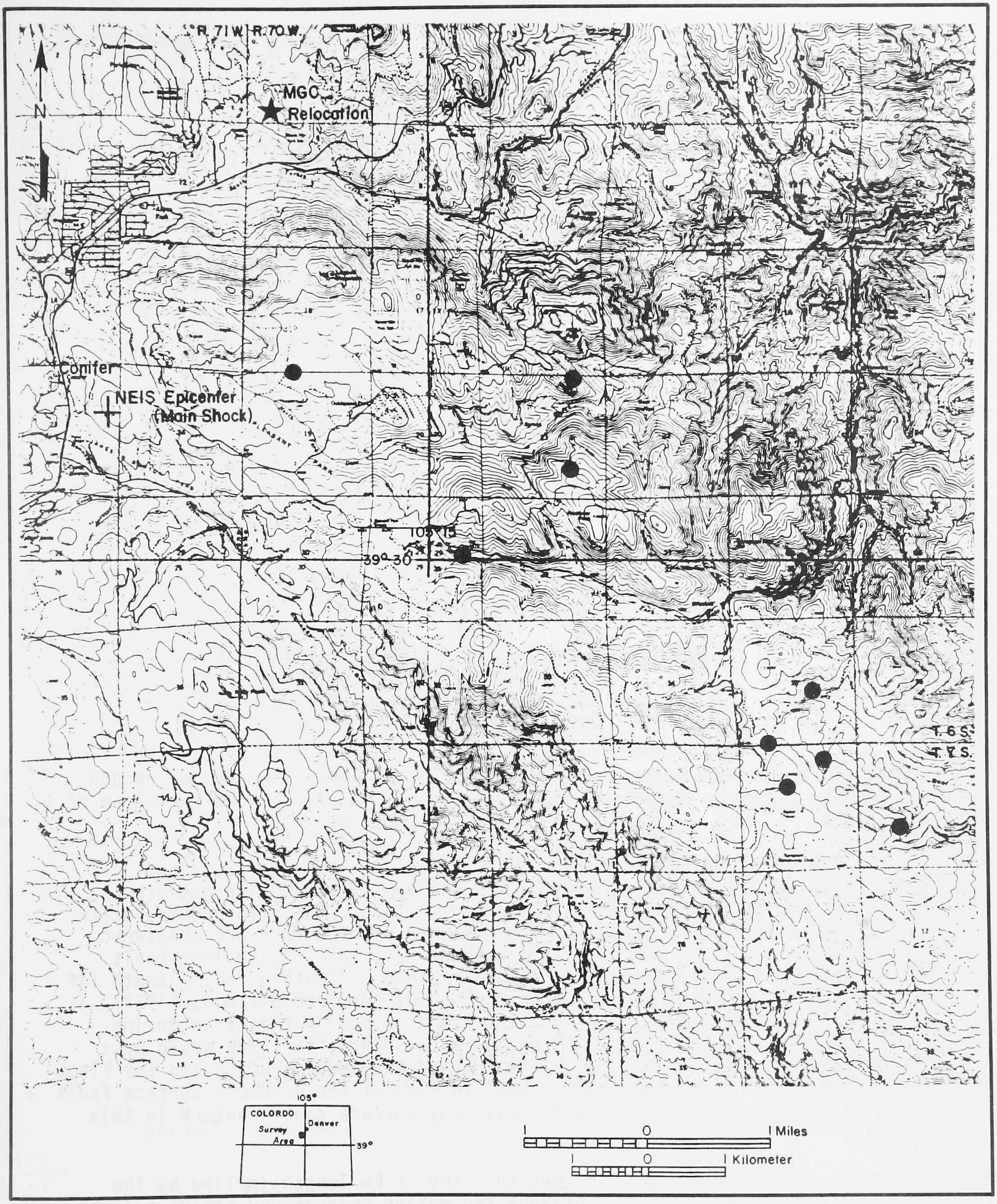

Figure 4. Map showing location of events consistent with the composite fault-plane solution.

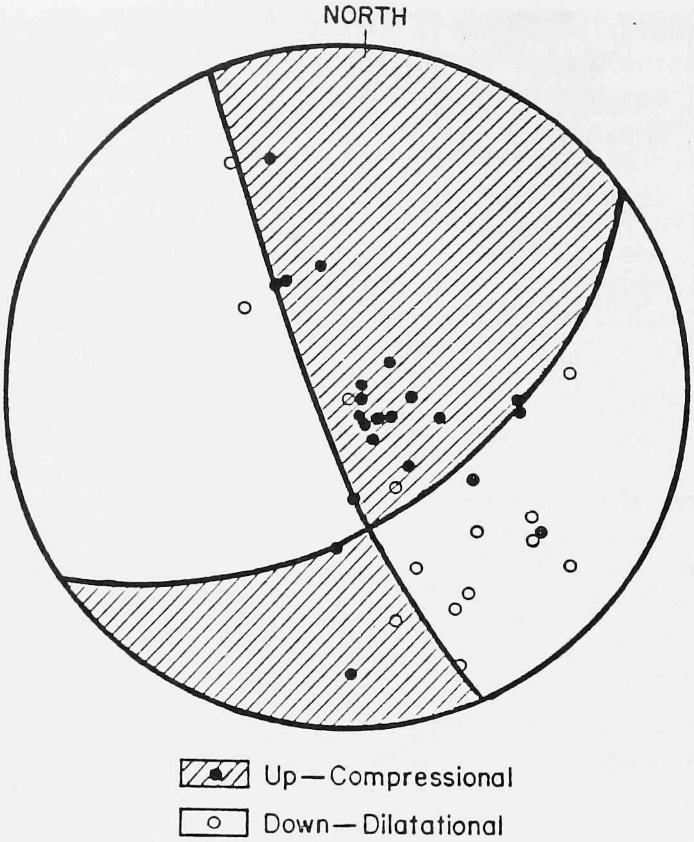

Figure 5. Upper hemisphere plot of the composite fault-plane solution for the November 2, 1981 Conifer earthquake.

of the estimates made below are based primarily on the seismological record with little geologic input; geological considerations are beyond the scope of this paper.

For the MCE estimate, the data include locations of the main event and aftershocks and the locations of the nine events located during network monitoring having a consistent fault plane solution. The aftershocks locate within two kilometers of the main event and the other events are scattered along a 12 km zone. If one takes a conservative view, a 12 km long fault trace might be inferred from these data. The MCE for such a fault length (if it ruptured the surface) determined by using methods from Slemmons (1977), is a magnitude 6.0. However, no such event has occurred in this area during historical time. Based on the seismological evidence, this MCE would most likely occur in an area located midway between the Kennedy Gulch and the Floyd Hill fault zone. A careful ground check in 1983 of the probable surface fault trace of the Conifer event did not locate any surface fault rupture in this area.

A less conservative approach assumes that the 12 km length implied by the foreshock and aftershock data outlines the entire underground active seismic volume. Rather than the surface rupture versus fault length curves of Slemmons, it is appropriate to use the functional relationship between total fault lengths and magnitudes determined by Wyss and Brune (1968). Faults with

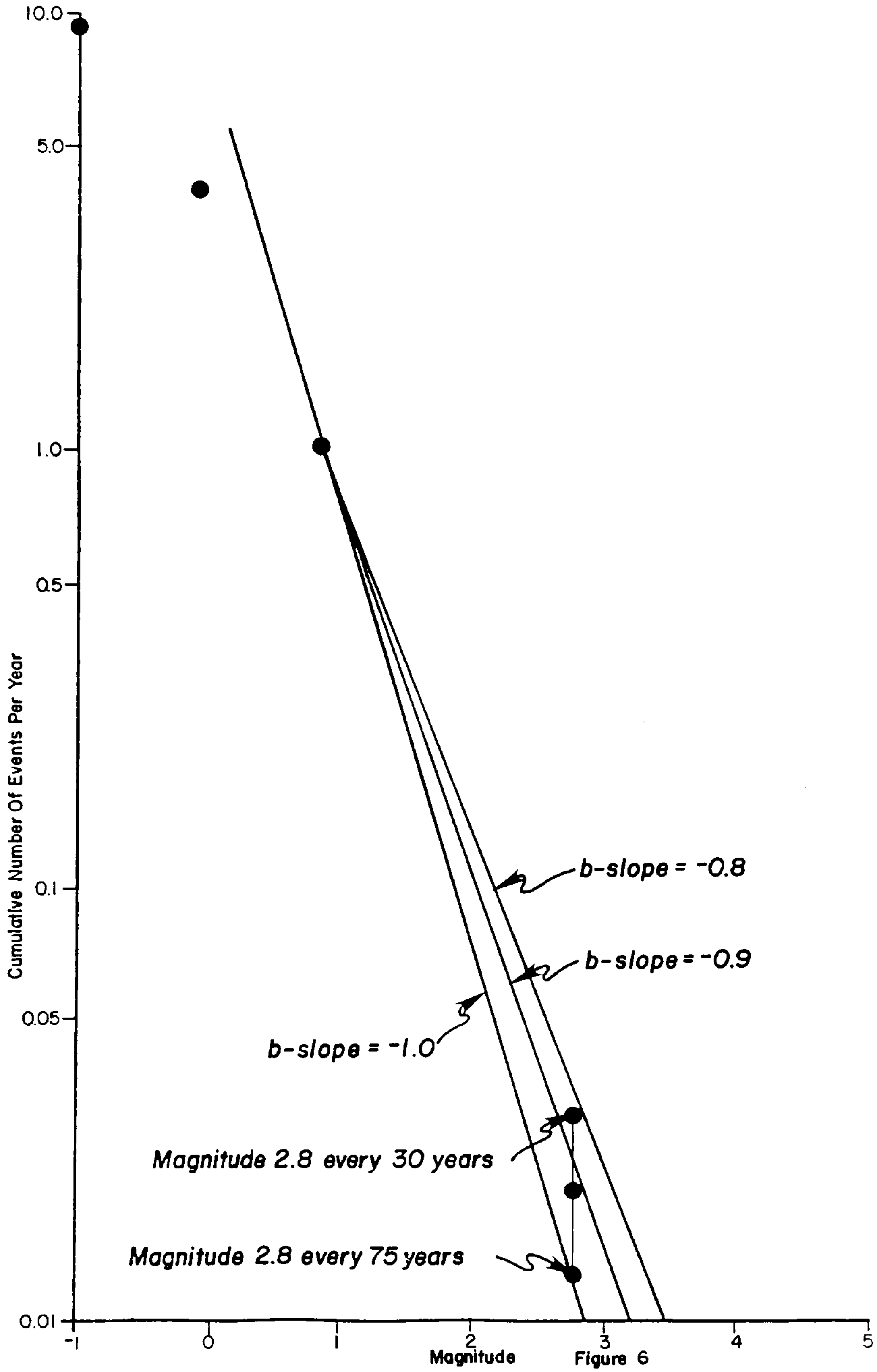

Figure 6. Recurrence curve for the November 2, 1981 Conifer earthquake.

active lengths of 12 km are associated with earthquakes of magnitude 4.25 (+/- 0.25) with this approach.

In summary, the two equally plausible methods give different answers. Rather than calculate an average, the authors would tend to give more weight to the Wyss and Brune (1968) method as it is based on subsurface information. However, in matters of public safety, conservatism is important and thus a 5.5 magnitude is chosen as a preliminary MCE. In the opinion of the authors this size event is high (conservative) possibly by one full unit on the magnitude scale.

The return time can be estimated based on two lines of evidence. If the nine events are considered only and a b-slope of -1.0 is used, the return time for a magnitude 1.0 is about one year, and for a magnitude 5.5 is about 50,000 years. The second line of evidence is based on the historical record. Because the magnitude 2.8 event is unique in the history of this area the return time for a magnitude 2.8 is probably greater than 50 years. The population density for at least the last 50 years has certainly been sufficient so that an event similar to the main event would not go unreported. With a b-slope of -1.0, such a return time implies that a magnitude 5.5 would have a return time of over 35,000 years.

CONCLUSIONS

Based on the seismological evidence, a preliminary MCE with an inferred magnitude 5.5 in the Conifer area is estimated to have a return time in excess of 35,000 years.

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THE DIVIDE EARTHQUAKE OF JANUARY 6, 1979

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INTRODUCTION

At 01:58 UCT on January 6, 1979 a magnitude 2.9 M_L (USGS) earthquake was felt in the area of Divide, Colorado about 30 km WNW of Colorado Springs, Colorado. The depth-constrained solution for the epicenter is 38.96°N, 105.16°W (see Figure 1). This paper discusses data from: 1) a microearthquake array deployed in an aftershock study and 2) an intensity study. In addition the site-safety implications of this earthquake will be discussed. Estimates of a maximum credible earthquake (MCE) and its return period will be made for the area near the epicenter based on these preliminary data.

ACKNOWLEDGMENTS

The Civil Air Patrol of Colorado should be congratulated for their enthusiastic public service in this investigation. Roger Bowman and Andy Staatz did much of the field work and planning under the sponsorship of MicroGeophysics Corporation. The Golden office of NEIS was also very cooperative during this study. Opinions and extrapolations contained herein are the sole responsibility of the authors.

MAIN SHOCK AND AFTERSHOCK DATA

Utilizing recordings from ten different seismic stations, the USGS determined the epicenter given above and shown in Figure 1. Considering the audible effects (see below), a source somewhat shallower than the 5.0 km assigned depth is indicated. If the depth was allowed to be unconstrained or was assigned a shallower value, the epicenter determined might be more consistent with the other data. A location 5 to 7 km south of the given epicenter is certainly feasible and more consistent with the aftershock and intensity data. The closest station used in the USGS determination is GOL at a distance of 85 km.

INTENSITY DATA

The earthquake produced two loud sounds audible in an area of more than 600 km^2, which led to an extensive air search for an air crash or meteorite source for the event. Once the air and ground search by the Colorado CAP was curtailed, the enthusiasm of the CAP volunteers was pressed into service to do an intensity survey. More than 50 reports were generated.

The reports varied from intensity III (felt indoors, hanging objects swinging) to V (sleeper awakened, small unstable objects displaced). The intensity map prepared from this data is also shown in Figure 1.

The population density is highest in the eastern portion of the area, but the lack of reports from Colorado Springs provide a good boundary for the felt area. The event was felt over an estimated 1,600 km^2 area. Note that the felt area centers somewhat south of the government epicenter.

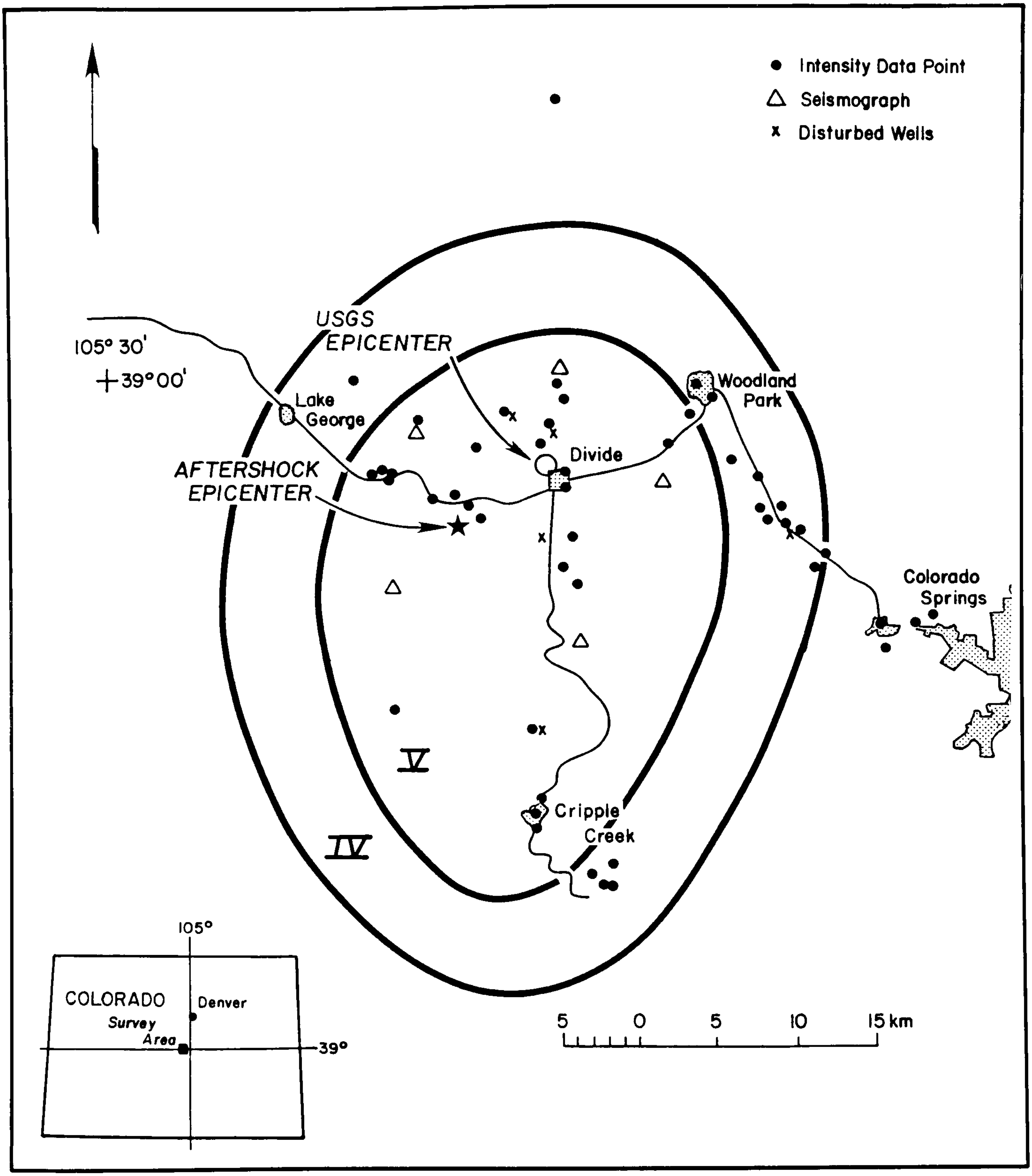

Figure 1. Isoseismal map for the January 6, 1979 Divide earthquake.

AFTERSHOCK STUDY

Seasonal weather hindered the investigation which usually would accompany such an event. However, MicroGeophysics Corporation did field five seismographs for two days within 48 hours after the event. Interference by snow plows and sub. zero weather limited the recording time, and only a single aftershock was recorded. Short aftershock sequences are usual for such a small event as the M_L 2.9 Divide event. The aftershock plots significantly south and west of the main shock epicenter. This aftershock might be considered when evaluating the location and uncertainty of the main shock.

GEOLOGIC CONSIDERATIONS

The following geologic analysis has been offered for the Divide event: (taken from Butler and others, 1983):

"Kirkham and Rogers (1981) assign this event to the Oil Creek fault which passes north/south through the town of Divide. Kirkham and Rogers show the mapped length of the fault as about 58 kilometers. From Taylor (1975) and the map of Scott, Taylor, Epis and Wobus (1978), it is clear that the Oil Creek fault is contained within Precambrian rocks and the Pikes Peak Granite. Near Divide the Oil Creek fault is covered by Pliocene and Miocene deposits. Taylor (1975) shows an offset of these beds in a sketch cross section of the area. Even if the Pliocene and Miocene cover is broken, this evidence merely states that the fault breakage is post-Miocene, i.e., post-20 million years before the present. If the Oil Creek fault is an active structure, its length of 65 km might imply a magnitude 7.0 Maximum Credible Earthquake (Slemmons, 1977)."

The potentially active faults of Kirkham and Rogers (1981) are structures which have exhibited post-Neogene (28 million years before the present) movement. Without proof of Quaternary fault breakage, the probability of renewed activity on these structures is slight. Results of geologic studies (Harza, 1985) along the structure indicate "The most recent documented movement is late Tertiary with no geologic evidence of Quaternary movement."

One should note that geologic investigation to date has not proven the continuity of this Miocene structure nor the presence of Quaternary surface rupture anywhere along its length.

SEISMIC HAZARD ESTIMATION

Seismic hazard estimation for site safety centers on the return period of events similar to the Divide event or larger. Population in this area has been high since the Gold Rush of 1859 due to the presence of the nearby Cripple Creek gold fields. However, in the early days, another boom in the night might have been assigned to mining activity rather than a natural phenomena.

If we conservatively estimate that no event as large as the Divide event has occurred in 50 years, a return period in excess of 500,000 years would be estimated for a magnitude 7.0 maximum credible earthquake (using a b-slope of -1.0).

In summary, the very conservative selection of the entire Oil Creek structure as potentially active and the very conservative selection of 50 years as a return period for events like this one leads to a negligible probability of a damaging earthquake (usually defined as an event with magnitude greater than 5.0) in the lifetime of critical structures now being considered for this area. Design lifetimes are typically less than 100 years. The most probable values of the input parameters are a shorter surface-breakage fault length (maybe 10 to 20 km) and a longer return time for events similar to this magnitude 2.9 event (maybe greater than 100 years).

CONCLUSIONS

Based on seismological extrapolations from the Divide earthquake, a MCE of magnitude 7.0 is estimated for the Oil Creek fault with a preliminary return period of greater than 500,000 years.

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PRELIMINARY RESULTS OF THE 1984 CARBONDALE, COLORADO EARTHQUAKE FIELD STUDY

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A magnitude 2.2 (M_L) earthquake in April 1984 began a series of small events in the Carbondale, Colorado area. Over the next four weeks, sixteen additional earthquakes ranging in magnitude from 1.9 to 3.2 (M_L) were located by the U.S. Geological Survey, National Earthquake Information Center (NEIC), using regional data from the U.S. Telemetered Network in Golden. Nine of the events were felt at or near Carbondale. The largest event in the series occurred on May 14, 1984 and caused modified Mercalli intensity IV effects at Carbondale. It was also felt at Glenwood Springs about 11 mi (18 km) northwest of Carbondale.

The continuation of this swarm and the occurrence of the magnitude 3.2 (M_L) event on May 14, 1984 indicated that an investigation to determine the source of these earthquakes should be conducted. This was initiated by the installation of a 9-station temporary seismic network in the epicentral area on May 16, 1984, which was fully operational from May 17, to May 31, 1984.

Seventeen additional earthquakes with duration magnitudes (M_D) from 1.3 to 2.6 were located using data recorded on the portable network. Only one of these was large enough to be located also by the NEIC telemetered network. Of these 17 locally recorded earthquakes, 13 are considered well-located and are shown in Figure 1. Ten of the epicenters are located about 3 miles (5 km) SSW of Carbondale, just north of Thompson Creek and east of the Grand Hogback monocline. The epicenters are situated at the northern terminus of the mapped axis of the northwest-trending Elk Mountain anticline (Poole, 1954) and form an elongate zone, 5 km by 3 km, oriented subparallel to the trend of the anticline. The earthquake depths range from 4.0 to 5.7 km. The other three well-located events occurred about 7 km southwest of the major cluster of earthquakes, with depths between 3.4 and 3.6 km. Since these earthquakes occurred toward the end of the series, this difference in focal region may indicate that there may have been some migration of the events during the series, although at this point the evidence is inconclusive.

The distribution of the seismicity was examined as a function of depth by constructing orthogonal cross-sections that are both parallel and perpendicular to the regional trend of mapped geologic structures in the area. The hypocenters do not define a plane, but rather show a scattered distribution between the depths of 3 and 6 km. The scatter of the hypocenters within the crest of the anticline suggests that the earthquakes did not occur along a single plane, such as a contact between bedding planes, but perhaps within a unit, such as the Eagle Valley Evaporite or Minturn Formation.

The U.S. Geological Survey plans to continue the study of the 1984 Carbondale earthquake series (Goter and others, in preparation). Of particular interest is the determination of whether or not there was a migration of epicenters from north to south as the sequence progressed. To investigate this possibility, accurate relocations of the 17 earthquakes that occurred prior to the installation of the local network will be attempted using joint hypocenter determination techniques.

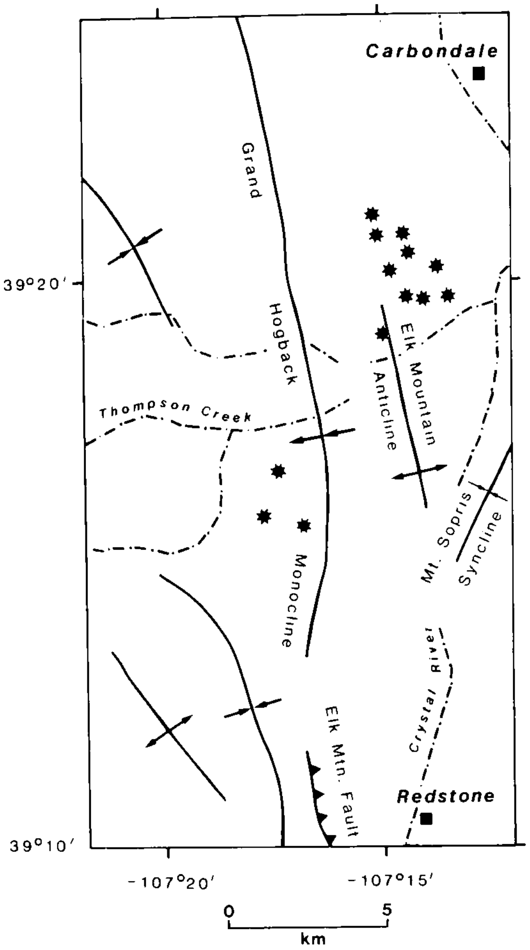

Figure 1. Carbondale earthquake area, modified from Tweto and others (1978), showing the 13 well-located epicenters (stars) recorded by the temporary local seismograph network between May 17 and May 29, 1984.

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RESULTS OF A LIMITED MICROSEISMICITY SURVEY IN THE PICEANCE CREEK BASIN, COLORADO

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INTRODUCTION

In 1981 Dames & Moore published a report suggesting that the magnitude 6.5 earthquake on November 7, 1882 occurred in the Piceance Creek Basin in northwestern Colorado (Dames & Moore, 1981; McGuire and others, 1982). As a follow-up to this report, a field investigation was undertaken in the area (Eckert, 1982). As part of this study seismicity was monitored for eight weeks during the summer of 1981 using a single vertical-component seismograph. This paper presents evidence from the seismicity monitoring for microseismic activity in the Piceance Creek Basin.

ACKNOWLEDGMENTS

This project was made possible by the loan of seismograph equipment from Mr. Lawrence Jaksha of the Albuquerque Seismological Laboratory of the U.S. Geological Survey. Dr. Stuart Wier (CIRES) helped in analysis of the seismic data. We would also like to thank Mr. David Butler, Mr. John Nicholl, and Mr. Robert Quillan of MicroGeophysics Corporation, who took time to review and discuss our seismograph records and confirmed our assessment that the Type A events are likely to be local earthquakes.

INSTRUMENT INSTALLATION

The equipment consisted of a Mark Products L-4C Seismometer and Teledyne Geotech Portacorder pen-and-ink recording system. The instrument was installed at 39°52'30" N latitude and 108°13'18" W longitude, within a graben (Figure 1) suggested as a possible location of the 1882 earthquake by Dames & Moore (1981).

The seismometer was buried in colluvium to a depth of about one foot at a location approximately 50 feet southeast of the seismograph. This location was in a small clearing at the top of a slope with trees no closer than 10 feet away to minimize wind noise.

The instrument recorded events from June 24, 1981, to August 18, 1981. During this eight weeks period, 46 days and 17 hours of actual recording time were logged.

Because the system was located in an area of gas well activity and due to the considerable wind and many thunderstorms in the basin, the gain was set at 84 db with 0.2 Hz high-pass filter and 12.5 Hz low-pass filter. The recording was done at five seconds per centimeter with the exception of three days (July 27, 28, and 29), when the recording was done at 10 seconds per centimeter.

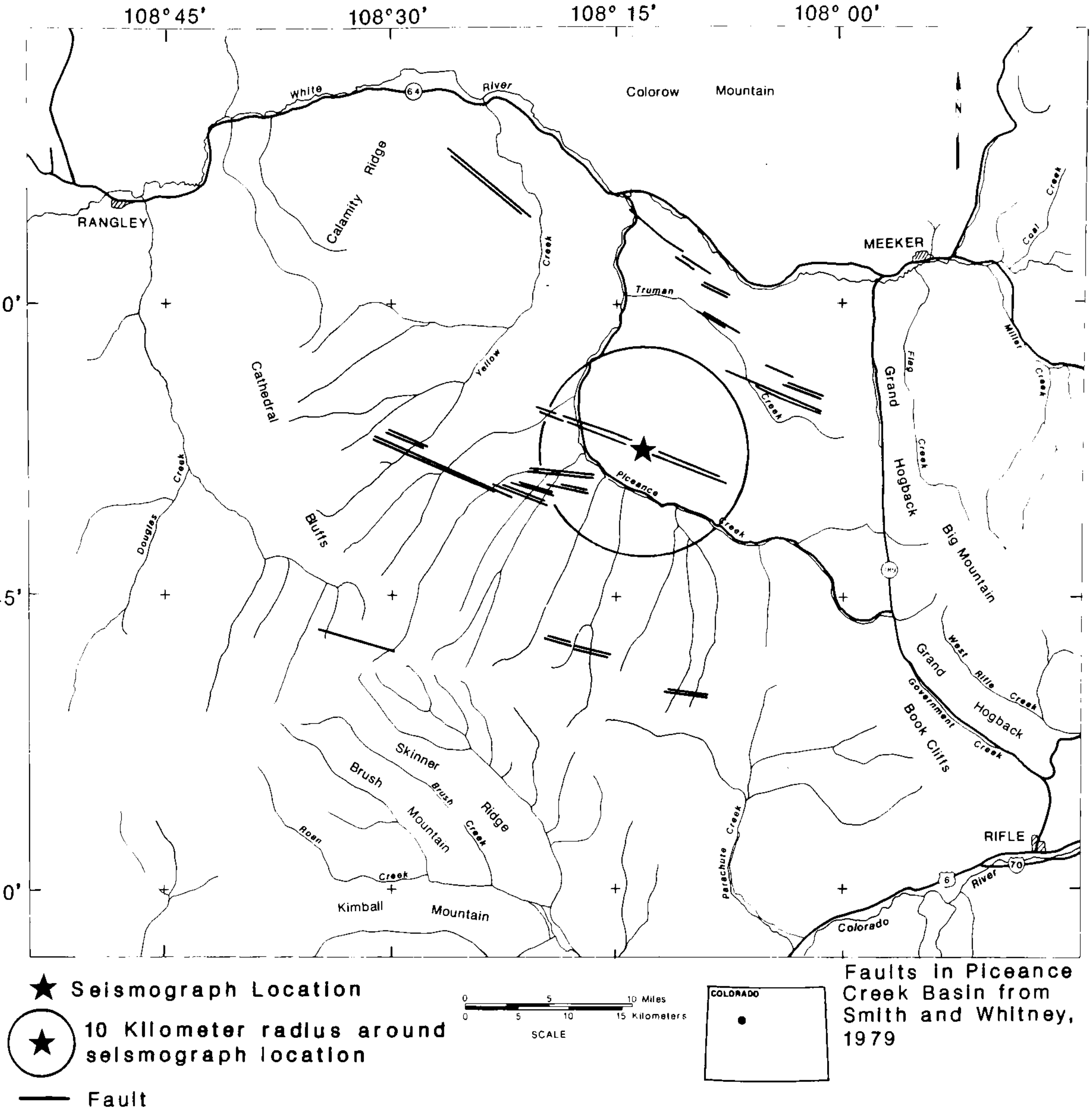


Figure 1. Map of seismograph location in the Piceance Creek Basin.

DATA AND RESULTS

A wide variety of signals was received during the time the seismograph was in operation. The signals were cataloged according to similarities in shape. These signals, along with their characteristics and respective times of occurrence, are discussed in more detail by Eckert (1982). Events having local and regional sources were recognized from the seismograms. Among these sources were sonic booms, teleseisms, local and regional man-made blasts, noise, and possible local earthquakes.

Of primary interest were 21 events which could be local earthquakes (within approximately 10 km of the seismometer) or might be local blasts. To resolve this, the blasting records from the following companies were compared to the time of each particular event:

Brown & Root (Oil Shale Tract C-b, surface construction)
Gilbert Construction (Oil Shale Tract C-b, subsurface construction)

Multi Mineral Corporation (Horse Draw)
Northwest Pipeline Corporation
Western Slope Gas Company
Mobil Oil Corporation
Equity Oil Company
Mike J. Thiel, Inc.

None of the 21 events could be attributed to blasting or work done by any of the above companies. These companies were the only ones known to have been working within 15 km of the seismograph during the time of monitoring. Therefore, either the signals in question were actually local earthquakes or blasts from some unknown source, or they were caused by some other unknown natural or man-induced process which has not been identified.

These 21 events have been cataloged as four types (A, B, C, and D), according to the appearance of their seismograms. The events categorized as Type A seem most likely to be local earthquakes.

Type A Events

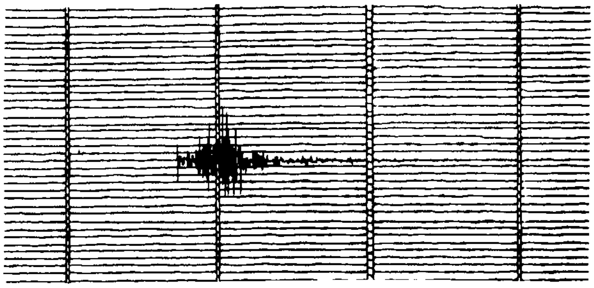
Signals from these events have identical waveforms varying only in size (Figure 2). The distance from the seismograph to the source of the signal can be estimated by the difference between shear-wave and compressional-wave arrival times. In this case, the S-wave minus P-wave arrival time is 1-1/4 seconds, corresponding to a distance of approximately 10 km from the seismograph. A circle of radius 10 km from the seismometer is shown in Figure 1.

Two of the nine Type A events occurred on Wednesday, July 22 around 4:30 a.m. (local time). Another occurred on Sunday, July 26 at about 2:00 p.m. The other six occurred on Wednesday, July 29 between 2:00 and 4:30 a.m. If these events are local earthquakes, it is a coincidence that eight of the nine occur early on Wednesday mornings. The time intervals between the signals on July 22 and July 29 range sporadically from about 2 to 90 minutes. This irregular spacing does not suggest a blast origin for these events. The configuration of the event sequence on July 29 suggests that two foreshocks, a main shock, and three aftershocks occurred that morning.

Magnitudes of eight of the Type A events were roughly estimated. Magnitude is a function of distance from source to seismometer, amplitude and period of the signal, and the seismometer response. The instrument response was estimated by comparing the teleseisms recorded on this seismometer with the same teleseisms recorded on another seismometer in Boulder. The resulting magnitude estimates are listed in Figure 2 with the corresponding Type A events.

The magnitude of the largest Type A event is estimated to be 1.7 +/- 0.3. The estimated magnitudes of seven of the other events range from 0.7 +/- 0.3 to 1.2 +/- 0.3. The largest Type A signal is probably greater than or equal to the size of any of the other twelve possible local earthquakes from Types B, C, and D.

The range of magnitudes for the Type A events is too small to allow a unique determination of a b-slope value. In addition the magnitude estimates have large uncertainties (+/- 0.3). Incorporating these uncertainties, Eckert (1982) generated extreme values for b of 0.65 and 1.99 for the Type A events.



Event of 22 Jul 81, 10:33:47 UTC

Note: Time interval between tick marks is 10 seconds.

Characteristics: These events are characterized by an impulsive beginning. The S-wave minus P-wave arrival time is 1-1/4 seconds. The peak-to-peak amplitude varies from 4 to 39 mm, however, the waveforms of the signals are very similar.

Schedule of Specific Events

Date	UTC Time	Local Time, Day	Remarks
22 Jul 81	10:30:13	04:30:13 a.m., Wed.	Magnitude = 1.1 ± 0.3
22 Jul 81	10:33:47	04:33:47 a.m., Wed.	Magnitude = 1.2 ± 0.3
26 Jul 81	20:17:15	02:17:15 p.m., Sun.	Magnitude = 1.1 ± 0.3
29 Jul 81	08:01:10	02:01:10 a.m., Wed.	Magnitude = 1.2 ± 0.3
29 Jul 81	09:34:40	03:34:40 a.m., Wed.	No Magnitude Calculated
29 Jul 81	09:36:22	03:36:22 a.m., Wed.	Magnitude = 1.7 ± 0.3
29 Jul 81	09:50:12	03:50:12 a.m., Wed.	Magnitude = 1.1 ± 0.3
29 Jul 81	09:58:36	03:58:36 a.m., Wed.	Magnitude = 0.7 ± 0.3
29 Jul 81	10:20:04	04:20:04 a.m., Wed.	Magnitude = 0.9 ± 0.3

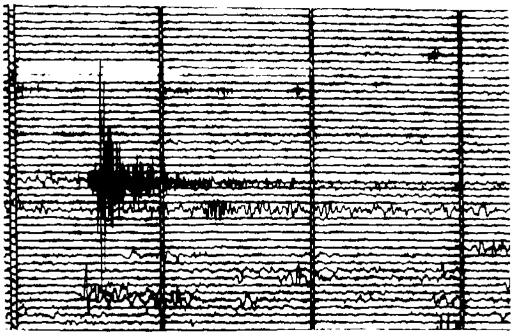
Figure 2. Type A events. Probable earthquakes at a distance of approximately 10 km from seismograph.

It was, therefore, not feasible to develop meaningful estimates of the recurrence intervals for possible larger earthquakes.

Other Local Events

The two signals from Type B events are all of similar waveform, but vary greatly in size (Figure 3). The S-wave minus P-wave arrival time is available from only the larger signal and indicates that the distance to the source is approximately 6 km. These are probably man-made noises, because both events occurred on Monday just before noon, a common time for blasting.

The Type C group includes five signals of unusual character (Figure 4). These vary greatly in shape and size. The distance to the source of these is variable and for four of these ranges from 0 to 10 km. One signal, however, seems to have a nine-second S-wave minus P-wave arrival time (72 km distance), but is unusual in that the P-wave envelope is very flat.



Event of 20 Jul 81, 17:48:05 UTC

Note: Time interval between tick marks is 10 seconds.

Characteristics: These signals are similar in shape, but the maximum peak-to-peak amplitude is 31 mm in the first case and 6 mm in the second case. From the S-wave minus P-wave arrival time available for the event on July 20, the distance is approximately 6 km.

Schedule of Specific Events

Date	UTC Time	Local Time, Day	Remarks
20 Jul 81	17:48:05	11:48:05 a.m., Mon.	S-P = 3/4 second
27 Jul 81	17:58:05	11:58:05 a.m., Mon.	

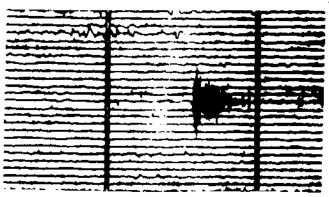
Figure 3. Type B events. Other potential local earthquakes at varying distances from seismograph.

Signals from Type D events are characterized by some high-frequency signals, but vary in shape and size (Figure 5). They are thought to be local events due to the high-frequency signal, but a S-wave minus P-wave arrival time is unavailable, so the distance to the source is unknown.

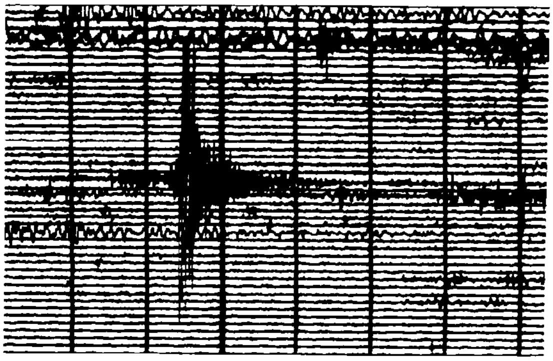
Numerous small impulsive blips were also recorded throughout the monitoring program. Although these could be local blasts, local earthquakes, or noise, they were considered as noise because of their small size and a waveform which is not generally characteristic of earthquakes.

CONCLUSIONS

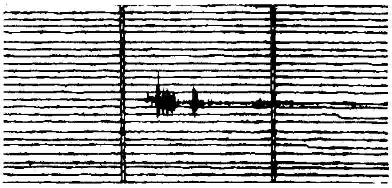
A single vertical component seismograph was installed in the Piceance Creek Basin, northwestern Colorado, for eight weeks during the summer of 1981. Among the seismic events recorded were sonic booms, teleseisms, local and regional man-made blasts, noise, and 21 possible local earthquakes. Of the 21 events, nine (Type A) events are most likely to be local earthquakes. They have identical waveforms with S-wave minus P-wave arrival times of 1 1/4 seconds. Six of the events occurred within a 2 1/2-hour time period and are suggestive of a sequence of foreshocks, a main shock, and aftershocks.



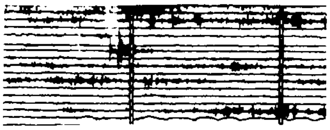
Event of 26 Jul 81, 21:04:26 UTC



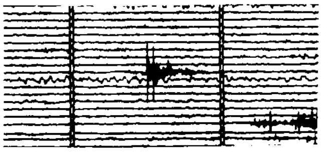
Event of 28 Jul 81, 20:52:45 UTC



Event of 09 Aug 81, 08:02:22 UTC



Event of 12 Aug 81, 17:23:08 UTC



Event of 12 Aug 81, 21:43:35 UTC

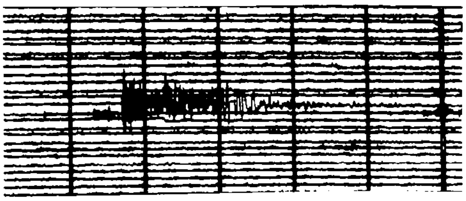
Note: Time interval between tick marks is 10 seconds.

Characteristics: Characteristics of these events vary, therefore, copies of all the events are shown above.

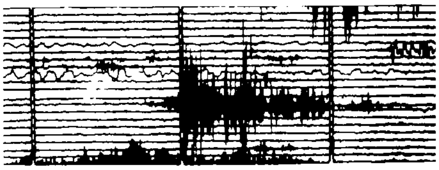
Schedule of Specific Events

Date	UTC Time	Local Time, Day	Remarks
26 Jul 81	21:04:26	03:04:26 p.m., Sun.	
28 Jul 81	20:52:45	02:52:45 p.m., Tue.	S-P = 9 seconds
09 Aug 81	08:02:22	02:02:22 a.m., Sun.	S-P = 1 second
12 Aug 81	17:23:08	11:23:08 a.m., Wed.	S-P = 1-1/4 seconds
12 Aug 81	21:43:35	03:43:35 p.m., Wed.	S-P = 1/2 second

Figure 4. Type C events. Other potential local earthquakes at varying distances from seismograph.



Event of 27 Jul 81, 18:04:17 UTC



Event of 12 Aug 81, 22:22:27 UTC

Note: Time interval between tick marks is 10 seconds.

Characteristics: This group includes a wide range of local (?) events of unknown origin. All are characterized by some high-frequency signals.

Schedule of Specific Events

Date	UTC Time	Local Time, Day
07 Jul 81	21:13:22	03:13:22 p.m., Tue.
24 Jul 81	19:08:08	01:08:08 p.m., Fri.
27 Jul 81	18:04:17	12:04:17 p.m., Mon.
03 Aug 81	02:50:39	08:50:39 p.m., Mon.
12 Aug 81	22:22:27	04:22:27 p.m., Wed.
13 Aug 81	12:55:52	06:55:52 a.m., Thu.

Figure 5. Type D events. Local sources (?).

To estimate magnitudes for these events, the instrument was roughly calibrated by comparing recorded teleseisms with recordings of the same teleseisms on another seismometer in Boulder. Estimated magnitudes for eight of the nine Type A events ranged from 0.7 +/- 0.3 to 1.7 +/- 0.3. The magnitude estimates were insufficient to develop meaningful estimates of the recurrence intervals for possible larger earthquakes.

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REGIONAL FAULT STUDY: CENTRAL FRONT RANGE, COLORADO

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ABSTRACT

A regional fault study was conducted in 1984 as part of a comprehensive evaluation of seismotectonic conditions in the east-central and southern Colorado Front Range. Objectives of the study were to collect data on the occurrence, surface characteristics, and most recent movement on faults previously mapped in the area that might affect design of proposed Denver Water Department (DWD) water storage projects. The study involved a review of geologic literature and geologic reconnaissance along the mapped traces of the selected faults that included several previously categorized by others as "potentially active", a term referring to structures with documented or inferred movement during or since the Neogene, and not necessarily implying present or Quaternary activity.

The presence of faulting was clearly confirmed along most of the length of each fault trace. Fault characteristics are variably exposed in the study area.

It is difficult to determine the age of most recent fault movement in the study area because of the paucity of datable Quaternary soils and geomorphic units. Nonetheless, no surface evidence of Quaternary movement was observed on faults not previously categorized as potentially active. Observations on last movement on faults previously identified as "potentially active" are:

1) The latest apparent movement on the Floyd Hill fault occurred more than 125,000 years ago in the northwest and more than 190,000 years ago in the southeast. Reported evidence for late Tertiary movement is subject to difference of opinion.

2) Last movement on the Ken Caryl fault, a "potentially active" extension of the Floyd Hill fault, probably occurred more than 190,000 years ago based on undisplaced soils.

3) The northwestern part of the Kennedy Gulch fault is not categorized as "potentially active" but extends to the "potentially active" southeastern trace. Here, no surface evidence for Quaternary movement was observed.

4) Evidence for Quaternary movement on the Ute Pass fault is circumstantial and reported only near the southern end of the fault. This area was not fully evaluated in the study, but no evidence of Quaternary movement was observed further north.

5) There is no evidence for late Quaternary movement on the Oil Creek fault, and overlying glacial deposits, 125,000-190,000 years old, apparently are not offset near the southern end of the trace. However, a Quaternary colluvial deposit may be offset by this fault, or a splay, to the north.

6) No evidence of Quaternary movement was observed or is reported on the Perry Park-Jarre Canyon fault.

7) Evidence for Quaternary movement on the Rampart Range fault is based on reported offset of a 600,000 year old pediment gravel by a fault splay. This offset was not confirmed in the reconnaissance mapping, but trenches were proposed to provide more conclusive data. Trenches subsequently excavated demonstrated the presence of faulting in this unit.

INTRODUCTION

A regional fault study was conducted during 1984 in the east-central and southern Rocky Mountain Front Range of Colorado to provide data on faulting that will assist in the seismic design of specific projects, as recommended by Kirkham and Rogers (1981) in their discussion of earthquake potential in Colorado. The study was one of several concurrent and related seismotectonic investigations performed within an area of about 5,200 km^2 (2,000 sq mi) that includes portions of Gilpin, Clear Creek, Jefferson, Douglas, Park, Teller, and El Paso Counties (Figure 1) and extends from Townships 2 to 16 South, and Ranges 66 to 75 West. The study area was selected to cover the full lengths of faults potentially affecting evaluations of proposed Denver Water Department (DWD) East Slope storage projects. The scope and areal extent are similar to the coverage of other regional geologic studies typically conducted as part of seismotectonic evaluations and conforms to the recommendations and guidelines of USCOLD (1985) and FEMA (1985) among others. The results of the study are documented in Harza (1985a). This paper provides a synopsis indicating the scope, objectives, and general conclusions of the study. Specific objectives were: 1) to collect data on the occurrence and surface characteristics of major faults mapped previously in the study area including field checking of air-photo lineaments; 2) to identify geologic features indicative of most recent movement on the faults; 3) to identify significant Quaternary deposits that could assist in recency determinations; and 4) to perform or propose detailed geologic studies and trenching in areas critical to determining most recent fault displacement.

Faults examined in the investigation, listed on Table 1 and shown on Figure 2, were selected from pertinent geologic literature and represent mapped faults potentially affecting seismic design of proposed DWD projects in the region. Although there was no intent to remap the entire area, reconnaissance, and locally detailed, geologic investigations, were performed along the mapped traces of the selected faults. Most of the mapped length of each fault was covered, however, some remote areas and other minor faults and splays could not be examined within the scope of the study. These areas did not include features critical to dating fault movement.

Table 1. Names, mapped lengths and trends of faults included in study.

Fault Name	Mapped Length	Principal Trend
Black Hawk	28 km (17.5 mi)	N50°W
Deer Creek	33.6 km (21 mi)	N60°W
Floyd Hill	60 km (38 mi)	N45°W
Green Mountain*	15 km (9.5 mi)	N35°W
Jackson Creek	23 km (14 mi)	N20°E
Ken Caryl	9.6 km (6 mi)	N45°W
Kennedy Gulch	74 km (46 mi)	N45°W-70°W.
Meridian Hill*	25.6 km (16 mi)	N60°W
No Name*	25.6 km (16 mi)	N65°W
North Mill Gulch*	17.6 km (11 mi)	N60°W

Table 1. Continued

Fault Name	Mapped Length	Principal Trend
Oil Creek	60 km (37 mi)	N-S
Perry Park - Jarre Canyon	31 km (19 mi)	N10°W
Pine Gulch	32 km (20 mi)	N50°W to N-S
Platte River*	20 km (12.5 mi)	N30°W to N20°E
Rampart Range	45 km (28 mi)	N10°W
Shawnee	40 km (25 mi)	N60°W
285*	7 km (4.5 mi)	N60°E
Ute Pass	92 km (57 mi)	N40°W to N15°E
Witter Gulch*	19 km (12 mi)	N45°W

Note: Underlined faults cited by Kirkham and Rogers (1981) as "potentially active".

*Previously unnamed fault. Arbitrarily named for convenience in this study.

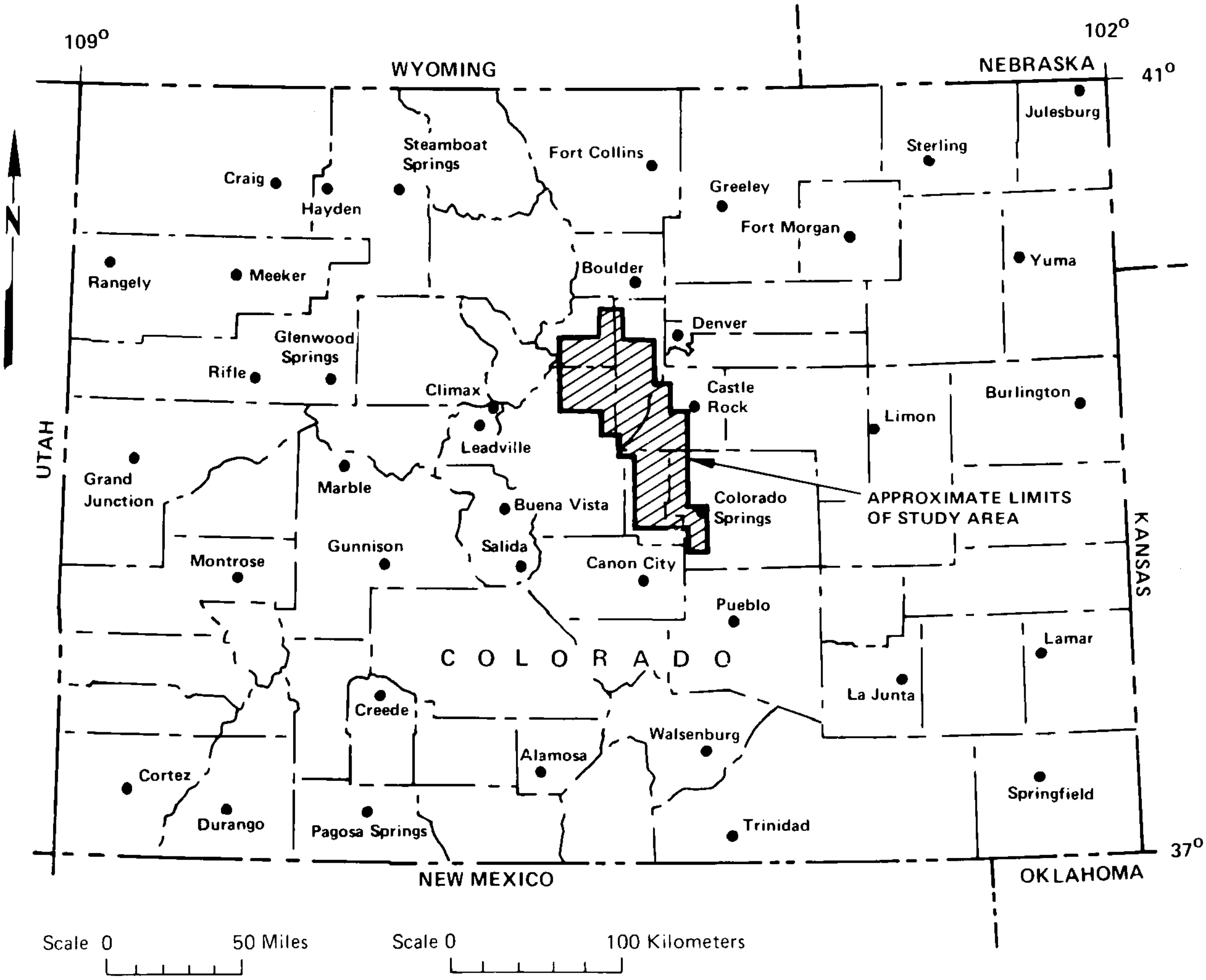

Figure 1. Location of study area in Colorado.

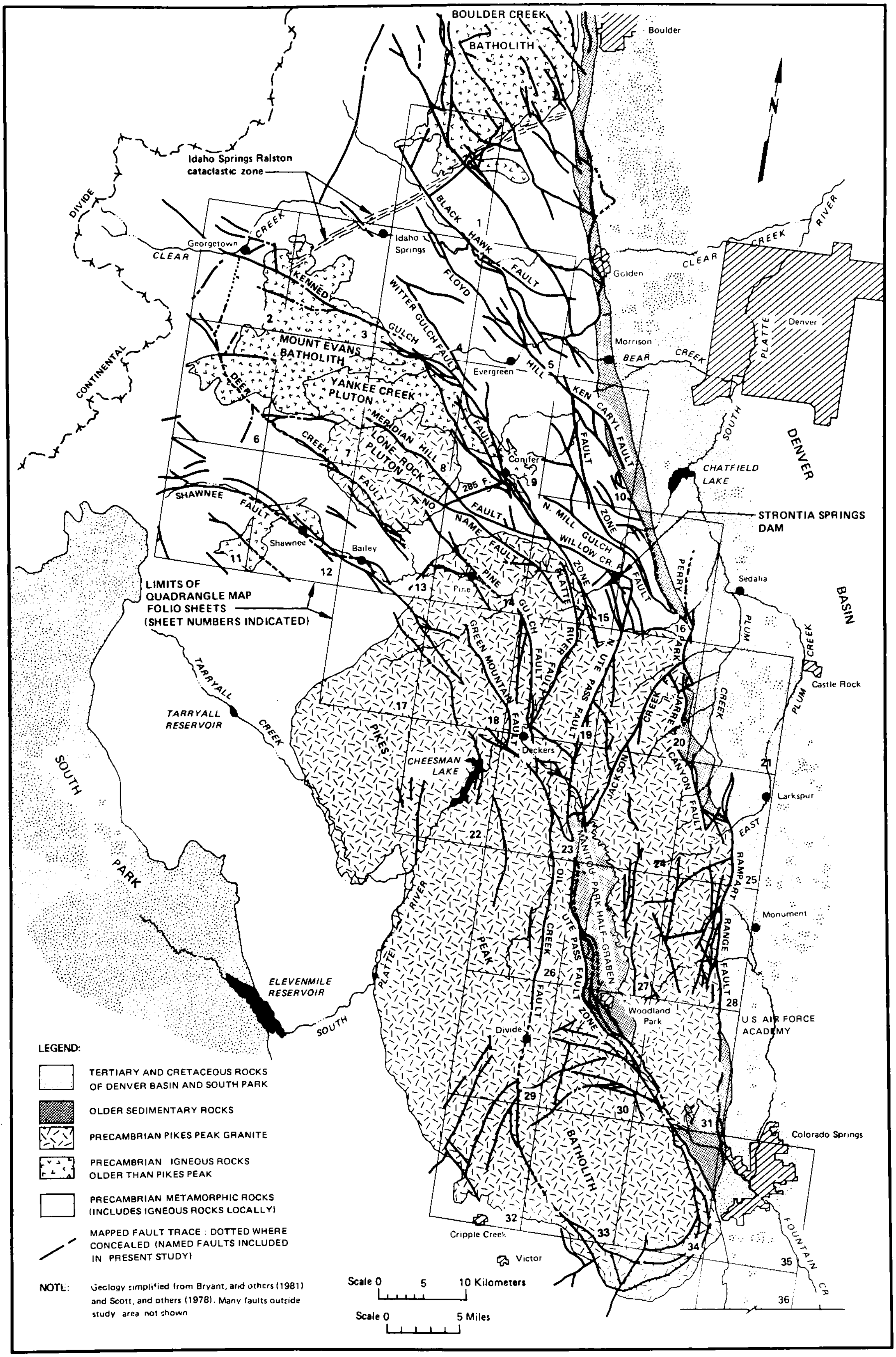

Figure 2. Generalized geology of the region between Boulder and Colorado Springs.

Geologic literature was reviewed prior to initiating the field work to: 1) compile a bibliography of relevant publications; 2) characterize the regional and historical geology; 3) obtain available data on the occurrence, nature and characteristics of faults; 4) establish the chronological sequence of literature available for each fault, from the earliest mention to the present; and 5) review data relevant to recency of fault movement. The literature review, confirmed by remote sensing analysis and the results of subsequent field reconnaissance, indicated that all major surface faults potentially important to seismic hazard assessment appear in one form or another on published geologic maps of the study area. Therefore, the faults examined in the study (Table 1) were selected from those previously mapped, to include structures of significant mapped length and continuity in the area, or those in close proximity to a proposed DWD project. The southeast part of the Kennedy Gulch fault and the Willow Creek fault, were studied in detail by others (Wallace and Friedman, 1985; Cochran, 1985; Hornback, 1985) and were not included in this investigation.

Emphasis was placed on faults categorized by Kirkham and Rogers (1981) as "potentially active", with movement during or since the Neogene period of tectonism (initiated about 25 to 28 m.y. ago). This designation does not imply present, or even necessarily Quaternary (about the last 2 m.y.), activity. A major objective was to evaluate evidence for the age of latest movement on each fault, particularly in the late Quaternary, a time period critical to developing seismic design parameters for the proposed DWD projects.

Field reconnaissance was conducted between July and October, 1984, using U.S. Geological Survey 7-1/2 minute quadrangle topographic maps, supplemented where available by aerial photographs and geologic maps. Local areas considered critical to evaluating recency of fault movement were identified for more detailed geologic study and were later mapped with surveyed control, tape and compass, and plane-table. The detailed mapping was used to determine the extent and continuity of key Tertiary and Quaternary age deposits spanning fault traces. Detailed mapping of alluvial terraces in the South Platte River drainage also was performed concurrently by geologists of the DWD (Wallace and Friedman, 1985).

Two potential sites for exploratory trenches were identified to help evaluate possible fault displacement of datable Quaternary deposits: 1) The Ken Caryl Ranch site on the Ken Caryl fault; and 2) the Air Force Academy site on a splay of the Rampart Range fault. Trenches at these sites were subsequently excavated in 1985 (Harza Engineering Company 1985b and 1985c; Dickson, 1986; Dickson and Paige, 1986). Other trenches, located on the Kennedy Gulch and Willow Creek faults were excavated by the DWD during other investigations (Shlemon, 1984; Hornback, 1984, 1985a, and 1985b; ESA, 1985).

GEOLOGIC SETTING

The study area is located in the eastern part of the Southern Rocky Mountain Physiographic Province where the mountains abruptly give way to the western portion of the Great Plains Physiographic Province, or Rocky Mountain Piedmont.

Within the study area, the Precambrian crystalline rocks, and the immediately adjacent Phanerozoic sedimentary rocks, are traversed by many faults with trends that reflect the structural fabric of the Front Range (Figure 2). The principal structural features in the region originated in Precambrian time with repetitive folding, batholithic intrusion, and faulting. Additional deformation occurred in the Paleozoic, but most of the present structural relief formed during the Laramide Orogeny from late Cretaceous to Eocene, by uparching and rejuvenation of previous uplifts mainly along reverse border faults, along with subsidence and infilling of the adjacent basins. Laramide tectonism gradually ceased by middle or late Eocene time, some 40 m.y. ago. Deformation and uplift, however, recurred in the Neogene, primarily as block faulting, producing most of the present relief in the Front Range. Fault movements continued on a diminishing scale through the Pleistocene, and locally during the Holocene, particularly along the Rio Grande Rift, west of the Front Range.

Most faults are normal dip-slip or strike-slip structures characteristic of the Front Range interior. However, the Perry Park-Jarre Canyon, Rampart Range and Ute Pass faults form part of the border fault system of the Front Range uplift and are mainly reverse structures. The predominant fault trend in the northern half of the study area is northwesterly. Structures with this trend include the Black Hawk, Floyd Hill, Ken Caryl, Witter Gulch, Kennedy Gulch, North Mill Gulch, Meridian Hill, No Name, Shawnee, Pine, and Green Mountain faults. North-trending faults are prominent in the southern half of the area and include the Platte River, Oil Creek, Ute Pass, Perry Park-Jarre Canyon, and Rampart Range faults. Parts of some of these faults trend northwesterly and northeasterly. Northeast-trending faults, including the 285 and Jackson Creek faults, are of minor significance in the area, although the Colorado Lineament has this trend, represented in part by the Idaho Springs-Ralston cataclastic zone (Figure 2).

CENOZOIC GEOLOGY

Some aspects of the Cenozoic geology are particularly important to evaluation of fault movement. However, a comprehensive review of all Tertiary and Quaternary geology of the Front Range was not undertaken, being beyond the scope of the study. Especially significant are the occurrence and origin of sedimentary deposits and geomorphic features that are critical in evaluating the recency of movement along specific faults.

Tertiary

Active geomorphic development of the region began in late Cretaceous time, about 67 m.y. ago, with Laramide uplift, erosion of the Rockies and deposition in the Denver Basin. Erosion continued through the Eocene, but uplift appears to have nearly ceased early in that period. Prolonged stability through Oligocene time, about 25 m.y. ago, led to the development of the late Eocene erosion surface (Epis and Chapin, 1975), remnants of which can be recognized in many parts of the Front Range, even where subsequently modified by erosion or disrupted by faulting (Scott, 1975). Displacement of the erosion surface, and of associated Oligocene rock units, often is cited as evidence of Neogene fault activity in the study area (e.g. Kirkham and Rogers, 1981).

Another major episode of uplift, erosion, and deposition occurred from early Miocene through Pliocene time, significantly disrupting the Eocene surface (Taylor, 1975). Offset of Tertiary gravels has been used by others as evidence of Neogene faulting (Kirkham and Rogers, 1981). In the southern part of the study area (Divide, Woodland Park, and Cripple Creek North quadrangles), extensive Miocene-Pliocene deposits, consisting of bouldery gravel and crudely stratified sand, silt, and clay (Wobus and Scott, 1977), occur infilling an east-northeast trending paleo-valley which was subsequently disrupted by faulting (Scott, 1975). In the northern part of the study area (Black Hawk, Squaw Pass, Evergreen, Indian Hills, Meridian Hill, Bailey, Pine, and Platte Canyon quadrangles), the remnants of Tertiary boulder gravels occur capping hills and ridges. They are composed of rounded to subangular boulders up to 4.6 m (15 ft) in diameter in a matrix of sandy-silty gravel with minor clay, are as much as 200 m (650 ft) thick and are generally more than 150 m (490 ft) above adjacent major streams (Scott, 1975). No ash beds or fossils have been found with which to date the Tertiary gravels and their Miocene-Pliocene age is inferred (Scott, 1975; Taylor, 1976). Because of imprecise age assessments and the absence of marker beds, it is difficult to correlate one deposit to another with any certainty. Further, correlation is thought to be complicated by late Neogene block faulting (Scott, 1975; Madole, 1982).

Greatly accelerated uplift in Pliocene time resulted in erosion of the deep canyons that presently characterize the mountain flanks (Scott, 1975). The location of most of the major canyons seems to have been controlled largely by superposition, although some stretches of present day streams are localized within zones of faulted rock.

Quaternary

Canyon-cutting and pedimentation at the margin of the Front Range continued in Pleistocene time (in the latest 1.6 m.y.), when major climatic changes and glaciation occurred. In the eastern part of the Front Range and its flanking piedmont area, successive base level changes are represented by a sequence of pediments and alluvial deposits which, as described by Scott (1960, 1963a, 1963b, and 1975) and Machette (1975, and others 1976), form the basis for a correlative sequence of Pleistocene deposits. Reported displacement of deposits in this sequence has been used by previous workers as evidence of Quaternary movement on some faults in the region.

The Pleistocene deposits are widely mapped in the piedmont areas adjacent to the mountain front, where the principal named units include the Broadway, Louviers, Slocum, and Verdos/Douglass Mesa alluviums, in increasing order of age. The deposits are composed of alluvial sand and gravel, intermixed colluvium, and related soil horizons. Although they are rare in the mountainous part of the study area, these deposits underlie locally well-preserved multiple terraces in some of the major drainages, including parts of the South Platte River, Clear Creek, and Bear Creek valleys. Other Pleistocene deposits of local significance to the fault study include bouldery glacial moraines of Bull Lake and Pinedale age in the Pikes Peak area.

With the exception of moraines, the absolute ages of Pleistocene deposits in the study area are not well established, and correlation of units between drainages is not always agreed upon by different workers (Machette and others, 1976). Determining the relative height of the units above present stream levels is one method used to establish general stratigraphic relations within a drainage, but is not always a defensible age criterion especially to correlate from one drainage to another (Scott, 1963b, p. 55; Machette and others, 1976, p. 341, fig. 2). Nonetheless, the alluvial deposits comprise a stratigraphic sequence for which at least relative ages can be determined and, where identified overlying a fault, they were studies in greater detail.

Deposits of Holocene age (up to about 10,000 years old) are widespread throughout the study area and include colluvium, talus, and stream alluvium, as well as upland meadow deposits, many of which are assigned to the middle Holocene Piney Creek. Although common in the study area, such deposits usually are thin or intermittent, and often difficult to correlate.

FIELD STUDY RESULTS

Each fault, or fault system, included in the study was examined separately. In the main study report (Harza, 1985a) discussions on each fault include: 1) the mapped length, location, orientation, sense of movement (if known), and relevant geologic conditions; 2) reference to publications related to the structure; 3) a description of field data collected during the study; and 4) a brief discussion of data relevant to most recent movement. The discussions are intended as summaries and do not presume to cover all available information. Reference is made to key publications or to the results of other studies directed by the DWD's Geotechnical Advisory Committee.

The study results are illustrated in a Quadrangle Map Folio attached to the main report, consisting of 36 sheets with acetate overlays, representing the USGS 7-1/2 minute quadrangle maps used in the study, the limits of which are indicated on Figure 2. Each base sheet shows topography, geographic place names, geologic features relevant to the study, and the traces of faults as previously mapped.

FAULT CHARACTERISTICS

Review of pertinent literature and the results of the field work indicated that the faults mapped previously in the study area have been located on the basis of a variety of criteria depending on the level of previous investigations. Descriptions of their surficial properties often are not available in the literature and some have not been confirmed by field study. Field criteria considered in this study to be possibly indicative of faulting, but not necessarily diagnostic, included one or more of the following: 1) fault breccia and/or gouge; 2) slickensides or other shear features; 3) crushing or pervasive fracturing; 4) iron-staining; 5) offset of geologic units; 6) deformation of rock structure of fabric; 7) sandstone dikes; 8) igneous dikes; 9) severe weathering; 10) mineralization; and 11) topographic or air photo linears. It should be noted that although sandstone dikes have been related to faulting in the Front Range (e.g. Harms, 1959 and 1965), they also occur locally with no other evidence of shearing, in places totally removed from the proximity of previously mapped faults, and thus may not necessarily reflect actual fault traces.

The study also provided data on the location and surface exposure of the faults. Many existing geologic maps show where faults have been only approximately located or are covered and inferred. In most cases, however, faults are shown as unbroken lines on regional maps because of scale limitations or where detailed field work was not necessarily performed (e.g. Bryant and others, 1981; Scott and others, 1978). Therefore this study included further delineation of these zones where possible.

CONCLUSIONS

The main findings of the regional fault study were:

1. The major fault traces shown on recent geologic maps of the region comprise mappable, linear zones of either faulting, shearing, or cataclasis.

2. The mapped faults examined in the study generally had been located accurately by earlier workers.

3. The faults are expressed by a variety of surface characteristics including fault breccia and/or gouge, slickensides and other shear features, crushing or pervasive fracturing, iron-staining, offset of geologic units, deformation of rock structure or fabric, sandstone dikes, igneous dikes, severe weathering, mineralization, and topographic or air photo linears. One or more of these characteristics are seen at different locations along each of the fault traces.

4. In general, the faults in the region are only intermittently exposed and portions are obscured or can be located only approximately from surface evidence. These fault sections often are not indicated as such on available geologic maps.

5. Quaternary deposits potentially useful for evaluating fault movement recency are sparse. Typical deposits include colluvium and talus derived from the crystalline rocks, grus and other weathering products, stream alluvium, and upland meadow deposits. Most of these deposits are Holocene in age (up to 10,000 years old) and are typically thin, intermittent, and difficult to correlate.

6. Older Pleistocene deposits (up to about 2 m.y. in age) occur sporadically, rarely overlying or on both sides of mapped faults. These include a series of pediment and alluvial deposits suitable for at least relative dating, multiple alluvial terraces in some major valleys, and glacial moraines. Remnants of Tertiary (Miocene-Pliocene) gravels also occur and are of local significance to recency of movement evaluations.

7. No evidence of recent movement was seen along faults not previously considered potentially active. The Black Hawk, Witter Gulch, No Name, Pine Gulch, and Platte River faults are locally overlain by apparently undisplaced Quaternary deposits for which at least relative ages could be postulated. These deposits are absent along the North Mill Gulch, Meridian Hill, 285, Deer Creek, Shawnee, Green Mountain, and Jackson Creek faults, where definitive conclusions on most recent fault movement do not appear feasible. Deposits that overlie these latter faults, although young geologically, apparently are undisturbed by faulting.

8. For faults previously considered potentially active, (i.e. in Kirkham and Rogers, 1981) the following observations relative to recency of movement can be made based on the study results.

   a. Floyd Hill Fault: Previously categorized as "potentially active" based on reported evidence for late Neogene offset of Tertiary boulder gravels and the Eocene erosion surface. The potentially active portion is shown as including the Ken Caryl fault splay but not the southern mapped segments of the Floyd Hill fault. Detailed studies of the Tertiary gravels north of Clear Creek and at Shaffer Hill revealed either no indication of faulting or the evidence was inconclusive, subject to differences of opinion. Study of Quaternary deposits along the trace suggests that the latest movement on the fault is at least pre-Louviers in age (60,000 to 125,000 years old) in the northern section at the Kermits Gulch locality, and pre-Slocum in age (125,000 to 190,000 years old) in the central section at Kittredge. Cretaceous igneous dikes in the southern section, near the South Platte canyon, do not appear offset.

b. Ken Caryl Fault: Previously shown as an extension of the "potentially active" Floyd Hill fault, but without specific evidence cited. Apparently undisplaced Quaternary deposits, including Slocum Alluvium, overlie parts of the fault. Trenching was proposed across the fault trace, the results of which subsequently confirmed that no displacement of the Slocum Alluvium has occurredthis (Harza, 1985b; Dickson and Paige, 1987).

c. Kennedy Gulch Fault: Study was limited to the northwestern part of the Kennedy Gulch fault, where Tertiary gravels and Holocene age deposits do not appear offset, but Pleistocene deposits are absent. The southeastern part of the fault, cited as potentially active, was investigated in detail by the DWD and others and is reported in Cochran (1984), Hornback (1984, 1985a, and 1985b), Shlemon (1984, 1985a, 1985b, and 1985c), Wallace and Friedman (1985), and ESA (1985).

d. Ute Pass Fault. Cited evidence for Tertiary and Quaternary movement on the Ute Pass fault is restricted to the southern part of the fault, between Woodland Park and Cheyenne Mountain. Neogene movement, based on reported offset of the Eocene erosion surface and Tertiary gravel deposits, is not disputed in this study. Evidence for Quaternary movement is described as "circumstantial" by Kirkham and Rogers (1981), and has not been established indisputably. The evidence is based on locations near Cheyenne Mountain which could not be fully evaluated due to restricted access. However, most of the fault trace north of Woodland Park was examined, and no evidence of Quaternary movement was observed. Parts of the fault in these areas are overlain by Pleistocene fan deposits and Holocene colluvium and alluvium, which are not disturbed.

e. Oil Creek Fault. Tertiary movement on this fault has been postulated on the basis of displaced Miocene-Pliocene gravels in the Divide area. This offset was not confirmed in the present study, but offset along splays to the east could not be disputed and late Neogene movement should be assumed. Quaternary movement on the fault is difficult to evaluate due to a paucity of datable soil units. Pleistocene glacial deposits (Pinedale and Bull Lake moraines) overlie part of the trace in the south and are not disturbed by faulting, establishing the most recent movement in that area as pre-Bull Lake (i.e. at least older than 125,000 years old). However, further north near Westcreek, a remnant colluvial deposit appears to be offset by the fault or a splay. This deposit, although not readily dated, is postulated to be early Quaternary in age based on circumstantial evidence obtained in this study. In the same general area, another fault splay is spanned in two locations by well preserved multiple terrace deposits that are not offset. The terraces are tentatively dated as pre-Bull Lake in age. The Divide earthquake of 1979 has been attributed by some to the Oil Creek fault (Butler and Nicholl, 1985).

f. Perry Park-Jarre Canyon and Rampart Range Faults. These faults, taken together, form a major part of the eastern boundary of the Front Range Uplift. Late Tertiary movement has been clearly demonstrated on both faults by displacement of the Eocene erosion surface and Oligocene rocks. The Perry Park-Jarre Canyon fault is not listed as exhibiting Quaternary movement and Pleistocene deposits overlying parts of the trace are not offset. However, Quaternary movement on the Rampart Range fault was postulated on the basis of reported offset of the Douglass Mesa Gravel by a splay of the fault at the U.S. Air Force Academy. The trace of the splay was located in the field study, but no evidence of offset was observed in the gravel. Trenches were proposed to help evaluate Quaternary movement. This trenching and other detailed studies in the Air Force Academy area were performed in 1985, the results of which are presented in Harza (1985c) and Dickson (1987). The presence of Quaternary faulting was revealed but the age of latest movement is assessed to be between 30,000 to 50,000 and 600,000 years ago.

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INVESTIGATION OF THE KENNEDY GULCH FAULT AT REYNOLDS RANCH PARK

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INTRODUCTION

This paper presents the results of investigations performed by ESA Geotechnical Consultants (ESA) in support of geologic studies for the Denver Water Department's (DWD) proposed East Slope Storage Projects. The study site, as specified by DWD, is located on Foxton Road approximately seven miles southeast of its intersection with Highway 285 in Jefferson County, Colorado. The primary objective of this study was to collect and document direct evidence in bedrock, surficial deposits, and landforms indicating the presence or absence of tectonic faulting and/or other tectonic effects within the area explored. The major elements of the ESA investigation were excavation and logging of an exploratory trench and road cut exposure, and mapping of Quaternary deposits and adjacent bedrock across photolineaments which may be associated with the Kennedy Gulch fault system. The results of this study were incorporated by others into a broader-scope evaluation of the seismotectonic framework of the central Front Range of Colorado (Geotechnical Advisory Committee, 1986).

This paper contains a summary of findings, a brief discussion of the geologic setting of the study site, and a narrative describing key features of the logged exposures. Although largely descriptive, the paper interprets the probable origin of bedrock structures and surficial deposits and their relative ages, based on field evidence. An unpublished report to the Denver Water Department (ESA, 1985), on which this paper is based, contains the complete detailed trench logs and full size figures from which the figures accompanying this paper were produced. The excavation, logging, and mapping methodologies employed in this investigation are essentially the same as those described in Appendix A of a previous report documenting the South Platte trench study of the East Slope Storage Project (ESA, 1984).

All aspects of this study were performed by or under the direct supervision of D.M. Yadon, ESA Senior Engineering Geologist. Drafting and clerical support were provided by ESA staff. Administrative, logistical, and field support were provided by V.Q. Hornback, S.G. Steele, J. Friedman, and D. Zavadil of the Denver Water Department. Enlightening discussions regarding the presence and significance of buried paleosols were held with Dr. R.J. Shlemon in the field.

GEOLOGIC CONDITIONS

Geologic Setting

The study site is located in Reynolds Ranch Park in Section 9, T7S, R70W on the Platte Canyon, Colorado 7.5-minute topographic quadrangle. The site occupies the lower southwest facing slope of Kennedy Gulch, northeast of the creek. As shown on Figure 1, the trench is located on the crest of a broad divide. The divide is flanked on the east by an intermittently-flowing drainage, and on the west by a local swale.

The site vicinity is underlain by Precambrian Idaho Springs Formation metasediments, migmatite and associated granitics (see Figure 1 and Peterson, 1964). Foliation within the Idaho Springs Formation is well developed and trends fairly consistently west-northwesterly with moderate to steep northeast dips. Examination of stereo-pairs of vertical color aerial photos revealed various photolineaments, as shown on Figure 1. A set of these linear features trends northwest through the area of the exploratory trench. Other lineaments trending more westerly are present southwest of the trench site. Northwest trending bedrock faulting of the Kennedy Gulch system is mapped by Peterson (1964) in the hills south of the creek. These possible fault splays are shown on Figure 1. Field mapping along the trend of the faults revealed some evidence of their presence. This included roughly linear segments of ridges and swales, local occurrences of sandstone dikes along the fault trends, and locally complex structure and hydrothermal alteration exposed in a shallow hand-excavated pit (presumably an old mine prospect). However, where the mapped splays cross Quaternary-age deposits, no evidence of their existence was found. Thus, if present, latest movement on these faults at least pre-dates deposition of the various overlying Quaternary units.

As shown on Figure 1, a variety of Quaternary to recent deposits are present overlying bedrock in the site vicinity. These include road fill, rock-debris slides, colluvial/talus deposits, alluvial fan deposits of various ages, stream channel gravels, and alluvial terrace deposits. The alluvial fan deposits have been tentatively subdivided into older and younger units based on geomorphic relationships and topographic position. The terrace units have not been subdivided, but may represent more than one episode of lateral stream cutting and deposition. An exposure of terrace gravels is present in the road cut immediately below the trench, but is too small to show separately on Figure 1.

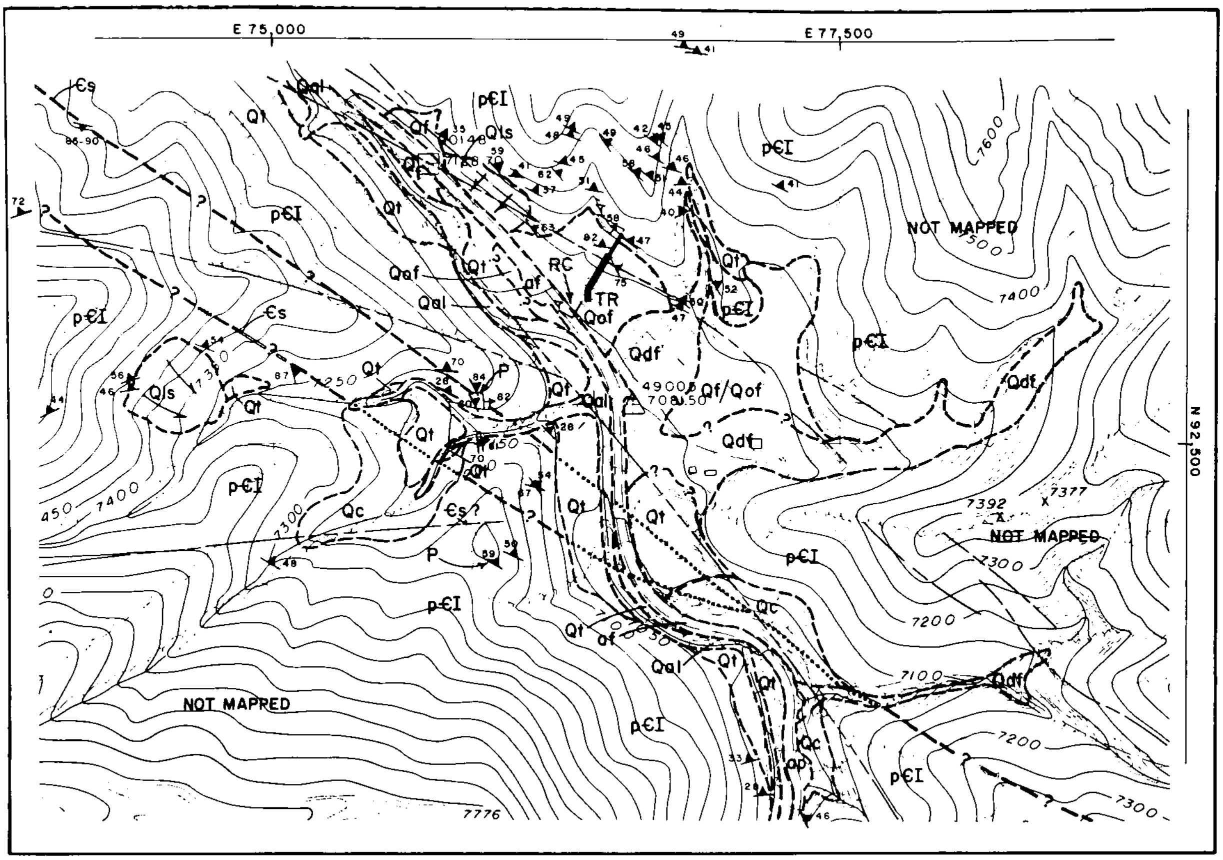
Exploratory Trench and Road Cut Exposures

An exploratory trench and road cut exposure were excavated in the locations shown on Figure 1. The trench location was selected to explore the preserved Quaternary section capping a low southwest trending divide. The trench was sited to intersect the northwest trending zone of photolineaments along the base of the hills northeast of Kennedy Gulch.

The trench was excavated with a 235 Caterpillar track excavator. Trench length was approximately 340 feet; depth varied from about six feet at the upslope end where bedrock was relatively shallow, to a maximum of 27 feet (machine limit) downslope where surficial deposits were thicker. The walls of the trench were benched in the deeper areas to facilitate logging. In order to extend coverage beyond the southwest end of the trench, a road cut exposure was developed along the existing cut slope on the northeast side of Foxton Road. The height of the road cut exposure was approximately 18 feet. A simplified cross-section showing interpreted geologic conditions as exposed in the trench and road cut exposures is shown on Figure 2.

Bedrock

Bedrock of the Idaho Springs Formation is exposed in the upslope end of the trench from station 0+00 to 1+13 as shown on Figure 2. The upper surface of



SCALE

0 500 1000 FEET

CONTOUR INTERVAL: 10 FEET

EXPLANATION

GEOLOGIC UNITS

	af	- Artificial fill
Quaternary	Qls	- Landslide deposits; typically shallow rock-debris slides
	Qc	- Colluvium/talus deposits
	Qdf	- Alluvial fan and debris flow deposits; typically cobbly, bouldery
	Qf	- Alluvial fan deposits; grades to colluvium/talus upslope
	Qof	- Older alluvial fan deposits
	Qal	- Stream channel alluvium
	Qt	- Fluvial terrace deposits; undifferentiated
Cambrian	€s	- Sandstone dike
Precambrian	p€I	- Idaho Springs Formation; gneissic granite, migmatite, monzonite, biotite gneiss, amphibolite gneiss in approximate descending order of abundance

SYMBOLS

- Geologic contact, dashed where approximately located, queried where uncertain
- Fault; dashed where approximately located, dotted where concealed, queried where uncertain
- Sandstone dike
- Photolineament from large-scale aerial photos
- Photo lineament from small-scale aerial photos
- Landslide, arrows show direction of movement
- 52 Attitude of metamorphic foliation
- 58 Attitude of shear
- TR - Exploratory trench
- RC - Logged road-cut exposure
- P - Hard-excavated pit (mine prospects?)
- A A' - Location of geologic cross-section

Figure 1. Geologic map of the Reynolds Ranch Park trench site.

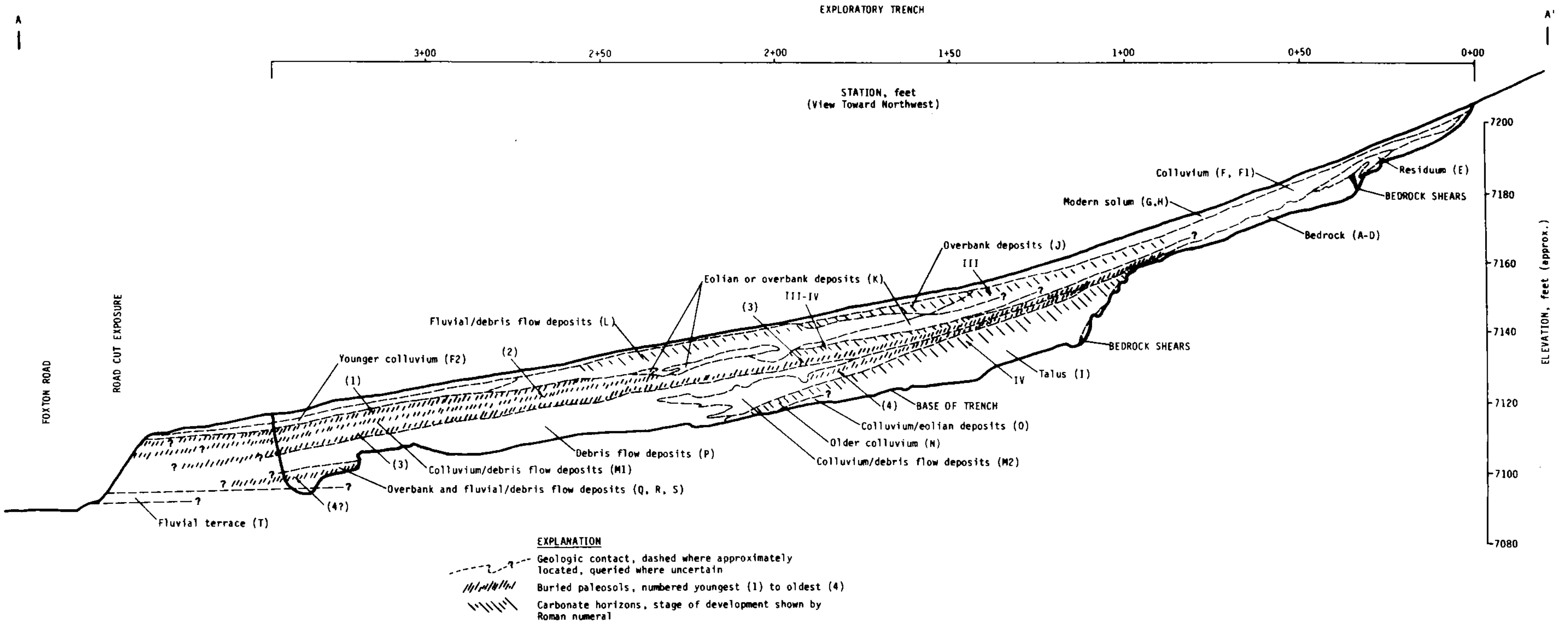


Figure 2. Simplified cross section of the exploratory trench at Reynolds Ranch Park.

the rock is very irregular in detail and locally grades imperceptibly to weathered residuum. Lithologies present include gneissic granite, migmatite, granitic rock (monzonite ?), biotite gneiss, and amphibolite gneiss, in approximate order of abundance. With the exception of intervals of relatively fine-grained granitics, the rock is moderately to very deeply weathered and closely to intensely fractured or jointed. Carbonate is pervasive, both as alteration of calcite veins and as secondary carbonate on fracture surfaces and interstitial to weathered grains.

The gneissic and migmatitic rocks exhibit moderately to well-developed foliation generally striking northwest with moderate to steep northeast dips. One prominent joint set is coincident with or subparallel to foliation throughout the rock section. Other joints and fractures are present at apparently random orientations. Bedrock deformation other than foliation or jointing was noted at two locations as described below.

At station 0+34 a bedrock fault is present juxtaposing gneissic granite in the hanging wall and migmatite in the footwall (see Figure 3). This fault is characterized by two subparallel shears trending northwest to north-northwest and dipping moderately to steeply northeast (generally conformable to foliation). The shears bound a zone of intensely fractured rock approximately six inches wide. The downslope shear is coincident with a prominent carbonate vein with well developed anastamosing shear fabric. Apparent drag folding evident in foliation and calcite/carbonate veins in the footwall block suggest a component of reverse movement, but amount of offset is indeterminant. The migmatite in the footwall block within five to ten feet of the fault is very weathered, and altered largely to clay and carbonate. The rock has a somewhat shattered and sheared appearance, although much of the apparent structure is relict jointing and foliation accentuated by weathering. A large block of granitic gneiss in the hanging wall of the fault is locally underlain by residual or colluvial debris terminating in a bedrock fracture. Deep weathering and downslope creep apparently resulted in opening and enlargement of the bedrock fracture in the near surface. Creep is also evidenced by local displacement of relict bedrock features in the deeply weathered residuum capping the rock. There is no evidence that the bedrock faulting extends into the overlying residuum, colluvium or modern solum. Local irregularities in the bedrock surface are best explained by differential weathering of contrasting lithologies.

As shown on Figure 4, the bedrock surface steepens from about 20-25 degrees to 50-55 degrees at approximately station 1+00. Bedrock is last exposed at approximately station 1+13 in the floor of the trench. The steep rock surface apparently continues beneath the trench, beyond the maximum reach of the excavating equipment. A zone of minor bedrock shears is present between stations 1+09 and 1+12 at the foot of the exposed portion of the steep bedrock surface. The shearing occurs where pods and lenses of relatively coarse-grained granitic rock have intruded amphibolite gneiss, biotite gneiss and gneissic granite. Orientations of shear surfaces are either nearly east-west with moderate dips to the north, or north-south with low to moderate dips to the west. The shears are characterized by undulating surfaces with waxy clay coatings; poorly developed slickensides are locally apparent. One of the shears is marked by a zone of vuggy, recrystallized amphibolite gneiss and concentration of calcite/carbonate. These shears appear to have formed under high temperature and pressure conditions, and are likely associated with emplacement of the granitic pods and lenses at much greater depths than at present. The talus, colluvium and buried paleosols overlying these shears are clearly not offset.

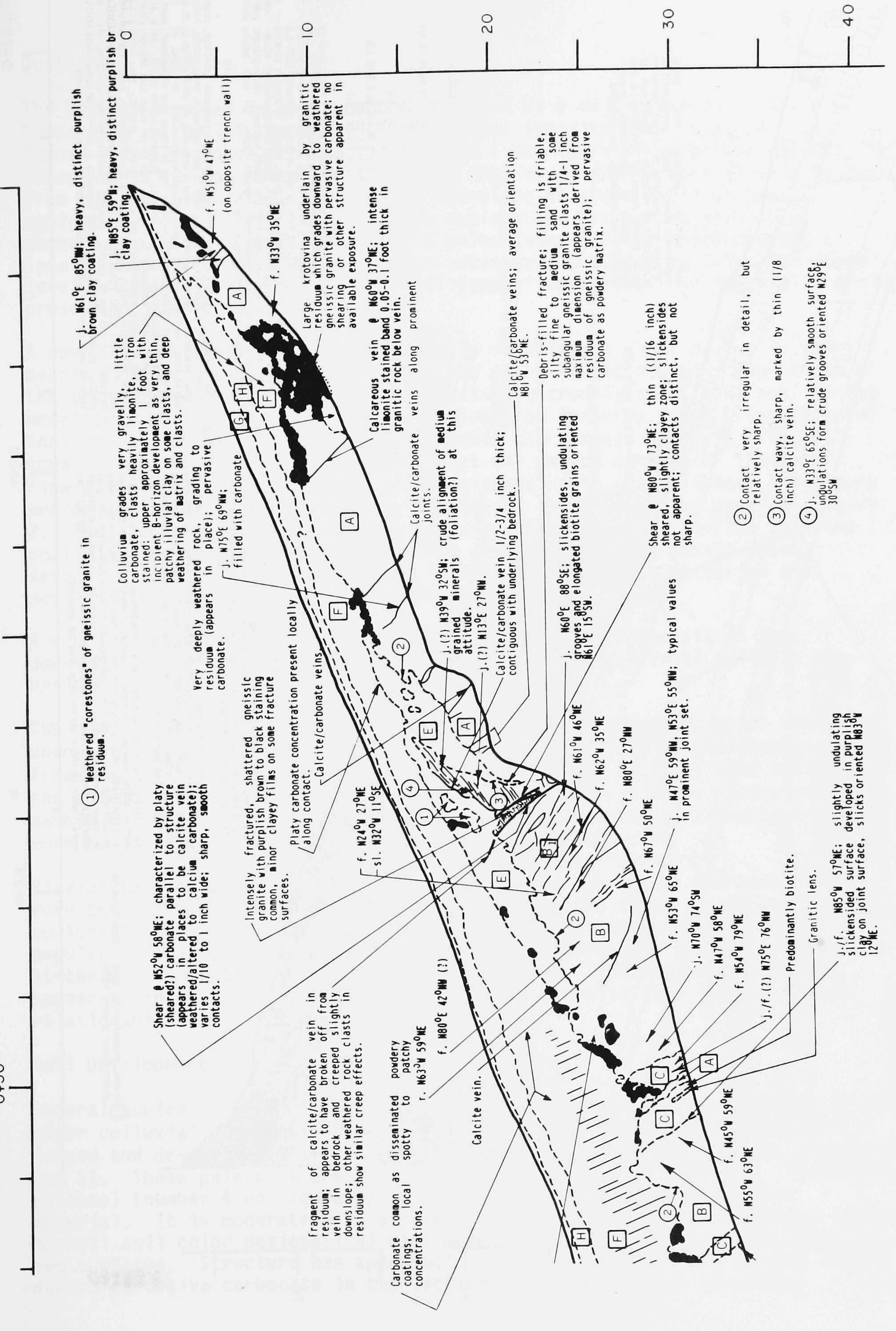


Figure 3. Representative protion of detailed log of the exploratory trench at Reynolds Ranch Park.

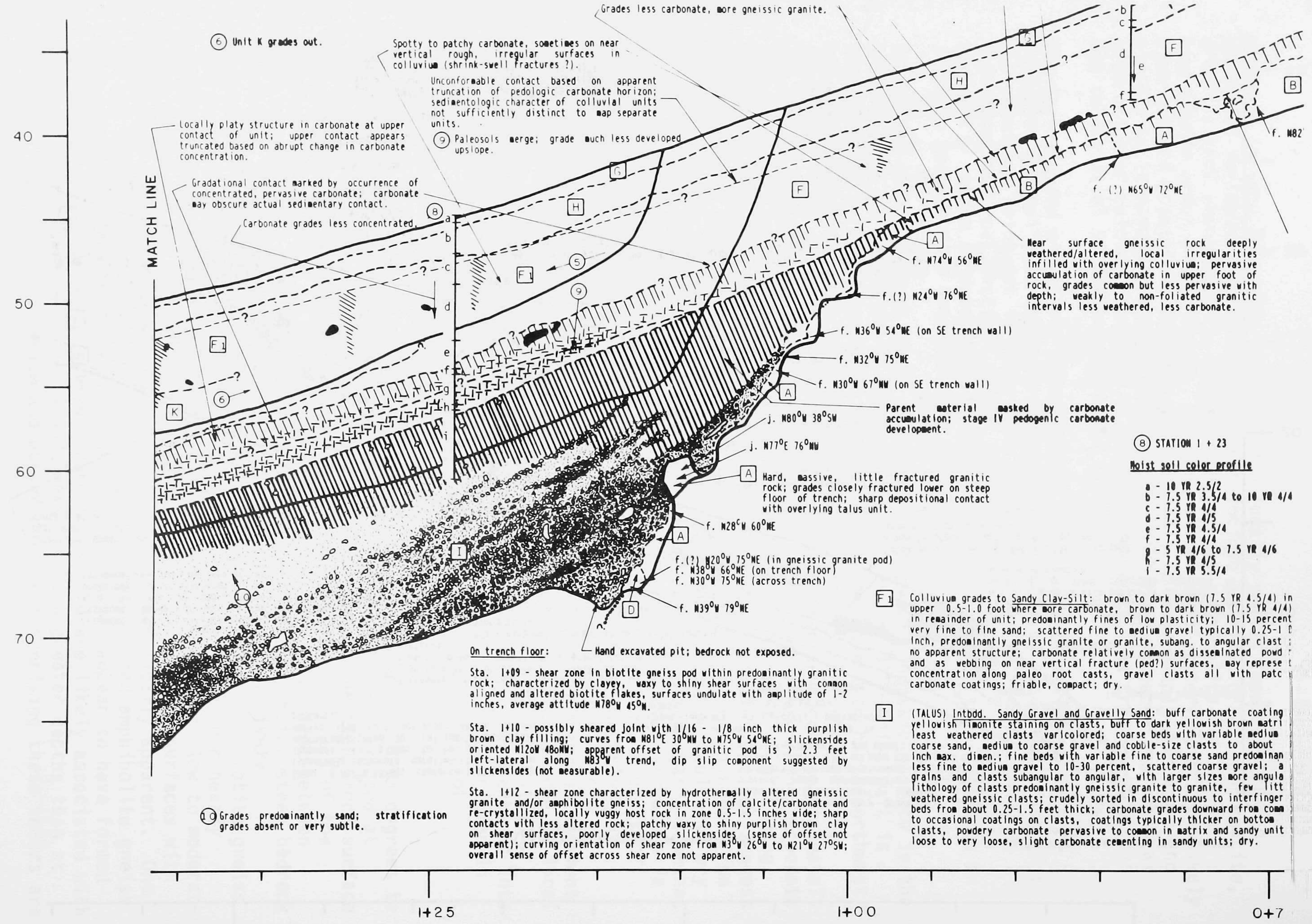


Figure 4. Representative protion of detailed log of the exploratory trench at Reynolds Ranch Park.

Quaternary Deposits

The bedrock exposed in the trench is covered by a well-preserved section of Quaternary colluvial, debris flow, and talus deposits (see Figure 2). A buried wedge of loose, coarse talus (unit I on Figure 4) is banked against the steep bedrock slope noted above. These angular fragments were clearly derived from outcrop immediately upslope and deposited at their angle of repose against the rock cliff. The simplest explanation for the relationships observed is that lateral erosion of a paleo-Kennedy Gulch creek created a locally oversteepened cliff which was subsequently buried by talus when base level dropped. Modern analogs of this type of topography and deposition are present at many locations nearby.

A downslope-thickening wedge of complexly interlensed older colluvial and debris flow deposits are present over the talus in the downhill two-thirds of the trench (see Figure 2). These deposits are crudely stratified and locally moderately well-sorted where fluvial deposition occurred. The orientation of thalwegs of local channelized fluvial sands and gravels indicate flow was toward the southeast. This suggests that the source of much of the debris flow material was the southeast trending swale north of the trench. Overbank and/or eolian deposits are locally present in the section, as shown on Figure 2. These units are typically much finer-grained and better sorted than the colluvial and debris flow deposits. As described in more detail later, several unconformities are apparent in this section based on buried soil development and erosional contacts between units.

A younger wedge of colluvium overlies the debris flow deposits at the downslope end of the trench. The upper portions of colluvial units in the upslope part of the trench may be of similar age.

The road cut downhill from the trench exposes the younger colluvium and underlying debris flow deposits present in the lower end of the trench. Small fragments of carbonized organic matter were noted in a clayey sand unit near the base of the exposure. However, they were too small and disseminated to sample for radiocarbon age dating. No other occurrences of carbonized matter were found in the road cut or the exploratory trench.

Fluvial terrace gravels (unit T on Figure 5) are present at the base of the road cut. These gravels are of similar lithology to those in the overlying colluvial and debris flow deposits, but are rounded to subrounded rather than angular to subangular. Apparently correlative subrounded gravels are present at the bottom of the downslope end of the trench. These fluvial deposits appear to interfinger with coarse debris flow deposits in a lateral facies relationship.

Soil Development

Several buried argillic paleosols are preserved within the finer facies of the older colluvial and debris flow sequence described previously. These are logged and described in detail on the trench logs (see, for example, Figures 4 and 5). These paleosols are also shown schematically on Figure 2. The oldest paleosol (number 4 on Figure 2) formed on silty to clayey sand parent material. It is moderately to strongly developed with 7.5YR to 5YR hue (moist Munsell soil color designation) with moderately well-developed clay films on ped surfaces. Structure has apparently been degraded to crude angular blocky due to pervasive carbonate in the section. This horizon is truncated

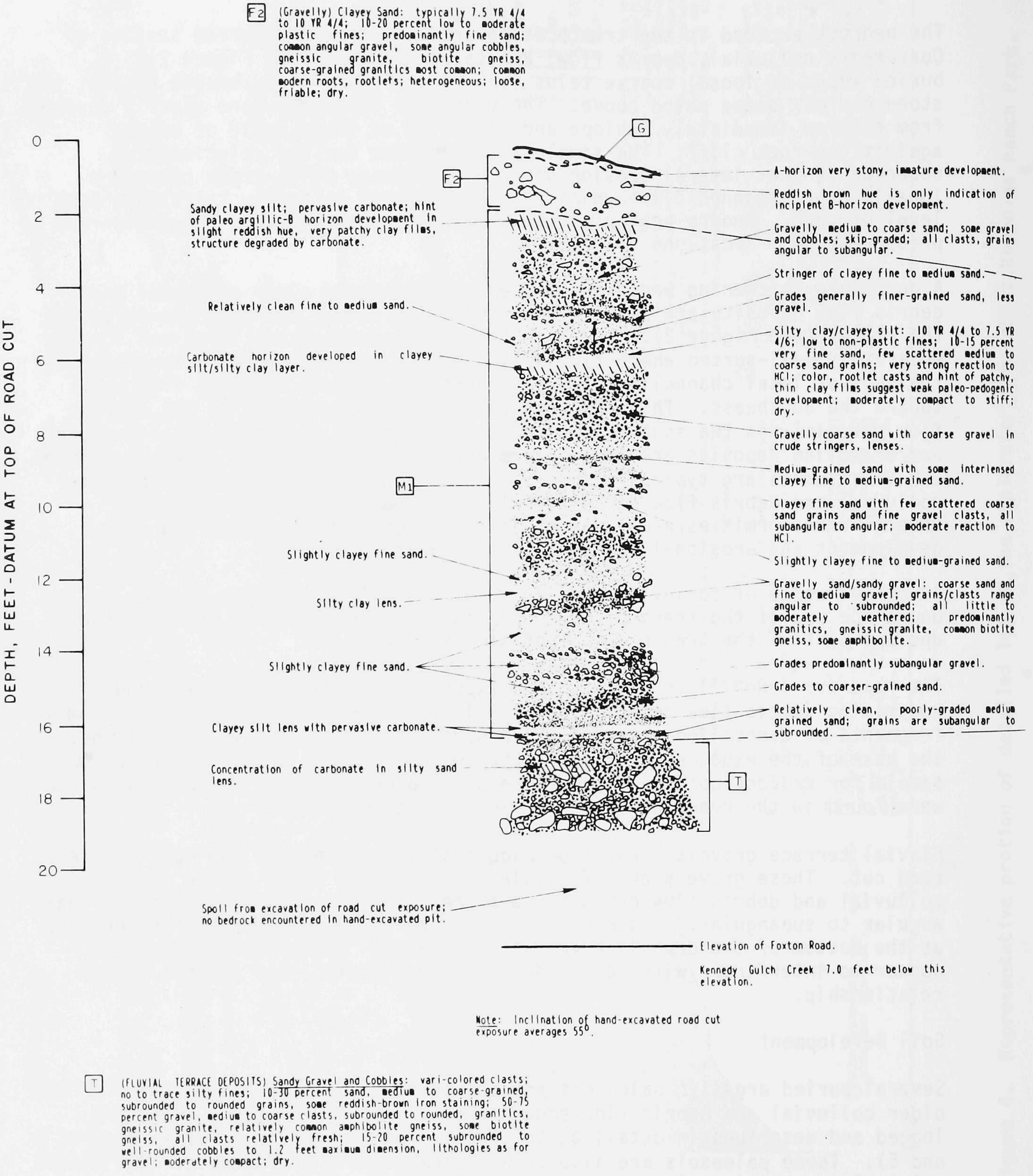


Figure 5. Detailed log of exploratory road cut exposure at Reynolds Ranch Park.

downslope by a fluvial channel deposit and merges upslope with paleosol 3. The strongly developed carbonates below paleosol 4 are interpreted as pedogenic calcic horizons (Bk and Ck) of stage IV development (Shlemon and Assoc., 1985). Weak to moderate paleosol development above the fluvial terrace deposits at the downslope end of the trench may be correlative to paleosol 4.

Paleosol 3 is the most extensive buried soil encountered. It extends from at least the downslope end of the trench to approximately station 0+90, where it merges with paleosol 4. The composite paleosol grades from strong to weak development upslope, and is no longer present by about station 1+15. Paleosol 3 is moderately well developed over most of its extent, with 7.5YR hue, crude angular blocky structure, patchy to well-developed illuvial clay films, and common rootlet casts. The lateral extent and degree of development of this buried soil clearly mark a significant unconformity in the section.

A third buried argillic soil (Paleosol 2) is present from about station 2+30 to the downslope end of the trench. The degree of pedogenic development grades from weak to moderate upslope, to weak downslope. There is some evidence of very weak development in the road cut exposure which may be correlative to this unit. Paleosol 2 appears to be truncated upslope by a coarser facies of the uppermost debris flow deposits, although the relationships are somewhat obscure.

The youngest argillic paleosol (number 1 on Figure 2) is very weakly developed, and is only present downslope of about station 2+50. Like paleosol 2, there is some evidence of correlative weak development of this youngest soil near the top of the road cut.

In addition to the calcic horizons described in association with paleosol 4, two other notable carbonate zones are present in the trench exposure. A laterally extensive zone of pervasive carbonate is present in the upper part of a colluvial/debris flow unit, and locally at the base of an overlying eolian or overbank deposit (see carbonate designated III-IV on Figure 2). Platy structure is locally present at the top of this carbonate horizon, particularly in the central portion of the trench. The generally sharp upper contact suggests that this horizon has been erosionally truncated. However, an unconformity is not readily apparent in the heterogeneous colluvial/debris flow deposits. This calcic horizon is interpreted as a pedogenic horizon of stage III to stage IV development. An apparently moderately-developed soil typified by vertical carbonate root fillings representing stage III development (Shlemon and Assoc., 1985) is present in the upper part of the trench from about station 0+90 to station 2+35 (see Figure 2). At about station 2+35, it appears to be truncated by the modern solum developing at the present ground surface. This pedogenic carbonate is superimposed on colluvial, debris flow, and overbank deposits.

A modern solum is present at the ground surface over the full extent of the trench, as shown on Figure 2. The profile typically includes an organic A-horizon ranging from a few inches to over a foot thick. An argillic B-horizon of moderate development underlies the organic horizon, except where the parent material is well-drained gravelly colluvium or debris flow deposits. Where present, the B-horizon is typically about a foot thick. In the upper part of the trench it may extend with weak development as much as two feet below the A-horizon. Development is typically weak to moderate, with strong brown (7.5YR 4/6) color, moderate prismatic to blocky structure, and generally thin, but continuous illuvial clay films. Humic staining is common on ped faces. Due to the active erosional environment at the base of the hillslope, the B-horizon is absent in the road cut exposure.

GEOLOGIC INTERPRETATION

As noted in the introduction, the main purpose of this investigation was to document geologic conditions exposed in the subsurface exposures and visible in existing exposures and outcrops. In order to place these detailed observations into their proper geologic perspective, the following interpretations are offered. These interpretations are based only on the data collected and reviewed during this investigation, and on fundamental geologic principals.

The character of, and relationships among, the bedrock and overlying Quaternary units exposed in the trench and road cut are consistent with normal erosional and depositional processes. No evidence of direct fault offset or secondary tectonic effects (such as liquefaction, folding, anomalous changes in depositional patterns, etc.) was found. The Quaternary units represent a complex history of erosion, colluviation, and debris flow in an alluvial fan environment. Evidence of at least six episodes of pedogenesis within the sequence indicates that it developed over many tens of thousands of years, and not during a relatively brief torrential episode.

As described previously, two areas of bedrock faulting were noted in the upslope portion of the exploratory trench, and evidence of possible bedrock faulting was observed along splays of the Kennedy Gulch system mapped by Peterson (1964). The faulting in the trench exposure is best explained as small-scale structural adjustments, probably related to formation of the Idaho Springs metasediments and migmatites, and/or subsequent regional deformation such as the Laramide or other orogenies. The association of calcite (subsequently altering to carbonate) and other apparent hydrothermal alteration with the faults, together with the brittle character of the shearing and fracturing, strongly suggest that the deformation occurred at great depth under conditions of high temperature and pressure.

As discussed by Shlemon and Assoc. (1985), the absence of any deformation or offset of Quaternary units and associated paleosols overlying the faults at about station 1+10 limits age of last displacement to at least 80,000 to 100,000 years before present. The bedrock "step" above this zone of faulting is best interpreted as resulting from differential erosion of contrasting lithologies. The available exposure suggests that the downslope rock is weaker amphibolite gneiss, and thus more susceptible to lateral cutting by the paleo-Kennedy Gulch creek than the much more resistant genissic granite upslope. The photolineament coincident with the bedrock "step" may be due in part to groundwater and vegetation control associated with the abrupt deepening of the Quaternary section. Also, this photolineament lies along a portion of a fence line which separates areas of contrasting land use (pasture to the southwest and open-space to the northeast).

The mapped splays of the Kennedy Gulch system southwest of the trench site shown on Figure 1 are based on the work of Peterson (1964) and field mapping by ESA. These faults appear to be very old features based on the absence of strong topographic expression, and the association of hydrothermal alteration in the mine prospect pit described previously. The age of last movement on these faults at least pre-dates deposition of overlying Quaternary units. Although the age of these units is unknown, they are interpreted as being relatively young based on their geomorphic expression and topographic location. No promising sites for subsurface exploration which might yield definitive data on the age of last offset of these features was identified in the area mapped.

CONCLUSIONS

The geologic investigations carried out at the Reynolds Park trench site have resulted in the following findings:

- The study area is underlain by Precambrian rocks of the Idaho Springs Formation. These rocks are overlain by a well-preserved section of Quaternary deposits on a local divide northeast of Kennedy Gulch Creek.

- The Quaternary section includes talus, colluvial, alluvial fan, debris flow, and associated deposits.

- A sequence of at least six paleo-pedogenic horizons occurs within the Quaternary section.

- No samples suitable for absolute age-dating were encountered in the subsurface excavations or in natural exposures.

- Bedrock faults, interpreted to have formed at significantly greater depths than at present, occur at two locations in the exploratory trench excavated for this study. Some evidence for bedrock faulting was found southwest of the trench site along trends originally mapped by Peterson (1964). All of the bedrock faulting is interpreted to be very old, as described later.

- Quaternary deposits and paleosols overlying the bedrock faults show no evidence of offset or other tectonic disruption. The relationships among the various Quaternary units and bedrock are consistent with normal geomorphic processes. No evidence of tectonically influenced erosional/depositional processes was observed.

- No evidence of recent tectonic faulting is present within the study area. The age of last displacement of faults exposed in the exploratory trench is judged to be at least 80,000 to 100,000 years before present (Shlemon and Assoc., 1985).

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INVESTIGATION OF THE KEN CARYL FAULT AT THE KEN CARYL TRENCH SITE, INDIAN HILLS QUADRANGLE, COLORADO

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ABSTRACT

Detailed investigations were conducted at the Ken Caryl trench site in Jefferson County to obtain and evaluate evidence of Quaternary faulting and to assess the minimum age for the most recent fault movements. Previous geologic mapping at the site had indicated the occurrence of datable Quaternary deposits overlying the Ken Caryl fault, a major splay of the Floyd Hill fault which has been indicated by others as potentially active.

A 192 m (630 ft) long trench was excavated to bedrock across an area that included the mapped trace of the Ken Caryl fault. The trench was geologically logged in detail and the surficial geology of the site and adjacent areas mapped.

Three major sedimentary units and their related pedogenic profiles were exposed in the trench. These and the bedrock-overburden contact are not offset by any tectonic features. The Quaternary sedimentary and soil units are thought to range in age from about 100,000 to perhaps as much as 250,000 years old. They all underlie a geomorphic surface at the site that extends completely across the mapped trace of the fault and which also shows no evidence of disruption by faulting. Because these deposits and the geomorphic surface show no evidence of tectonic disturbance, it is concluded that the latest movement on the Ken Caryl fault took place in this area more than 100,000 and possibly well before 250,000 years ago.

INTRODUCTION

This paper describes detailed geologic investigations at the Ken Caryl site conducted during 1985 as part of extensive seismotectonic evaluations for proposed East Slope water storage projects of the Denver Water Department.

The primary objectives were to collect and document evidence in bedrock, surficial deposits, and landforms that could be related to the presence or absence of tectonic faulting within the study area and to assess the age of the latest fault movements. The investigations involved excavation and logging of an exploratory trench and mapping of Quaternary deposits and bedrock exposures across the previously mapped trace of the Ken Caryl fault. This fault is a major splay of the Floyd Hill fault and both are indicated as potentially active by Kirkham and Rogers (1981). The site had been identified earlier as being suitable for investigation by trenching because of the presence of Quaternary deposits overlying the mapped trace of the Ken Caryl fault (Harza, 1985, 1985a; Dickson and others 1987). Interpretation of the ages of undisplaced Quaternary deposits overlying the fault provides a minimum age for the most recent fault movement and an indication of relative fault capability. The results of the 1985 investigations are documented by Harza (1985b).

Location

The Ken Caryl site is located in Jefferson County, 22.4 km (14 miles) southwest of Denver, on land formerly part of the old Ken Caryl Ranch. The site is shown on Figure 1 in the NE 1/4, sec. 36, T5S, R70W on the Indian Hills 7-1/2 minute quadrangle sheet.

Geologic Setting

The study area is situated on a dissected geomorphic surface sloping eastwards away from the Front Range foothills. It is in a broad valley between the Front Range foothills to the west and prominent hogbacks to the east and between Turkey Creek to the north and Deer Creek to the south. This piedmont area is drained by small intermittent streams that join to form Massey Draw, a tributary of Deer Creek.

The Indian Hills geologic quadrangle map (Bryant and others, 1973) shows that the mountainous area to the west is underlain by a Precambrian metamorphic rock complex of gneisses, migmatites, amphibolites, and quartzites. The broad Ken Caryl Ranch valley is underlain largely by sandstones belonging to the Fountain Formation of Pennsylvanian-Permian age. Sedimentary rocks ranging in age from Permian to Cretaceous occur to the east with more resistant units forming the prominent hogbacks.

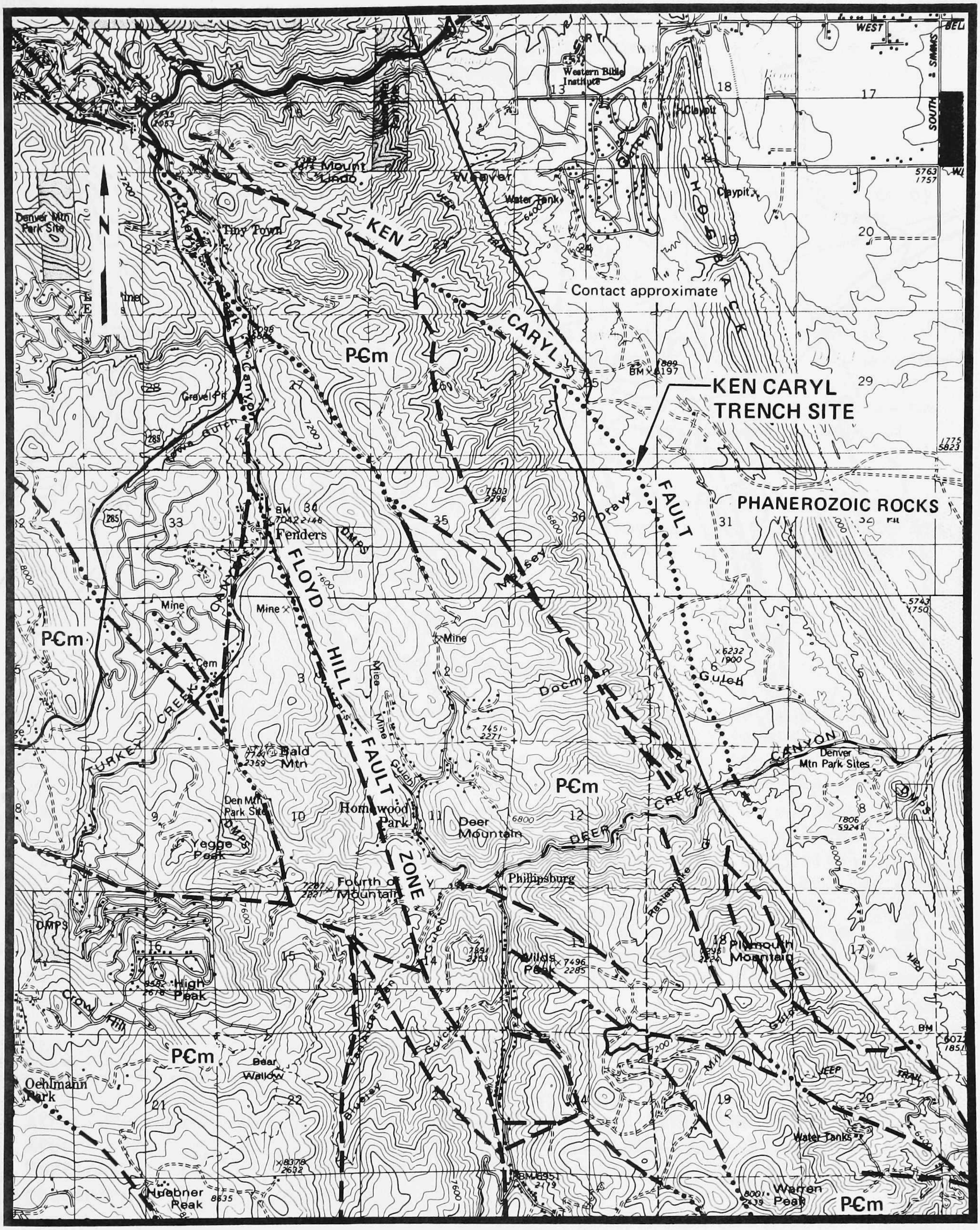
The Fountain Formation bedrock in the study area is largely concealed beneath various Quaternary alluvial and slopewash deposits. According to Bryant and others (1973), these include in order of decreasing age, Slocum Alluvium, undifferentiated older Pleistocene alluvium and colluvium, Pre-Piney Creek Alluvium, and Post-Piney Creek Alluvium. The source areas of these deposits are steep, narrow drainages in the mountain front to the west. Thus the provenance of most material is largely the Precambrian metamorphic rock complex, but also includes some reworked sand and rock fragments from the Fountain Formation.

The USGS map indicates that the older sedimentary formations dip mostly ENE at about 15° to 30° (Bryant and others, 1973). A segment of the Ken Caryl fault is shown passing through the study area concealed by surficial deposits. The closest exposures of the fault exist about 0.8 km (1/2 mile) to the northwest and south of the site. Bryant and others (1973, p. 6) infer that the direction of past-Fountain movement was predominantly dip-slip with the east side of the fault thrown up about 152 m (500 feet).

Geologic Mapping

Reconnaissance geologic mapping was conducted in 1984 along the entire length of the Ken Caryl and Floyd Hill faults, the results of which largely confirmed their previously mapped locations as shown on Figure 1 (Harza, 1985a). Additional detailed outcrop mapping was performed in 1985 in the vicinity of the trench site (Figure 2). Stereoscopic pairs of aerial photographs were also examined, revealing the absence of any linears crossing the area that could be attributed to tectonic structure.

Considerable construction activity associated with housing developments has taken place recently in the Ken Caryl Ranch area. Foundation excavations for roads and houses as well as pipeline trenches were routinely examined during this study as a further source of geologic information. The nearest exposures of the Ken Caryl Fault to the trench location were found 975 m (3,200 ft) to



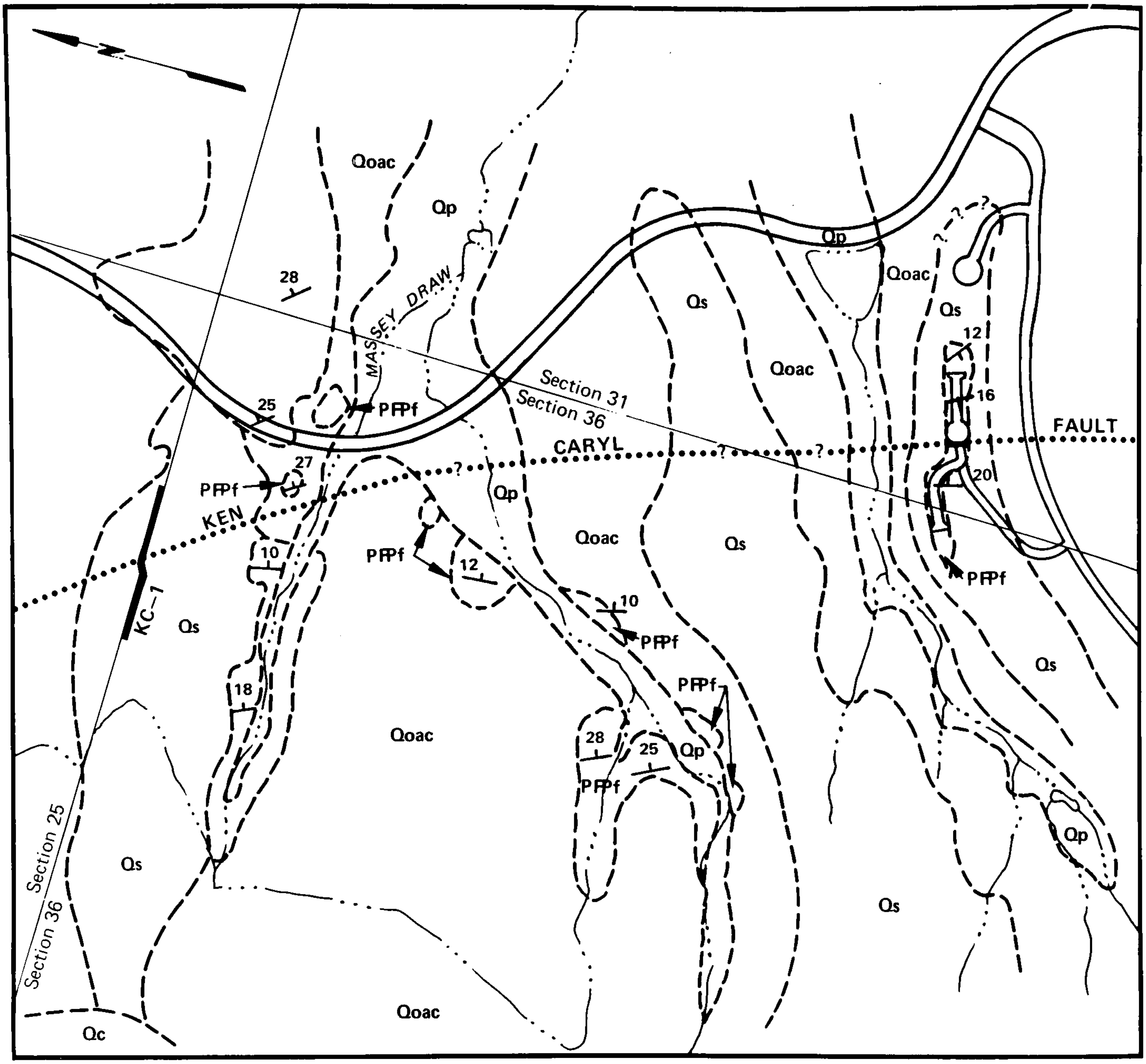
P€m	Precambrian metamorphic rocks
— — · · · ·	Faults, approximately located, dotted where concealed

Geology simplified from Bryant and others (1973)

Scale 0 — 1 Kilometer

Scale 0 — 1 Mile

Figure 1. Map showing location of Ken Caryl trench site, Indian Hills 7 1/2' Quadrangle, Colorado.



EXPLANATION

GEOLOGIC UNITS

af	Artificial Fill
Qp	Piney Creek Alluvium (Holocene)
Qc	Colluvium and Talus (Holocene)
Qoac	Older Alluvium and Colluvium (Pleistocene)
Qs	Slocum Alluvium (Pleistocene)
PPf	Fountain Formation (Permian/Pennsylvanian)

Scale 0 100 Meters

SYMBOLS

Geologic contact

Fault; dotted where obscured, U on upthrown side, location as shown on Bryant and others (1973)

10 Strike and dip of bedding

KC-1 Trench Location

NOTES:

1. Geology revised from Bryant and others (1973)
2. Topography from real estate plat, JR Developers Ltd., Englewood, CO
3. Some outcrops now obscured by contruction

Figure 2. Geologic map of the Ken Caryl site.

the south and about 1 km (3,500 ft) to the NNW. The former consists of a 15.2 m (50 ft) wide zone of highly sheared Fountain Formation (now obscured by new buildings) and the latter of faulted Precambrian hornblende and calcsilicate gneiss.

ACKNOWLEDGMENTS

Permission to enter the property to conduct the required work was granted by Valley Joint Venture of Littleton, Colorado. The assistance of Mr. Stan Brown, Development Manager, concerning access and site reclamation, is acknowledged.

The work was reviewed by the Geotechnical Advisory Committee of the Denver Water Department. Several interested geologists who were not part of this investigation team took time to visit the open exploratory trench and provided technical discussion in the field. These included Glenn Scott, Bruce Bryant, Rich Madole, and R.A. Wobus of the U.S. Geological Survey; Bob Kirkham of the Colorado Geological Survey; and several geologists from the U.S. Bureau of Reclamation, including Dave Allen, Ben Bennett, and Dean Ostenaa.

The administrative and logistical support provided by Denver Water Department staff Jack Parsons, Quent Hornback, and their geologists and surveyors during this study is greatly appreciated. Thanks are also due to Roy Shlemon who provided valuable interpretive expertise.

TRENCH GEOLOGY

Trench Excavation

A 192 m (630 ft) long exploratory trench, KC-1, was excavated by backhoe in the location shown on Figure 2. The trench location and alignment were selected to explore the preserved Quaternary section along the top of a low east-west trending ridge that extends completely across projections of the Ken Caryl fault trace. The ridge is the remnant of a dissected geomorphic surface capped by deposits shown by Bryant and others (1973) as Slocum Alluvium. The results of site reconnaissance and aerial photo examination suggested that the ridge was probably the best of several possible sites that would provide good prospects for preservation of older Quaternary deposits over the full width of the Ken Caryl fault trace. The excavation was oriented approximately east-west and reached bedrock along its entire length, the depth of the vertical cut ranging from 1.8 m to 5.2 m (6 to 17 ft), and its width averaging about 1.2 m (4 ft).

The south side of the trench was selected for detailed geologic logging which included descriptions of grain size, sorting, rounding, lithology, weathering, color (using the standard Munsell Soil Color Chart), contacts, and structures. The opposite trench wall was locally cleaned and examined in order to follow contacts, structures, or units in the third dimension. Portions of the log are shown for example on Figure 3. The complete logs are presented in Harza (1985b).

Bedrock Geology

Bedrock exposed at the bottom of the trench comprised various interbedded sandstone facies characteristic of the Fountain Formation. The two dominant lithologies are a moderately hard, coarse-grained sandstone, mostly yellow-brown to off-white (possibly bleached), and a moderately hard to soft shaley sandstone which is typically dark red-brown to purple and commonly micaceous. These alternate in massive and near homogeneous beds ranging in thickness from 0.3 m to 3 m (1 to 10 ft). Occasional thin red-brown to purple shale beds and gray-green sandstones also occur. Most contacts are sharp, but transitional facies are also present. Weathering is pronounced within the depth to which bedrock was exposed, and typically involves loss of cementation and mobilization of iron and manganese oxides, and possible bleaching of the characteristic red color in the sandstones. The differing physical properties among the interlayered sandstone beds resulted in the varying depth to which it was possible to excavate the trench.

Bedrock strata strike about N20°W with dips ranging from 10° to 30° to the east. No abrupt changes in dip or strike over short distances were apparent in the trench other than a slight dip-reversal which occurred a quarter of the trench length from the east end. Rock jointing is generally indistinct, probably largely because of the coarse-grained nature of the sandstone. The most prominent fractures are subvertical joints oriented about N-S to N20°W. Closely spaced fractures, some with conspicuous displacement and clay-infilling, are concentrated at three locations. Sheared rock occurs in two areas comprising zones of closely spaced jointing, slight brecciation, and strong staining by manganese and iron oxides. Considerable displacement may have taken place within these zones as indicated by the rotated fabric of some blocks between shear joints.

No area of obvious faulting, such as a zone of pervasive brecciation or gouge, was observed, despite the fact that the trench spans the mapped trace of the Ken caryl fault. The following possibilities are offered in explanation: 1) the fault by-passes the trench location; 2) the fault is manifested by the previously-mentioned shear zones; 3) the fault is present underlying the trench alignment and for some reason was not detected or recognized; or 4) the fault does not exist as a major rupture at this location.

The trench is thought to have been correctly located because geological reconnaissance had confirmed the mapped location of the fault in nearby exposures 975 m (3,200 ft) south of the trench site (see Figure 2) and about 1 km (3,500 ft) to the north. Several scattered outcrops of apparently unfaulted Fountain Formation, shown on Figure 2, constrain passage of the fault trace through a somewhat limited corridor which was spanned by the trench.

The areas of sheared rock observed in the trench are conceivably evidence of faulting, but are not comparable to breccia zones of undisputed faulted Fountain Formation seen elsewhere in the region. It is also possible that the fault in this area is manifest in subtle features that were not observed in the trench because of deep weathering or occurrence in a particular lithology that does not obviously display tectonic structures.

It is even conceivable that the fault does not, in fact, occur at this point, that it is a discontinuous structure at the bedrock surface, rupturing only a limited thickness of sediment cover above the Precambrian basement. This faulting style appears to be the case for the same fault south of Deer Creek and other faults in the region.

Geologic reconnaissance and air photo examination did not reveal any geomorphic evidence of surface breakage along the Ken Caryl fault except in the Precambrian terrain to the northwest of the study area. A geomorphic surface capped by deposits shown as Slocum Alluvium by Bryant and others (1973), extends across the fault trace at many locations with no apparent sign of disruption. It is therefore difficult to speculate on the presence or absence of the fault in the study area considering the paucity of outcrop data. Nevertheless, it is assumed that any logical projection of the fault does pass under the trench location. A more plausible explanation exists for its apparent absence in the trench than its bypassing the trench entirely.

Quaternary Geology

Stratigraphy

Three major geological units, each with related pedogenic profiles, are exposed in the trench and are described below as Units 1, 2, and 3.

Unit 1. A basal (oldest) fanglomerate deposit occurs unconformably on the Fountain Formation bedrock. It consists of a general fining-upward sequence of interbedded and lenticular sand, gravel, and cobbles with small boulders up to 0.6 m (2 ft) in diameter. A reddish color (Munsell 5YR-2.5 YR) is typical throughout the sequence.

The coarser-size fractions (Unit 1a on Figure 3, gravel, cobbles, and boulders) are more prevalent in the lower part of the section, but also occur as lenses and channel infillings elsewhere. Clasts consist of angular to subrounded rock fragments derived from Precambrian metamorphic formations to the west. Little or no stratification is apparent, while in places imbricate clast arrangement can be seen. Generally the mapped unit 1a is grain-supported, but in places is matrix-supported where there is a large sand fraction. Weathering of the rock fragments ranges from relatively fresh (rare and only applicable to quartz pegmatite and finer-grained felsic and quartz monzonite gneisses) to decomposed (common, especially in amphibolite and biotite gneiss fragments). Lenticular coarse-grained channel sands and sandy gravel facies (Unit 1b) are common. These deposits are poorly to well stratified and grade into or interfinger with other units.

Deposits of clayey silt and silty sand (Unit 1c) occur towards the top. These materials are generally rather uniform with only occasional coarse sand or pebble stringers. Stratification is faint to absent, marked only in places by thin laminae of clay or clean sand. Unit 1c contains vertical carbonate root and fissure infillings and thin horizontal carbonate accumulations (extending laterally up to 3 m, 10 ft), the depth and geometry of which suggest that they are remnants of a truncated buried paleosol (Bkb or Ckb horizons).

A discontinuous silty clay layer (Unit 1d) is present in two small areas and is thought to have resulted from localized ponding. This is enriched in carbonate (thin laminae, stringers, pore fillings, and grain coatings) and has a pink-gray color (2.5Y 4/2).

An unconformity separates the basal Unit 1 from the succeeding Unit 2. This is readily apparent throughout most of the trench, but in places is masked by carbonate accumulations (Units 2c and 2d). Evidence of the unconformity includes a) local erosional relief, b) truncation of vertical carbonate infillings of the buried paleosol Unit 1c, and c) the red color of the basal Unit 1 (Munsell 5YR-2.5YR-10YR colors), presumably derived mainly from reworked sands from the Fountain Formation and not pedogenic.

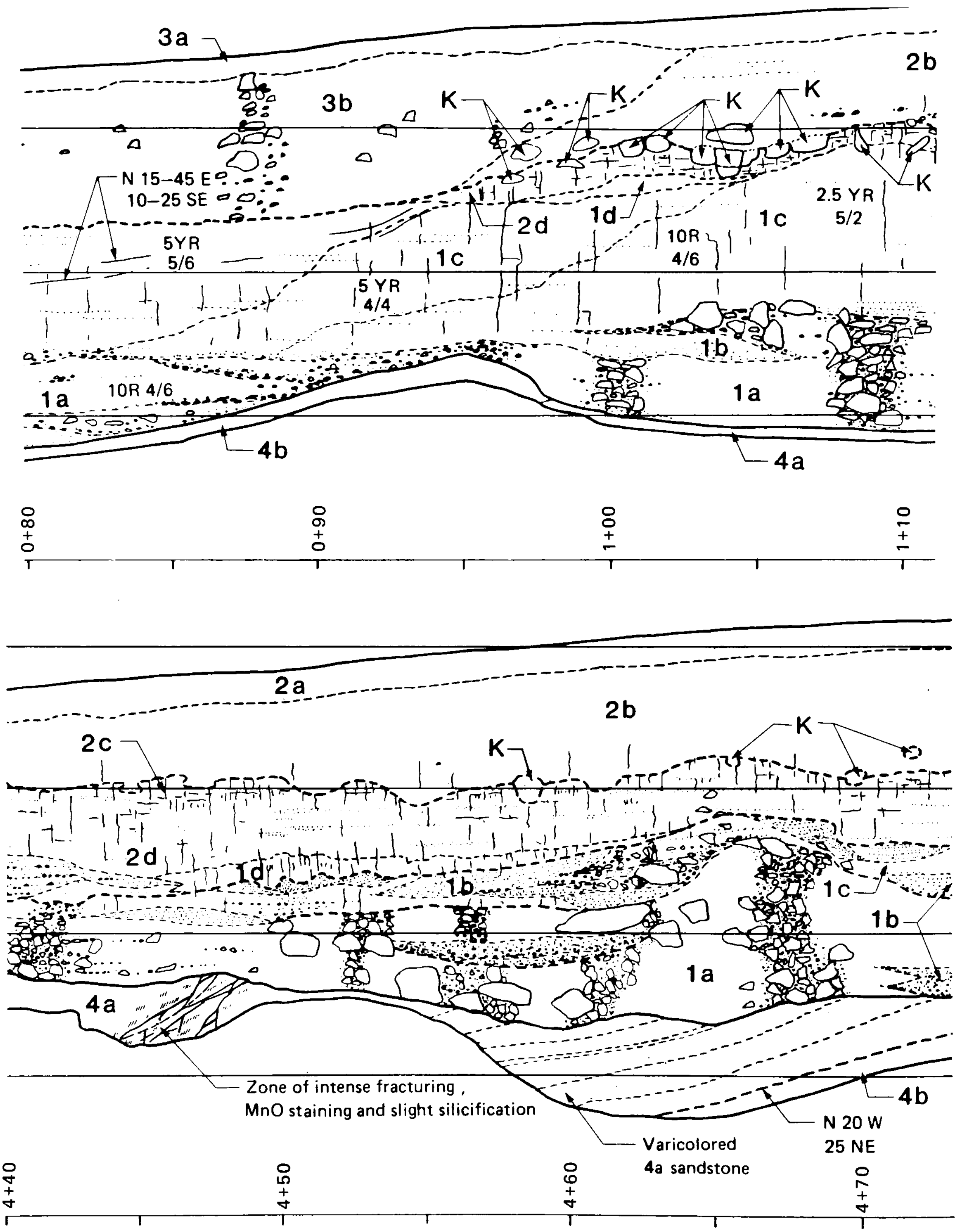


Figure 3. Two representative portions of trench log, stations 0 + 80 to 1 + 10 and 4 + 40 to 4 + 70. Stratigraphic subdivision of surficial deposits, as discussed in text, indicated by 1a-d, 2a-d, 3a-b; Fountain Formation bedrock, 4a and 4b; K signify Krotovina. Also indicated are Munsell Soil Colors and strike and dip of soil or bedrock units. Stationing in feet.

Unit 2. Deposits of clayey silts and sands with a few lenses of sandy gravel succeed the basal fanglomerate deposits. This geological unit bears a sequence of cumulic organic and weakly- to moderately-developed argillic soil horizons, 0.76 m to 1.5 m (2-1/2 to 5 ft) thick.

A sandy silt loam 15-40 cm thick (6-16 in) occurs at the top of the cumulic soil profile (Unit 2a). It is dark brown (10 YR), non-plastic, and being the modern organic horizon, contains much root matter. Some angular gravel occurs sporadically. The horizon grades downward to slightly clayey (slightly plastic) sand, dark yellow-brown (10 YR) to strong brown (7.5 YR) in color, with crude blocky structure.

The Bt argillic horizons comprise clayey silty sand (Unit 2b). These are red-brown (7.5 YR-5 YR) in color, fine- to coarse-grained, with slightly plastic fines, and some sandy subangular gravel lenses. Thin, continuous illuvial clay films line ped faces, fill root pores, and bridge mineral grains. The unit is strongly bioturbated and modern roots are common throughout.

Stage II carbonate accumulations are superimposed on the lower part of the argillic horizon (Bk). Multiple stage III carbonates of both pedogenic and groundwater origin (Ck) form a prominent, almost white, stratigraphic marker observed along much of the trench. These were logged as Units 2c and 2d and tend to mask the unconformable contact between Units 1 and 2.

Unit 3. Younger debris-flow deposits, consisting of poorly-sorted silty sand, gravel, cobbles, and small boulders, occur at the eastern and western ends of the trench. The unit truncates geological Units 1 and 2 and overlies bedrock at the western end of the trench. The materials mostly have a chaotic, dumped appearance. A faint stratification is apparent only in places, particularly where associated with rare sandy gravel channel infills. Although the unit bears a slightly- to moderately-developed soil, subdivision is harder than for Units 1 and 2.

An organic horizon (Unit 3a) occurs at the top of the sequence. This is similar to 2a, but is much thinner (15 cm [6 in] maximum thickness) at the eastern end of the trench. An argillic horizon (Unit 3b) occurs below this which is similar to 2b, but is thinner and exhibits a less developed blocky structure at the eastern end of the trench. It also contains more gravel and cobbles, including clasts of Fountain Sandstone not seen in 2b. Stage II carbonate accumulations (Unit 3c) are superimposed on the lower part of the argillic horizon. These are discontinuous in the eastern part of the trench, but are slightly more pronounced to the west.

Structure in Surficial Deposits

Within the trench, the well-exposed contact between bedrock and surficial deposits is clearly not offset at the locations of possible bedrock shears. Similarly, no deformation was observed in the various surficial units that could be attributed to tectonic disturbance. Primary sedimentary structures and those that are pedogenic, diagenetic, or groundwater in origin are all clearly undisturbed.

Vertical cracks infilled with carbonate are frequent in geological Unit 1 and have random orientations. They are interpreted to be non-tectonic in origin, probably pedogenic, and in many places are truncated by the unconformable contact with Unit 2. Some low-angle curving, discontinuous cracks are present in the upper part of Unit 1 in a limited area in the eastern part of the trench. These are carbonate-filled and dip at 10° to 25° to the southeast. They are thought to have been caused by shallow gravity movements, such as creep or slumping towards the southeast, possibly related to the time of erosion and deposition of Unit 3.

Interpretation of Quaternary Geology

From examination of the trench geology, the following sequence of events are interpreted in the Quaternary history of the study area:

1. Deposition of a basal fanglomerate (Unit 1) on top of an eroded bedrock surface during a period of regional alluviation.

2. Formation of a paleosol on this parent material during a period of relative landscape stability.

3. Truncation of the paleosol and deposition of Unit 2 in another period of instability and alluviation.

4. A thick cumulic soil profile formed on Unit 2 indicating that deposition was relatively slow and pedogenesis kept pace with sedimentation.

5. Truncation of Units 1 and 2 and their related soil profiles occurred with deposition of debris-flow unit 3.

6. Development of a soil profile on Unit 3.

7. Dissection of the pediment surface by recent stream erosion.

It is pointed out, however, that at the eastern end of the trench, Unit 3 soil is apparently forming on the eroded eastern edge of the geomorphic surface and therefore may not be a profile indicative of sediment age. On the other hand, at the western end of the trench, Unit 3 soil is more strongly-developed, with a cumulic character similar to that of the Unit 2 soil profile. It is possible of course that the two Unit 3 deposits and their related soil profiles at each end of the trench may not be contemporaneous.

It is important to note that geological Units 1, 2, and 3 all underlie and therefore comprise the depositional geomorphic surface (pediment of some authors, e.g. Scott, 1963; Bryant and others, 1973) extending across projections of the Ken Caryl fault. Examination of aerial photographs and topographic maps revealed that this surface is sufficiently high and removed from source areas in the mountains to the west, such that no sediments are currently accumulating on it. For this reason, most soils capping this surface are interpreted to be relict paleosols.

Age of Sediments

Approximate ages for the various deposits exposed in the Ken Caryl trench can be assessed by the relative development of both the relict and buried paleosols, and by the relative preservation of the geomorphic surface that all the units underlie. Dr. Roy J. Shlemon provided this assessment (Shlemon, 1985) and a summary of his findings is presented in Table 1.

Table 1. Ages of sediments and soils, after Shlemon (1985).

	Approximate Age	Equivalent Marine Isotope Stage
Unit 3 soil	50,000	
Unit 3	50,000	
Unit 2 relict paleosol	70-125,000	5
Unit 2	125-190,000	6
Unit 1 buried paleosol	190-250,000	7
Unit 1	250-275,000	8

These estimates are viewed as conservative (i.e. probable minimum ages) and are in agreement with the opinions of G.R. Scott and R.F. Madole that the soils bear evidence of considerable antiquity and are at least pre-Bull Lake, or equivalent to Slocum Alluvium, in age (personal communications in the field, 7/16/85).

CONCLUSIONS

Based on the study of soils and sediments exposed in the Ken Caryl trench and on geologic mapping in the study area, the following general conclusions can be drawn:

1. Sediments and related pedogenic profiles, ranging in age from about 100,000 to perhaps as much as 250,000 years old, are found in the trench and are not offset by any tectonic features.

2. The deposits underlie a geomorphic surface that extends completely across the inferred trace of the Ken Caryl fault. The surface also shows no evidence of disruption by faulting.

3. Because these deposits and the geomorphic surface apparently are undisplaced by faulting, it is concluded that last movement along the Ken Caryl fault in this area took place more than 100,000 and possibly well before 250,000 years ago.

4. The seismic hazard posed by the Ken Caryl fault is thus interpreted to be very low to nonexistent within the context of normally held seismic hazard or risk criteria.

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INVESTIGATION OF THE RAMPART RANGE FAULT AT THE AIR FORCE ACADEMY TRENCH SITE, COLORADO SPRINGS, COLORADO

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ABSTRACT

Detailed investigations were conducted in 1985 at the U.S. Air Force Academy (El Paso County, Cascade quadrangle), to document and evaluate evidence of Quaternary movement on a southeast-trending splay of the Rampart Range fault. Geomorphic features, in particular a swale trending across a gravel-capped pediment ridge, had been identified in previous studies and interpreted as prima facie evidence of Quaternary faulting. This feature, with other evidence, has resulted in designation of the Rampart Range fault as potentially active by others.

The investigations involved the excavation and detailed logging of two trenches, geological mapping of bedrock and surficial deposits in the site vicinity, and studying the geomorphology of the area. Aerial photographs and the results of geotechnical explorations for construction at the nearby Colorado Springs water treatment facility also were examined.

A 152 m (500 ft) long exploratory trench was excavated along the eastern slope of the pediment ridge and across the mapped trace of the fault to expose the contact between bedrock and overlying Douglass Mesa Gravel, a Quaternary pediment deposit. This trench revealed the presence of several bedrock faults that have resulted in the absence of 760 to 915 m (2,500 to 3,000 ft) of the Mesozoic bedrock succession. Slip-surfaces project up from most of the bedrock faults into the Douglass Mesa Gravel, indicating that subsequent movement has occurred in Quaternary time.

A smaller 23 m (75 ft) long trench was excavated across the swale on the ridge top. This revealed a slip-surface in Douglass Mesa Gravel at the base of the cut, inferred from trend and proximity to be equivalent to one exposed in the first trench. The fault is overlain by undisplaced swale-filling sediments, including a basal stoneline and a moderately-developed buried paleosol. This soil unit and covering sediments are considered to represent about 30,000 to 50,000 years of weathering and deposition.

Extensive landsliding has occurred in the study area. Some of this post-dates formation of the swale, and the fault assumed to underly it, but pre-dates Husted Alluvium of about 8,000 to 12,000 years age.

From study of the trench logs, local geomorphology, and the results of geologic mapping, it is concluded that the last fault movement in the study area occurred on a structure underlying the swale noted earlier by Scott (1970) and that this movement took place between about 600,000 and 30,000 to 50,000 years ago.

INTRODUCTION

This paper presents the results and interpretations of detailed geologic investigations conducted in 1985 at the Air Force Academy site. The work was performed as an integral part of extensive seismotectonic evaluations for proposed East Slope water storage projects of the Denver Water Department.

The study objectives were to collect and document evidence in bedrock, surficial deposits, and landforms that could be related to tectonic faulting along a portion of the Rampart Range fault, central Front Range, Colorado, and to assess the age of the latest fault movements. Published geologic maps show that the area is crossed by a splay of the Rampart Range fault. This is one of many regional faults indicated as potentially active by Kirkham and Rogers (1981). The investigations included excavation and logging of exploratory trenches and mapping of Quaternary deposits and bedrock exposures across the fault splay. Interpretation of the ages of undisplaced surficial deposits overlying the fault would then provide a minimum age for the most recent fault movement and aid in evaluating earthquake potential along the Rampart Range fault in particular, and in the Front Range in general. The results of the 1985 investigations at the Air Force site are documented in Harza (1985b).

The site had been identified during a regional fault mapping study conducted in 1984, as being suitable for investigation by trenching because of the presence of Quaternary deposits overlying the mapped trace of the fault (Harza, 1985a).

Location

The study site is located in El Paso County, about 15 km (9-1/2 miles) northwest of Colorado Springs (Figure 1), in the NE 1/4, Sec. 33, T12S, R67W on the Cascade 7-1/2 minute quadrangle sheet. Investigations focussed on trench excavations in the southwest corner of the U.S. Air Force Academy property. Geologic mapping extended west, however, onto land leased by the City of Colorado Springs for its Pine Valley water treatment facility.

Geologic Setting

The study site is situated in the dissected pediment area at the foot of the Rampart Range on a north-trending ridge bounded to the east and west by small valleys that drain north to West Monument Creek. This is the principal drainage of the area, emerging from a steep canyon in the mountain front. The area is vegetated by scrub oak, brush, and grasses, with occasional pine.

A comprehensive geologic report of the Air Force Academy was published by Varnes and Scott (1967). An accompanying geologic map shows a branch or splay of the Rampart Range fault traversing the southwest corner of the property. The main Rampart Range fault, a north-trending, regional, high-angle reverse fault, is a major component of the eastern frontal fault system of the Front Range. The trace of this main fault lies mostly just outside the western boundary of the Air Force Academy. The mapped splay is also a high-angle reverse structure, but trends about N25°W with a steep westward dip. It truncates a sequence of Mesozoic sedimentary rocks to the west and places them against the Cretaceous Pierre Shale to the east. This faulting is assumed to have occurred during the Laramide period of regional deformation.

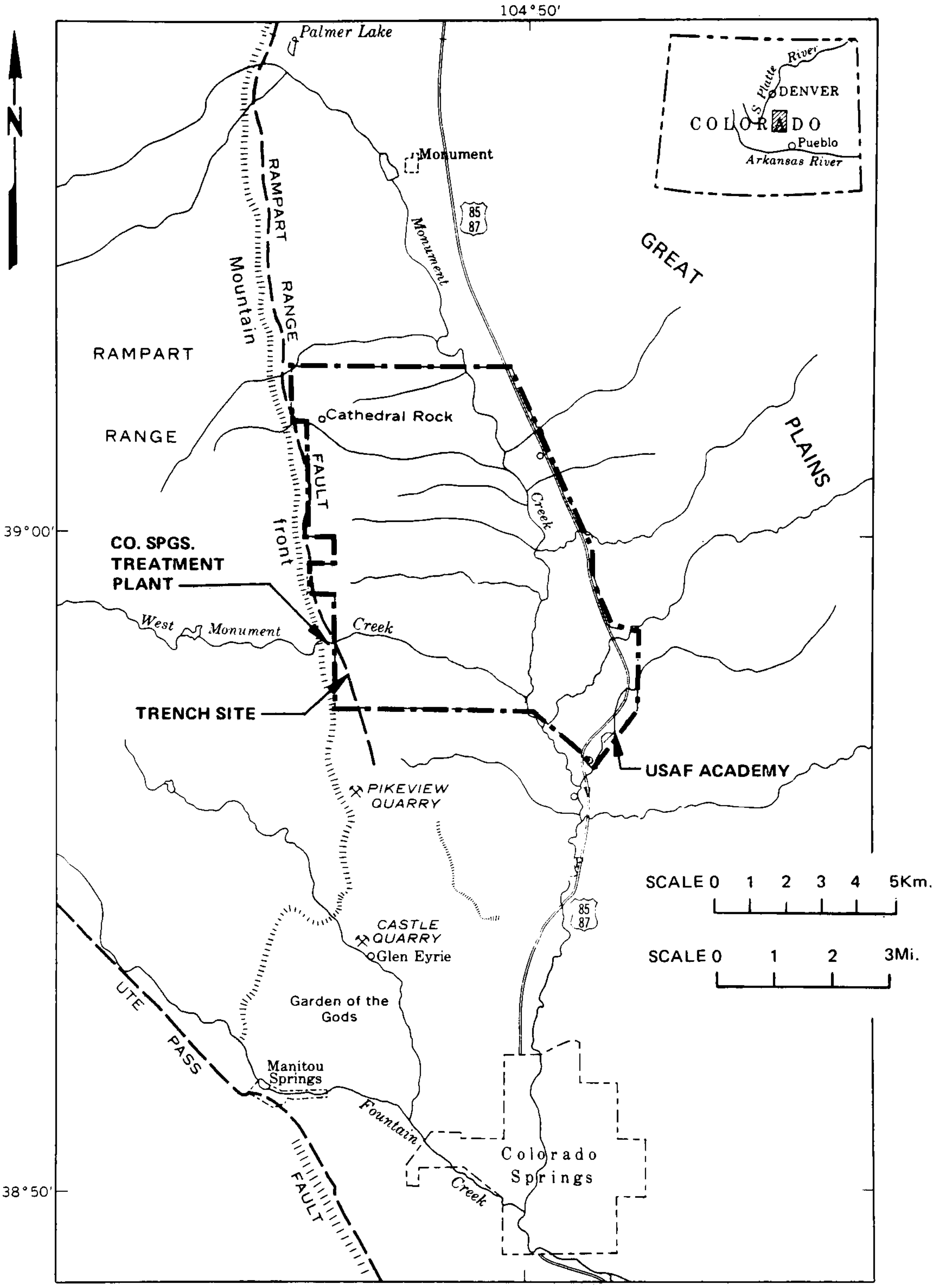


Figure 1. Location map of U.S. Air Force Academy, El Paso County, Colorado, modified from Varnes and Scott (1967).

Part of the fault trace is overlain by an eroded remnant of a Quaternary pediment gravel, shown by Varnes and Scott (1967) and Scott (1970) capping the north-trending ridge. This unit was mapped as Douglass Mesa Gravel, one of three pediment gravels occurring in the Academy area. Varnes and Scott (1967) did not indicate the Douglass Mesa Gravel as being displaced by the fault splay. However, further investigation at this locality caused Scott to revise this interpretation (Scott, 1970). He subsequently inferred that the gravels southwest of the fault had been displaced downward about 7.6 m (25 ft), a sense of movement opposite to earlier displacements, and with a possible slight right-lateral component. This movement supposedly resulted in the formation of an erosional swale across the ridge top. The presence of another swale trending south almost along the ridge crest, suggested to Scott that this is possibly evidence of an additional contemporaneous strike-slip branch of the Rampart Range fault. The location of these swales are indicated on Figure 3.

Kirkham and Rogers (1981) indicate the Rampart Range fault as being potentially active, citing the findings of Scott (1970) as evidence of Quaternary movement on the fault. Holocene alluvial deposits, however, are described as undisturbed.

A geologic reconnaissance study was conducted in 1984 along the traces of many major faults in the region, including the Rampart Range fault. This study established general fault characteristics and identified possible trenching sites in Quaternary deposits overlying faults. The results, reported in Harza (1985a) and summarized in Dickson and others (1987), confirmed the extent of the pediment gravels and the location of the truncated Mesozoic rock units in the south-western corner of the Academy. However, displacement of the gravels was not apparent and one or more trenches were proposed to expose the fault under the gravel.

ACKNOWLEDGMENTS

The work was reviewed by the Geotechnical Advisory Committee of the Denver Water Department. Several interested geologists who were not part of this investigation team visited the site and provided helpful technical discussion in the field. These included Glenn Scott, Bruce Bryant, Mike Machette, John Rold, Pat Rogers, Bob Kirkham, Bruce Stover, John Ivey, and several geologists from the U.S. Bureau of Reclamation including Dave Allen, Ben Bennett, and Dean Ostenaa. Glenn Scott kindly offered his opinions on bedrock stratigraphy and collected paleontological samples for further examination by himself and William A. Cobban of the U.S. Geological Survey. The results of their work were made available and are greatly appreciated.

The administrative and logistical support provided by Denver Water Department staff Jack Parsons, Quent Hornback, their geologists and surveyors during this study is appreciated. Thanks are also due to Roy Shlemon who provided valuable interpretive expertise and Earl Komie who reviewed the manuscript.

The Department of the Air Force is acknowledged for permission to excavate exploratory trenches on United States Air Force Academy land. Col. Willet R. Stallworth (DCS/Civil Engineering) and Mr. Mel Rezac (Chief of Natural Resources) arranged for the digging permit and reviewed the excavation and rehabilitation procedures. The Academy Department of Civil Engineering provided topographic maps of the area.

The City of Colorado Springs Water Department is acknowledged for use of the access road to the Pine Valley Filtration Plant, and allowing geologic mapping and geomorphologic studies in the area. Don Mulligan and Black and Veatch Engineering Company of Kansas City, Missouri, allowed review of air photos and geotechnical data pertaining to expansion plans for the existing water treatment facility.

FIELD EXPLORATION

Trench Excavations

Two exploratory trenches, AF-1 and AF-2, were excavated in 1985 at the locations shown on Figure 2. Following surface geologic reconnaissance, the location and alignment of trench AF-1 were selected so as to explore the contact between Douglass Mesa Gravel and underlying bedrock across the fault trace as shown by Scott (1970). The trench was extended as a side-cut bulldozer excavation for approximately 152 m (500 ft), with bedrock exposed throughout except in a few small areas. The smaller trench AF-2 was aligned across the topographic swale on the ridge top and measured about 23 m (75 ft) in length with a maximum depth of 2.4 m (8 ft). Both trenches were logged in detail and photographed. The geologic logging included descriptions of grain size, sorting, rounding, lithology, weathering, color (using the standard Munsell Soil Color Chart), contacts, and structures.

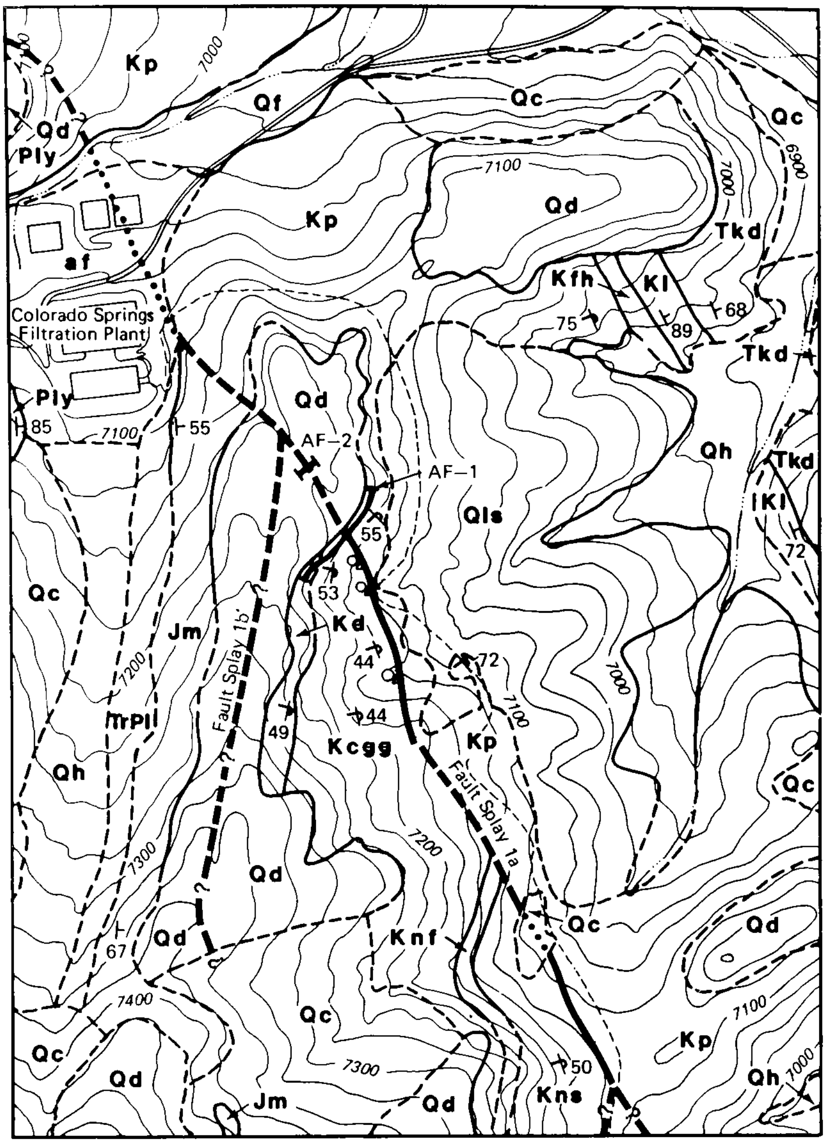
Geologic Mapping

Detailed field mapping was conducted in the study area to obtain information on: 1) topographic swales or other linear features observed on air photos that could be fault related; 2) bedrock geology in the vicinity of the trenching sites to aid interpretation of the trench stratigraphy and structure; and 3) surficial geology and geomorphology in the study area that could bear on interpretation of age and nature of ground displacements, including faulting and landsliding.

A revision of Scott's (1970) earlier geologic map was prepared from the results of geologic mapping (Figure 2). Examination of air photos revealed the presence of several distinct linear structures in the study area which were then field checked. The most prominent of these are indicated as A-A', B-B', C-C' and D-D' on Figure 3. Numerous north-trending and steeply dipping structures west of the Rampart Range fault are not shown on Figure 3 and were not investigated in the study.

The main trace of the Rampart Range fault (A-A' on Figure 3) is indicated by an indistinct lineament comprising discontinuous vegetative and soil linears. The fault is probably concealed beneath talus and colluvial deposits in most areas. A small branching lineament, indicated as B-B', occurs just north of West Monument Creek. Field checking found that it coincides with a fault zone previously mapped by Varnes and Scott (1967) in which Pierre Shale is in fault contact with upturned Dawson Arkose.

A 1.83 km (6,000 ft) long, southeast-trending lineament, marked C-C' on Figure 3, crosses West Monument Creek just north of the Pine Valley Filtration Plant. From its apparent intersection with the Rampart Range lineament to West Monument Creek, the lineament is indistinct and consists of several vague vegetative and topographic linears. Southeast of the creek to the trenching



EXPLANATION

GEOLOGIC UNITS

QUATERNARY
- af — Artificial Fill
- Qc — Colluvium
- Qf — Flood Plain Alluvium
- Qh — Husted Alluvium
- Qls — Landslide
- Qd — Douglass Mesa Gravel

TERTIARY
- Tkd — Dawson Arkose

CRETACEOUS
- Kl — Laramie Formation
- Kfh — Fox Hills Sandstone
- Kp — Pierre Shale
- Kns — Niobrara Formation, Smokey Hill Shale Member
- Knf — Niobrara Formation, Fort Hays Limestone Member
- Kcgg — Carlile Shale, Greenhorn Limestone, Graneros Shale
- Kd — Dakota Sandstone

JURASSIC
- Jm — Morrison Formation

PERMIAN / TRIASSIC
- Tr Pl — Lykins Formation

PERMIAN
- Ply — Lyons Sandstone

SYMBOLS

- Geologic contact, dashed where approximately located
- ?••• Fault, dashed where approximately located, dotted where concealed, queried where uncertain
- 50 Strike and dip of beds
- 67 Strike and dip of overturned beds
- Intermittent spring
- AF–1 Trench location

N

Scale 0 100 200 300 Meters

Scale 0 250 500 Feet

NOTES

1. Map modified from Scott (1970, fig.3)
2. Stratigraphy from Varnes and Scott (1967)
3. Topography from U.S. Air Force Academy

Figure 2. Geologic map of U.S. Air Force Academy site area.

site, it is expressed in the field by a prominent topographic swale and in places by vegetative linears. The structure is less distinct southeast of the trenching site, consisting of an aligned series of slight topographic and vegetative breaks. This entire feature coincides with the previously mapped trace of the Rampart Range fault splay (Varnes and Scott (1967), and splay 1a on Figure 2). For over 610 m (2,000 ft) southeast of the trench site, a fault could be mapped separating overturned and truncated Cretaceous rock units to

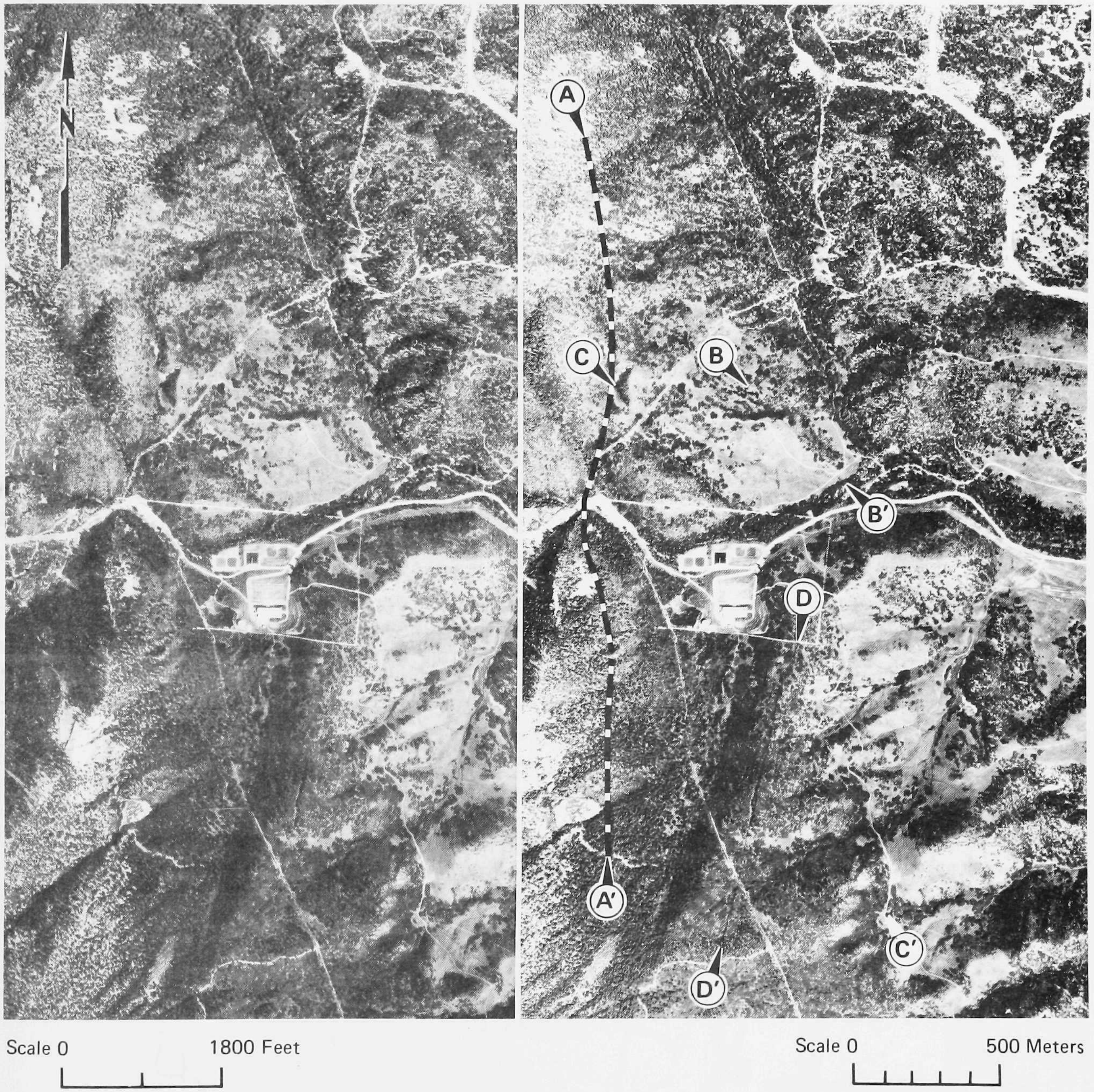


Figure 3. Air photo stereopair of U.S. Air Force Academy site showing lineaments A-A', B-B', C-C', and D-D'.

the west from Pierre Shale to the east. The attitude of the Pierre Shale is uncertain, but bedding is thought to be overturned, dipping steeply to the west and southwest, contrary to that shown on the earlier map. Mapping along this fault trace northwest of the trench found no exposure of a fault, but confirmed its earlier mapped location on the basis of float and regolith examinations. There is no apparent evidence that the fault displaces Holocene alluvium where it crosses West Monument Creek.

No exposure was found of the postulated south-trending fault splay indicated as 1b on Figure 2. However, its trace follows lineament D-D' on Figure 3 which is similar to C-C' and consists largely of a ridge-top swale, locally very prominent, and vegetative linears. Field reconnaissance revealed that this feature probably involves a series of smaller en echelon topographic linears. A fault in this area would simplify interpretation of the structural geology in that it would apparently separate east-dipping strata to the west from overturned, west-dipping units to the east.

Structures C-C' and D-D' are, according to Scott (1970), both prima facie evidence of Quaternary age faulting because they apparently affect or displace Quaternary deposits. It was concluded from air photo examination and field reconnaissance that these are the only geomorphic features that could be attributed to relatively recent faulting in the study area. Moreover, there is no geomorphic expression of any of the several faults discovered in trench AF-1 except that associated with lineament C-C'.

A major finding of the mapping study was the pervasive occurrence of mass movements of various scales mostly involving the Pierre Shale. Drill logs and excavations associated with construction at the water treatment plant indicate the presence of Pierre Shale overlying Quaternary deposits in several locations east and north of the trenching site. Remnants of landslide-displaced Douglass Mesa Gravel and Pierre Shale dominate the geomorphology just east of the trench site. Previous mapping indicated the presence of the early Holocene Husted Alluvium in the small valley on the eastern edge of the study area (Varnes and Scott, 1967). Drill logs supplied by the City of Colorado Springs and field observations confirm this, but, more importantly, also indicate that the Husted Alluvium overlies landslide debris. In addition, the ridge-top swale which forms part of lineament C-C' on Figure 3 is thought to be truncated on the east by a landslide scarp.

Extensive landslide deposits also probably occur north of West Monument Creek on the flank of the Rampart Range, but were not mapped in this study. Some are shown on an existing small scale map of the area (Trimble and Machette, 1979).

GEOLOGY OF TRENCHES

Trench AF-1

Bedrock Stratigraphy

Bedrock in trench AF-1 was exposed for almost the entire length of the cut face up to a depth of 3.4 m (11 ft) (Figure 4). In most parts of the trench, bedrock is highly deformed by folding and faulting and is severely weathered. These factors made recognition of stratigraphic units difficult and it is possible that stratigraphic designations may not be correct. The bedrock sequence in the trench becomes younger to the north and tentatively is thought to comprise the following Cretaceous units:

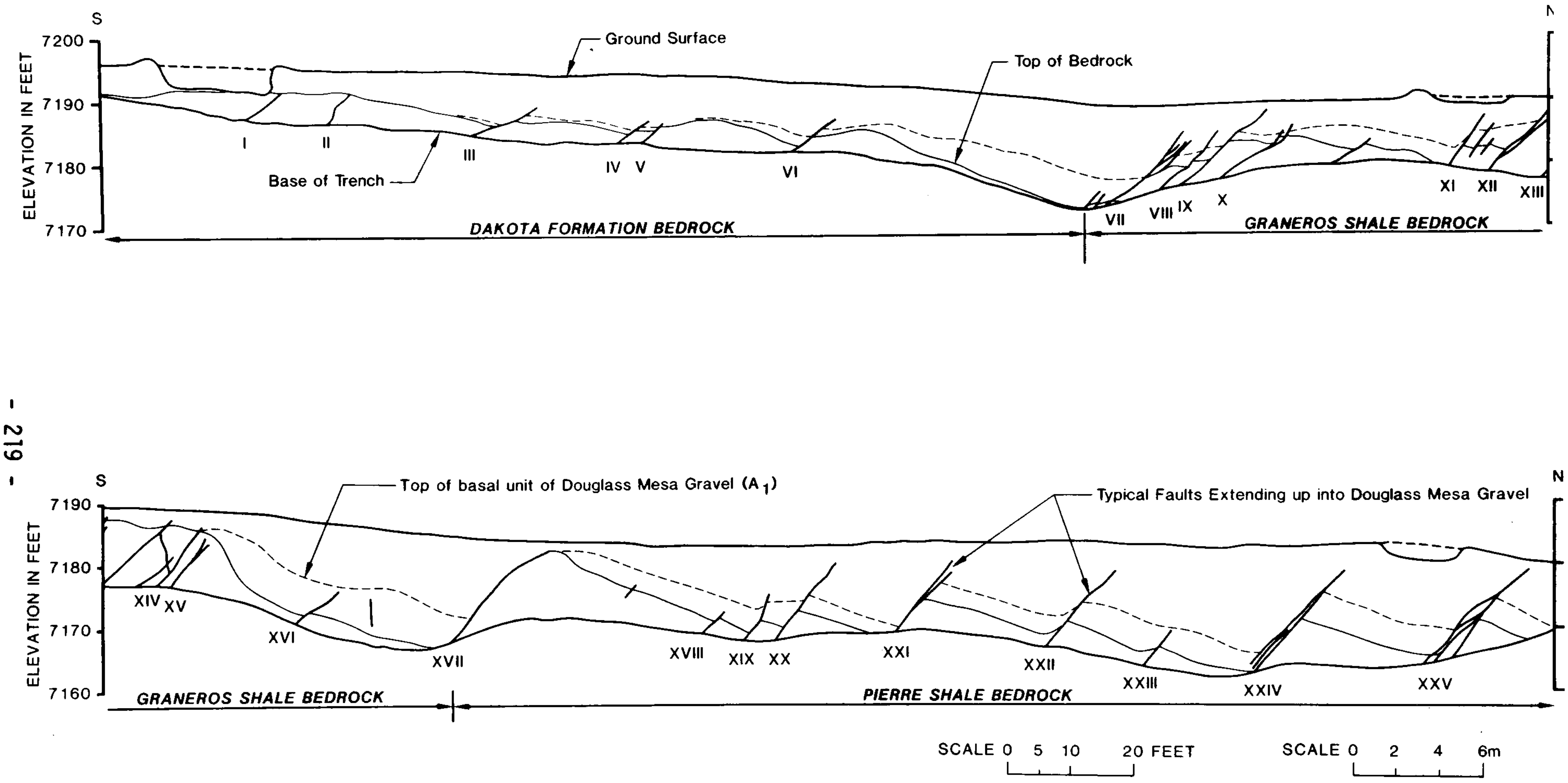


Figure 4. Summary log of Trench AF-1, U.S. Air Force Academy, showing location of faults I through XXV. Location of trench shown on Figure 2.

Dakota Sandstone(?). A sequence of predominantly fine-grained quartz sandstone, with interbedded siltstone and claystone layers or lenses, was logged in the first 47.3 m (155 ft) at the southern end of the trench. Tentatively this entire sandy sequence has been assigned to the Dakota Sandstone on the basis of mapped stratigraphic relations outside the trench (Figure 2). The sequence may, however, belong wholly or in part to older formations. If these units are not Dakota, then it is thought that they most likely belong to members of the Purgatoire Formation as described by Finlay (1916), and only remotely to the Morrison Formation.

Graneros Shale. A sequence of bentonitic shales, siltstones, and fine-grained sandstones was logged in the next 40m (130 ft) north and are referred to the Upper Cretaceous Graneros Shale.

Pierre Shale. Bedrock in the remainder of the trench consists of a generally uniform olive-brown to olive-gray shale. This has a variable sandy component, is slightly calcareous in places, and is locally quite fossiliferous. After examining fossils collected from this unit in the trench, Dr. William A. Cobban, Invertebrate Paleontologist at the U.S. Geological Survey, concurred with the opinion given at the site by Dr. Glenn Scott that the bedrock in this area probably belongs to the upper part of the Pierre Shale sequence.

Surficial Deposits

Materials overlying bedrock at the trench site reportedly belong to the Douglass Mesa Gravel (Varnes and Scott, 1967; Scott, 1970). This unit is one of three major pediment gravel formations occurring in the Academy area and has been correlated with the Verdos Alluvium of the Denver region (Varnes and Scott, 1967; Scott, 1970; Trimble and Machette, 1979) which has been assigned an age of about 600,000 years on the basis of a dated ash (Pearlette Type O Ash; Machette and others, 1976; Van Horn, 1976).

The Douglass Mesa Gravel at the trench site is a poorly stratified fanglomerate and debris-flow sequence consisting of bouldery and cobbly gravel with coarse sandy layers. The deposits were derived from the Rampart Range to the west and as such are almost entirely the products of weathering and erosion of Pikes Peak Granite.

Subdivision of the Douglass Mesa Gravel was not attempted by previous workers. However, during logging of trench AF-1, several sedimentary units were distinguished. These generally have gradational contacts and are probably discontinuous. They have little stratigraphic significance other than providing evidence of sedimentary and tectonic structures within the sequence as a whole. An exception to this generalization is found in the basal unit (A_1 on Figure 4). In contrast to the rest of the sequence, which is basically granitic, this unit contains a relatively high percentage of gravel-sized sedimentary rock fragments, mostly derived from nearby Paleozoic and lower Mesozoic formations. Other minor components, including volcanic rock fragments, bear similarities to lithologies found in Tertiary gravel deposits southwest of the Rampart Range. No ash layers were observed, however. As indicated by the disparate provenances, it is probable that the entire sequence represents a considerable time span of sedimentary deposition.

The only continuous soil horizon present in the AF-1 trench is a thin organic A horizon, or mollic epipedon. A weakly-developed argillic horizon occurs locally, typified by yellow-red (Munsell 5 YR) colors and clay films lining ped faces. It is, however, discontinuous.

Structure

Bedding of rocks exposed in the trench ranges in strike from about N15°E to about N40°W and dips moderately steeply, 45° to 65°, mostly to the west and southwest. From stratigraphic relations, it is deduced that the bedrock strata are overturned.

Primary sedimentary structures in the Douglass Mesa Gravel include bedding, small cut-and-fill channels, and some slump features. The majority of slumped units, however, could have deformed at any time up to or after faulting. It is thought that in many instances, localized slumped areas, involving both bedrock and surficial units, are a reflection of the unstable pediment surface, which is underlain by weak betonitic formations.

Several faults were mapped in the trench, many of which project up into the overlying Quaternary Douglass Mesa Gravel (indicated by Roman numerals on Figure 4). They range in strike from N20°E to N30°W and dip steeply, 45° to 80°, to the west and southwest, similar to bedding. Some smaller offsets apparently die out in the gravel, whereas the larger slip-surfaces pass almost to the top of the trench where they can no longer be distinguished in the uppermost units which probably are not in situ but rather the product of creep, mass-wasting, etc. Fault zones in the gravel range in width from 0.15 to 0.6 m (0.5 to 2 ft) and commonly contain rotated clasts, many re-aligned along the plane of shear.

It was interpreted from field relations that compressional deformation took place first, with the formation of high-angle reverse faults, probably in late Laramide time. Bedrock moved up on the southwest side of these faults relative to units on the northeast side. Later extensional deformation occurred in the Quaternary involving normal-type slippage on several of these pre-existing fractures and other planes of weakness. It is possible that some new normal faults were formed at this time. This period of faulting resulted in units dropping down on the southwest side of the faults, opposite to the earlier sense of displacement.

The earlier phase of deformation resulted in the loss of a considerable portion of the stratigraphic section and locally the formation of secondary drag-folds. Stratigraphic units that are notably absent include the lower Pierre Shale, the Niobrara Formation, the Carlile Shale, the Greenhorn Limestone, and some, or possibly all, of the Dakota Sandstone. The total amount of absent stratigraphic section is unknown, but could be as much as 760 to 915 m (2,500 to 3,000 ft). In addition to faulting, most lithologic contacts show evidence of varying amounts of displacement or bedding plane shear along them.

In trench AF-1, more than 29.3 m (96 ft) of Quaternary dip-slip displacement is indicated by offset of Douglass Mesa Gravel beds and of the overburden-bedrock contact. The amount of strike-slip displacement is not known, but is interpreted to be relatively minor as only dip-slip type slickensides were observed. In addition to dip-slip movement, over 27.4 m (90 ft) of rotation, or tilting, is indicated, with strata at the northern end of the trench downdropped relative to the southern end.

Possible evidence of tectonic thickening (or wedging) in the Douglass Mesa Gravel is seen only in the basal unit A_1. The amount, extent, and its interpretation are however complicated by two factors: contemporaneous soft-sediment deformation (slumping) which may or may not have been earthquake-related, and a probable angular unconformity separating the basal unit from its successors.

The uppermost soil layer, the organic A horizon, is not displaced by any fault structure. Other pedologic units are hard to discern and are poorly preserved, if developed at all, due to the non-depositional, or erosional, location. Thin and weakly developed pedologic profiles are present in places and do not show any evidence of tectonic displacement. However, although these overlie faults, they are discontinuous and cannot be easily correlated.

Discussion. There has been a history of faulting at the site, but the style of deformation has changed through geologic time from a compressional to an extensional regime (see discussion in Warner, 1985). Information on Quaternary recurrence is sparse. The presence of an angular unconformity above the basal Douglass Mesa Gravel unit and the different provenance of this material from other units, suggest that a period of tectonism (possibly minor) occurred early in Douglass Mesa time before later faulting caused displacement of all Douglass Mesa units.

Trench AF-2

The objective of the smaller excavation, trench AF-2, was to investigate the sediments and their related soil profiles in the topographic swale on the ridge top, earlier postulated as the geomorphic manifestation of an underlying Quaternary age fault. It could be argued further that it is the expression of the latest movement on one of the several faults observed in trench AF-1. Moreover, this was considered to be probably the only location in the study area where the geomorphic aspect (i.e. the swale) has permitted sediment accumulation and the development of a more significant soil profile than found in trench AF-1 over the fault trace.

Stratigraphy and Structure

The trench was excavated into Douglass Mesa Gravel for its entire length. Three distinct geological units were identified overlying the gravel and partially filling the swale (Figure 5). These comprise: unit 1, a basal stoneline and coarse sand layer bearing a moderately-developed buried paleosol; unit 2, an intermediate-level clay with very coarse columnar structure (vertisol); and unit 3, an upper, granular unit bearing the modern, dark-colored soil organic horizons (mollic epipedon). Dr. Roy J. Shlemon has made comprehensive descriptions and interpretations of these units (Shlemon, 1985).

A slip-surface, possibly tectonic in origin, was exposed at the base of the trench in the cobbly granitic Douglass Mesa Gravel (Qdm on Figure 5). From trend and proximity, it is inferred that this slip-surface might be a continuation or splay of the largest fault seen in trench AF-1, fault No. XVII. Evidence of the slip-surface is lost in the upper 0.3 to 0.38 m (12-15 in.) of the Douglass Mesa Gravel, a zone of structureless, weathered parent material (Coxb) probably affected by creep and bioturbation (Qdma on Figure 5 and analogous to the uppermost units of trench AF-1). The overlying geological units 1, 2, and 3 are not displaced by this slip-surface.

The basal stoneline unit (unit 1) mantles the bottom of the swale, is about 0.4 m (16 in.) at its thickest, and is interpreted to be derived from the

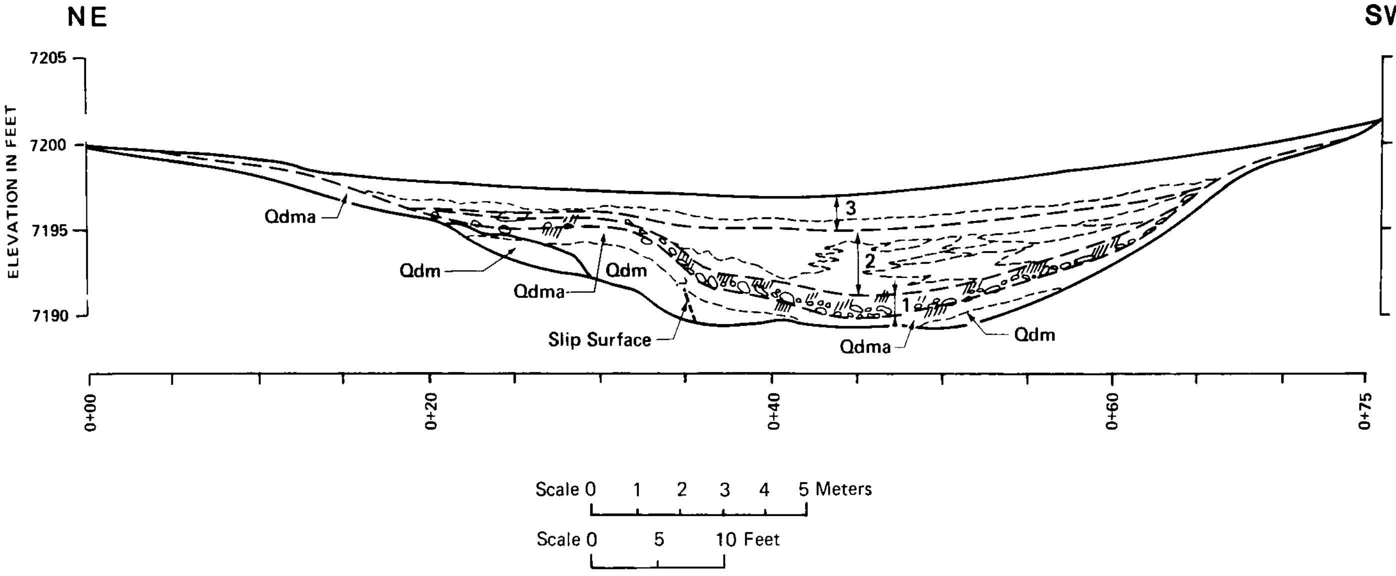


Figure 5. Log of Trench AF-2, U.S. Air Force Academy site, excavated across ridge-top swale, location shown in Figure 2. Qdm is Douglass Mesa Gravel; Qdma is zone structureless, weathered Douglass Mesa; Units 1, 2, and 3 are displaced sevale-filling sediments and related soils described in text.

adjacent sideslopes. The cobbles and pebbles are granitic, subrounded, and mostly highly weathered, in some cases decomposed in situ to grus. These clasts and their coarse-grained sandy sediments bear a moderately-developed buried paleosol (Btb) characterized by an argillic qone with common, moderately-thick, yellowish-red (Munsell 5 YR 4/8) clay films lining ped faces and filling tubular pores. Fines are sticky and slightly plastic. A slight calcic horizon is also present in this zone, with the carbonates consisting of diffuse coatings on some less weathered clasts and as small nodules (less than 1.3 cm [1/2 in.] dia.) within the clayey sand matrix (stage II calcic horizon of Gile and others, 1966). The buried paleosol and its parent material pinch out on the steeper swale margins but might exist as a small 3 m (10 ft) lens at the northern end of the trench.

At its thickest, geological unit 2 is about 1.4 m (4-1/2 ft) thick. It consists mainly of a brown (10 YR 5/3) clay with a strong, coarse columnar structure. In places, especially near the swale margins, the unit incorporates lenses of clayey coarse sand and scattered granitic pebbles. Manganese stains are common on pressure faces but are thought to be derived from the overlying unit 3. This clay unit is interpreted by Shlemon (1985) to be primary in origin, deposited almost entirely from slopewash rather than from pedogenesis. Shlemon also notes that accretionary swale filling is indicated by the gradual-smooth lower contact with the buried paleosol of unit 1.

Geological unit 3 attains a thickness of almost 0.6 m (2 ft) but thins considerably to each side of the swale. It is mainly a brown (7.5 YR 4/2 - 10 YR 5/3), fine granular clay loam, similar to the mollic epipedon seen in trench AF-1. A cambic, or possibly weak argillic, horizon occurs in the lower 15 cm (6 in.) of the unit. Other indistinct pedogenic horizons are probably also present but were not differentiated. An abrupt-smooth lower contact separates this unit from clays of unit 2.

Soil-Stratigraphic Age Assessment

Estimation of the age of undisplaced swale-filling sediments exposed in trench AF-2 was accomplished by soil stratigraphic and geomorphic assessment. The principal factors influencing this assessment were:

1) The presence of a moderately-developed paleosol in unit 1, indicating that the swale existed for perhaps thousands of years before slow accretionary swale-filling took place with deposition of unit 2 clays;

2) The slow deposition of unit 2 clays probably represents a long period of time because the swale occurs on a topographic divide and its drainage, or source, area is very limited;

3) The gradual-smooth contact between unit 2 clays and the buried paleosol of Unit 1 is indicative of slow accretionary infilling;

4) The abrupt-smooth contact between units 2 and 3 (probable unconformity) might reflect a regional climatic/sedimentologic change; and

5) Considerable time must have elapsed since deposition of the basal stoneline for many clasts to have decomposed in situ to grus.

It was concluded upon evaluation of these factors that the buried paleosol of unit 1 and its covering sediments represent about 30,000 to 50,000 years of weathering and deposition (Shlemon, 1985). The buried paleosol may in fact be considerably older, possibly comparable to post-Louviers age soils, the parent material of which may be about 100,000 years old.

CONCLUSIONS

The primary objectives of the study were to collect and document evidence, by geologic mapping and trenching, that could be related to the occurrence of faulting in the Air Force Academy study area and to assess the age of the latest movement on these faults.

The presence of faults in the study area as shown by previous workers has been confirmed. However, the southeast-trending splay of the Rampart Range fault, which was the main object of study, was found to consist of a multiple fault zone in trench AF-1 and not a simple planar structure. It is recognized that the trench might not have covered the full width of the fault zone. The fault zone existed, wholly or in part, prior to deposition of the Quaternary Douglass Mesa Gravel. The faults probably formed as high-angle reverse structures in late Laramide time as a result of compressional deformation. As much as 760 to 915 m (2,500-3,000 ft) of the Cretaceous bedrock section may have been faulted out.

Subsequent movements in Quaternary time resulted in displacements along the pre-existing faults exposed in the two trenches and possibly the creation of new faults. These displacements are evidenced by offset of the overlying Quaternary Douglass Mesa Gravel. Of critical importance is the assessment of the age of latest movement on the faults. This assessment takes into account the main findings of the field investigations which are summarized below:

1) The site tectonic history involves Laramide reverse faulting and Quaternary normal faulting. The latter might have been preceded by another tectonic episode early in Douglass Mesa time, as evidenced by an angular unconformity and provenance differences.

2) The age of the Douglass Mesa Gravel is estimated to be about 600,000 years old. Faults that displace this unit must therefore be younger than 600,000 years old.

3) Only one of several faults appears to have any geomorphic expression. This is a topographic swale on the Douglas Mesa Gravel surface which was interpreted previously as prima facie evidence of Quaternary age faulting (Scott, 1970). It is assumed that the youngest fault movement to occur in the area took place on the fault underlying this swale.

4) Trench AF-2 was excavated into the swale-filling sediments and exposed a buried paleosol and other soil horizons extending undisplaced across the swale and overlying a slip-plane at the base of the trench. The buried paleosol and its covering sediments are interpreted to represent about 30,000 to 50,000 years of weathering and deposition, and perhaps considerably more (Shlemon, 1985).

5) Landsliding on the east side of the ridge caused truncation of the swale and a reduction in the source area for swale-filling sediments. This landsliding post-dates formation of the swale (and the assumed causative faulting) but pre-dates Husted Alluvium in the valley to the east. Husted Alluvium is early Holocene in age, say 8,000 to 12,000 years old. The landslide deposits, therefore, could be considerably older.

6) Holocene alluvium is not apparently displaced where the Rampart Range fault splay (or splays) cross West Monument Creek.

From the main findings outlined above it is concluded that the last displacement in the fault zone probably occurred on a fault underlying the swale noted earlier by Scott (1970). This movement is judged to have taken place between about 600,000 and 30,000 to 50,000 years ago. It is conceivable that later movements may have occurred on other faults, some of which may not have been trenched. This, however, is not considered likely because of the lack of geomorphic evidence in support of such an argument.

Although Quaternary faulting in the study area is not denied, it should be noted that at least some of the observed offsets in Quaternary deposits might be attributable to mass movements involving structurally weakened, weathered, and in some cases bentonitic, bedrock. Landsliding and slumping involving the Pierre Shale is well-known in Colorado and in at least one area has been interpreted as the origin of geomorphic features previously attributed to tectonic faulting (West, 1977).

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GEOLOGY OF NORTHWEST-TRENDING FAULT ZONES IN THE EAST-CENTRAL COLORADO FRONT RANGE

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ABSTRACT

Detailed studies of fault zones proximate to proposed alternate sites for major water storage reservoirs in the east-central Colorado Front Range were carried out as part of a comprehensive geotechnical program by the Denver Water Department. The purpose of these studies was to assess seismicity as it would affect the location and design of dams. Geological mapping, bedrock trenching, and core drilling were accomplished to determine the nature of prominent linear topographic valleys, previously mapped by the U.S. Geological Survey as containing through-going faults.

The Kennedy Gulch, Willow Creek and Shawnee faults were found to be broad fault zones comprised of no or limited amounts of outcrop, broken rock, and numerous, small, discontinuous faults and shears. The fault zones, as far as is known, are continuous structures, but there are no strong, single strand, faults running the entire length of the fault zones. They are typical of the dozen or so prominent northwest-trending fault zones in the central Colorado Front Range. As a result of the geotechnical investigations it has been shown that the most recent movement occurred along these fault zones more than 190,000 y.b.p. (years before present). It is apparent that because of the discontinuous nature of faults and shears within the fault zones, the magnitude of earthquake vs rupture length of fault relationship would require that only minor earthquakes could be generated by these structures.

INTRODUCTION

The Denver Water Department (DWD) is the main supplier of raw and treated water for the Denver metropolitan area and has had long range plans to meet the increasing demand for water as growth and development continue. These plans include the development of additional water storage on the east slope of the central Colorado Front Range. Approximately fifty dam and reservoir sites have been studied as part of a comprehensive program to select the alternative site most suitable to meet both short and long term storage and operational requirements. The Two Forks, Ferndale, Estabrook and New Cheesman project sites eventually emerged from the study as viable alternatives requiring additional study. After additional studies and evaluation, the Two Forks, Estabrook and Cheesman sites were selected as alternative projects upon which to base the Environmental Impact Studies necessary for right-of-way and permit acquisition.

In late 1982 DWD initiated a comprehensive geotechnical program to assess the seismicity of the central Colorado Front Range as it would affect the location and design of dams. The program included photo lineament analysis of an area of approximately 4,500 sq. mi., a regional fault study, regional mapping of terrace gravel deposits, an analysis of the seismotectonic history of the Colorado Front Range, microseismic monitoring, trenching and radiometric dating of Quaternary stratigraphy, and detailed geologic mapping, bedrock trenching, and core drilling of critical fault zones.

The program, completed late in 1985, was carried out under the direction of the Geotechnical Advisory Committee (GAC) to the DWD. Members of the GAC include consultants Dr. E.E. Wahlstrom (Chairman) and Dr. L.A. Warner; J.P. Parsons (Project Manager), V.Q. Hornback, and S.G. Steele of DWD; R.W. Wengler, E.E. Komie and R.A. Paige of Harza Engineering Co.; and D. Butler and J.J. Nicholl of MicroGeophysics Corp. Special consultants retained to assist with the program include Dr. Clarence R. Allen, Dr. Roy J. Shlemon, and Dale M. Cochran. ESA Geotechnical Consultants were retained for trenching and analyzing Quaternary stratigraphy. Members of the GAC and consultants have reported on the work accomplished in three interim reports (August 1984, August 1985, November 1985) and a summary report (January 1986). This paper summarizes the results of detailed geologic mapping, bedrock trenching, and core drilling of fault zones proximate to the proposed Two Forks and Estabrook dam and reservoir sites.

KENNEDY GULCH AND WILLOW CREEK FAULT ZONES

The Kennedy Gulch fault as located and defined by Peterson (1964), Bryant (1974), and Bryant and others (1981) is a prominent, through-going fault extending northwest from the vicinity of Nighthawk in T8S, R69W through the confluence of the North Fork of the South Platte and the South Platte River at South Platte, through Conifer and to the vicinity of Georgetown in T4S, R74W. Kirkham and Rogers (1981) designated a portion of the fault as potentially active and have assigned a fault length of 34 km (21 mi) extending from its southeast extremity to approximately 6.5 mi northwest of Conifer (figure 1).

The fault, as defined, occupies prominent, linear topographic valleys, the strongest of which is Kennedy Gulch extending southeast from Conifer for approximately 5.5 mi to Reynolds Park. From Reynolds Park southeast to South Platte the fault occupies Kennedy and Kennedy/Long Gulch that are less well defined than Kennedy Gulch proper. From South Platte to the southeast extension of the fault there is only a poorly defined linear topographic feature.

Willow Creek fault as located and defined by Peterson (1964) is a prominent, through-going fault occupying Willow Creek, a prominent linear topographic valley that branches from Kennedy Gulch approximately one mi east of Reynolds Park and extends east-southeast to the South Platte River at Stevens Gulch.

Reconnaissance mapping of Kennedy/Long Gulch and Willow Creek did not reveal any obvious, strong, single strand through-going fault in either valley; nevertheless, these prominent topographic features have developed along linear zones that are more easily eroded than the adjacent rock. Because these faults, as defined by the U.S.G.S., are relatively close to the existing Strontia Springs dam and the proposed Two Forks dam and reservoir, it was deemed necessary to determine the exact nature of these linear features in order to assess their potential as sources for natural or reservoir-induced seismic events. Therefore, a comprehensive program of detailed geologic mapping, bedrock trenching, and core drilling was undertaken by the DWD to make the determination.

In 1983 Dale M. Cochran, consulting engineering geologist, was retained to map Kennedy Gulch from Reynolds Park to approximately 2 mi southeast of South Platte, and Willow Creek from the junction with Kennedy Gulch to the South Platte River. The mapping accomplished in 1983 was reported in the First Interim Report by GAC to DWD (Cochran, 1984. It included a preliminary geologic map of Willow Creek, Reynolds Park, and the upper Kennedy/Long Gulch area. Mapping was done at scales of 1:2,400 and 1:6,000 where the topographic bases were available and compiled at a scale of 1:12,000. Cochran completed mapping in 1984, Hornback added some detail in 1985, and presented a completed, modified version of the map in the GAC Third Interim Report (Hornback, 1985).

Bedrock trenches were excavated across Kennedy/Long Gulch (KG-BR-1) 0.5 mi north of South Platte in 1983 and at the junction of Kennedy Gulch and Willow Creek (KW-BR-2) in 1984. Two core holes (DDH-1 & 2) were drilled adjacent to the KG-BR-1 trench and a third core hole (DDH-3) was drilled across the Kennedy/Long Gulch lineament approximately 1.75 mi northwest of South Platte in 1983 (Figure 1).

GEOLOGY OF THE KENNEDY GULCH AND WILLOW CREEK FAULT ZONES

Bedrock in the study area is comprised of the metamorphic units of the Idaho Springs complex, Silver Plume quartz monzonite, and granite of the Pikes Peak batholith, all Precambrian in age.

The metamorphic units are the oldest rocks and include biotite gneiss, migmatite, granite gneiss, and minor amounts of amphibolite and calc-silicate gneiss. The rocks are moderately to well foliated with foliation generally conforming to a regional strike of northwest and a northeast dip. Intrusions of small pegmatite bodies concordant and/or discordant with foliation are common.

Silver Plume quartz monzonite was identified by Bryant (1974) as a rock unit of widespread distribution in the Conifer quadrangle immediately west of the DWD study area. Cochran found this rock type to be abundant in the Kennedy Gulch - Willow Creek area also. Bryant (1974) describes the rock as coarse-grained to fairly fine-grained light-gray to moderate-orange-pink muscovite-biotite quartz monzonite. It is locally foliated and contains numerous inclusions of migmatite, biotite gneiss and sillimanite-muscovite-biotite schist. In the detailed mapping of bedrock in trench KW-BR-2, the fine-grained variety of this rock was commonly mapped as gneissic aplite, and had foliation generally conformable with that of the host biotite gneiss or migmatite.

Pikes Peak granite is the youngest of the predominant rock types. It is a very coarse-grained, white to moderate-orange-pink biotite and hornblende-biotite granite.

Kennedy Gulch and Willow Creek valleys are characterized by zones of no-outcrop that occupy the central part of each valley and range from a few tens of ft up to 2,000 ft wide. In Kennedy Gulch, the no-outcrop zone that extends northwest from South Platte for about 2 mi, includes and runs parallel to the contact between the Pikes Peak granite and the metamorphic rocks of the Idaho Springs complex. In that area, the low degree of preferred orientation of fractures, the limited extent of fractures, the fracture density distribution, and the pervasive alteration products along the fracture trends and filling of the fractures, combined with the type and distribution of rock alteration, suggest that the altered, fractured zone in the contact area is the result of stressing and hydrothermal alteration associated with emplacement of the granite in the metamorphic host rock rather than shearing associated with a major fault. Furthermore, as observed in the bedrock trench

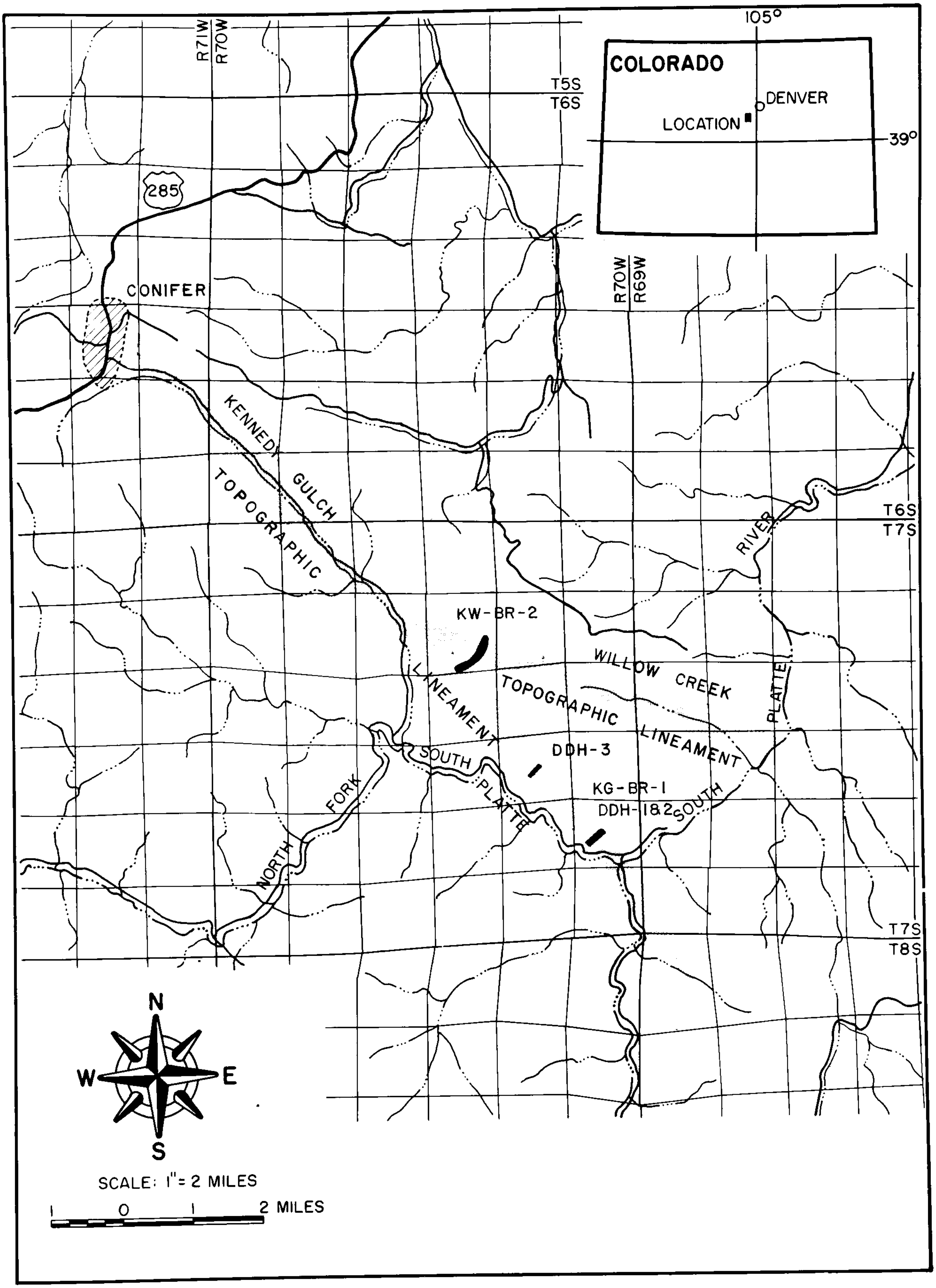

Figure 1. Location map of Kennedy Gulch and Willow Creek study area.

KG-BR-1 crossing the contact, the original structure or fabric of both the granite and metamorphic rock has not been destroyed or even distorted as it would have been if it had been subjected to shearing along a major fault (Hornback, 1984).

Permeability of the altered, fractured rock along the granite-metamorphic rock contact zone in Kennedy/Long Gulch is generally low. Water pressure tests were conducted in each of the three core holes drilled. Permeabilities ranged from zero to a high of 5.5×10^{-5}cm/sec for one isolated case. The greatest percentage of the rock mass tested has permeabilities ranging from 6.2×10^{-6}cm/sec to 2.4×10^{-5}cm/sec. DDH-1 and DDH-2 are crossing holes, inclined 35° from horizontal and aligned approximately perpendicular to the trend of the granite-metamorphic rock contact and located so as to span the contact zone. DDH-3 is inclined 35° from horizontal and aligned perpendicular to the trend of the contact. It is collared in granite, crosses the contact zone, and bottoms in metamorphic rock.

Water takes generally showed very poor correlation with fracture density, core loss, or rock type. The highest takes were usually in the areas of lowest fracture density for the particular hole, suggesting that these are areas of more competent rock that is less fractured, but capable of sustaining more open fractures.

Faulting within the altered, fractured zones is minor although more prevalent in the metamorphic rock than in the granite. Observations from surface mapping and from core drilling show that, at least in the study area, the strongest faulting is directly associated with sandstone dikes. Sandstone dikes commonly occur within or adjacent to the rock contacts. A few were noted within the granite body at a distance of up to several hundred feet from the contact. More sandstone dikes occur within the metamorphic rock complex, but tend to be localized within and trend parallel to the more prominent valleys.

A detailed examination of bedrock exposed in the KW-BR-2 trench located at the junction of Kennedy Gulch and Willow Creek reveals that there is no major, single strand through-going fault in either of the zones defining the Kennedy Gulch and Willow Creek lineaments. The bedrock, within the zone of no-outcrop that occupies the central part of each topographic lineament, is mostly brittle granitic rock that is generally highly fractured, hydrothermally altered, and faulted. Faults within the zone of no-outcrop are predominantly minor and foliation controlled; some faults cut across foliation and are generally stronger than foliation controlled faults. Faults that trend more or less parellel to each other tend to occur in groups such that well to poorly defined zones of faults can be identified.

The high degree of fracturing of the bedrock is expressed as joints. The most prominent joints present in the trench belong to the joint sets that are expressed on a regional basis. The lack of slickensides on joint surfaces and the fact that the basic structure (primarily foliation) of the rock is intact, even in highly weathered rock, indicate that there has been no shearing characteristic of a major fault.

CONCLUSIONS

Trenching, exploratory core drilling, and surface geologic mapping all lead to the same general conclusions regarding the internal characteristics of the

Kennedy Gulch and Willow Creek faults in the study area. The faults, as they extend to the south and southeast of their junction, have proved to be poorly defined zones of locally, closely-jointed, brittle rocks containing only minor faults. Major shear dislocations along planar zones of weakness are not readily apparent. Of all bedrock faults identified, no slip surface extended into overburden, nor was offset of overburden observed.

The Kennedy Gulch and Willow Creek topographic lineaments, from their junction to the South Platte River, can best be described as fault zones composed of highly fractured and weathered rock with numerous, minor, discontinuous faults.

SHAWNEE FAULT ZONE

The Shawnee fault, as defined by Bryant and others (1981) is another prominent, northwest trending fault that extends from east of Estabrook westward along the North Fork of the South Platte River to Kenosha Pass (Fig. 2). The fault is of concern because it is located within 0.75 mi of the proposed Estabrook dam site, and some portion of the fault exists within almost the entire length of the reservoir. It was studied in considerable detail, although it was not trenched or core drilled. It has not been designated as a potentially active fault.

The prominent topographic lineament expressed as the valley of the North Fork of the South Platte River west of Estabrook, including the Shawnee fault, is a broad zone of limited amounts of outcrop ranging from a few hundred feet to more than 2,000 ft wide. It occupies what was probably an ancestral North Fork river channel that is located, for the most part, south of and higher in elevation than the present North Fork channel.

The zone contains numerous sandstone dikes, discontinuous sheared rock masses, and locally broken, iron-stained rock, some of which has been hydrothermally altered. There is little evidence for a prominent, single strand through-going fault within the zone. Faulting in the zone is inferred by topographic lineaments, lack of outcrop, some hydrothermal alteration, and by the numerous sandstone dikes. Regionally, the sandstone dikes are perhaps the best evidence for faulting. Faults and shear zones, with few exceptions, are seen only in road cuts or other man-made excavations.

Remnants of terrace gravel deposits are present along the North Fork valley ranging from 10 to 140 ft above the present river elevation. At least five levels of terraces can be defined. Some of the terraces cover sections of the fault zone and others can be matched or paired across segments of the fault zone; however, no single terrace or paired terraces completely span the entire fault zone. Within the accuracy of location of the terrace levels no vertical displacement could be detected.

Based on height above the present river level and comparison with a similar sequence of terrace levels located several miles downstream on the North Fork, the age of the highest terrace is in the range of 400,000 to 500,000 years old. The study results provide further evidence in support of the Shawnee fault system being considered as inactive.

The Shawnee fault, in the study area, is located within the metamorphic rocks of the Idaho Springs complex. It has similar characteristics to the Willow Creek fault zone and the Kennedy Gulch fault zone at locations where Kennedy Gulch is in metamorphic rocks.

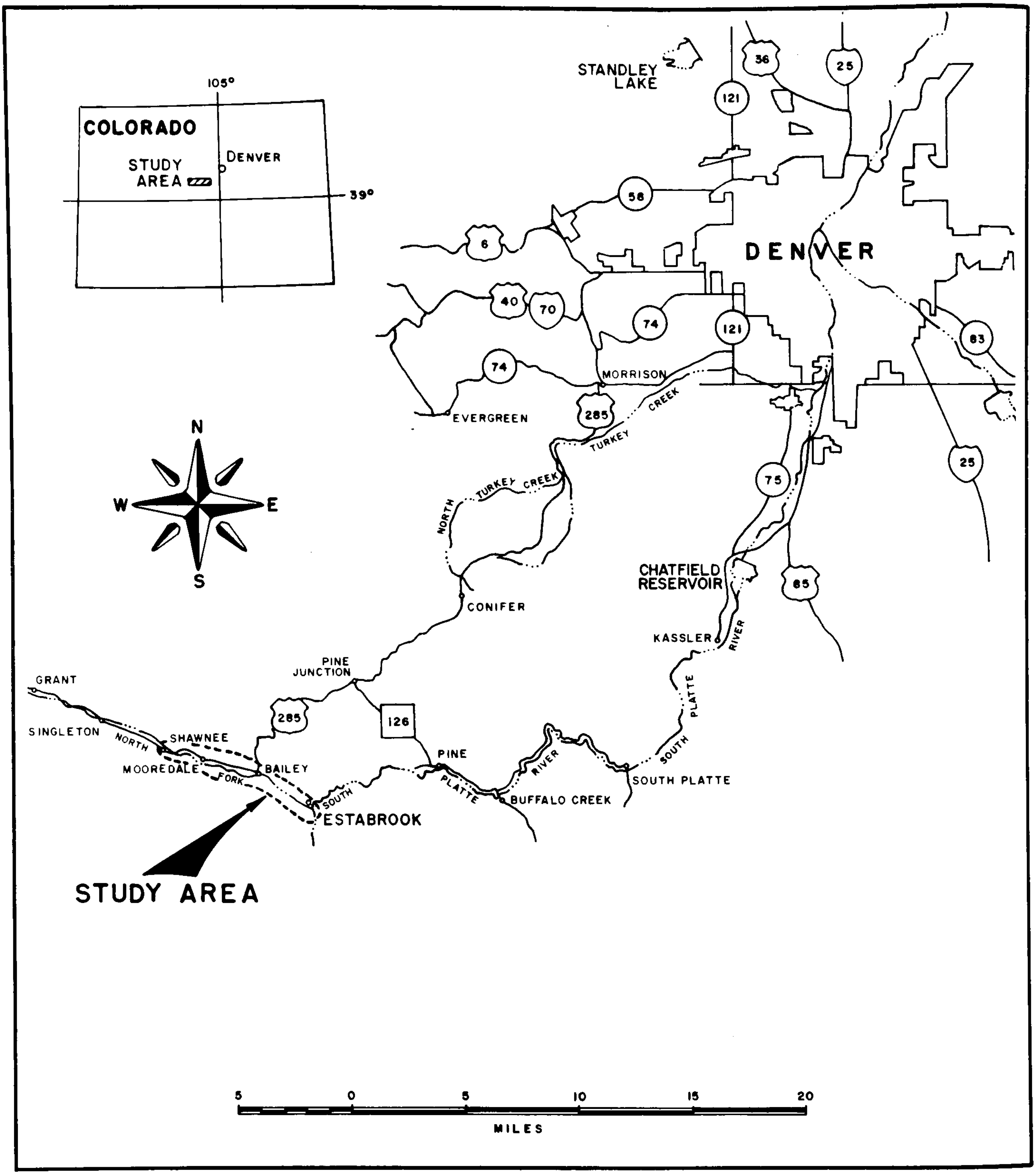

Figure 2. Location map of Estabrook-Shawnee study area.

CONCLUSIONS

The Kennedy Gulch, Willow Creek, and Shawnee fault zones are typical of the dozen or more prominent northwest-trending faults in the central Front Range of Colorado. These faults have similar characteristics, and therefore, probably have a common mode and time of origin, and have reacted similarly to the different stress regimes that have prevailed at various times during the geologic history of the area. The studies by DWD (Wallace and Friedman 1985) and others (Harza 1985) show that the most recent movement along these faults occurred more than 190,000 y.b.p. Because these fault zones are not strong, single strand through-going faults, but are composed of broad zones of broken rock and numerous small discontinuous faults and fault zones, the magnitude of earthquake vs rupture length of fault relationship would require that only minor earthquakes could be generated by any of these structures.

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AIR-PHOTO LINEAMENT ANALYSIS
EAST-CENTRAL FRONT RANGE COLORADO

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ABSTRACT

A systematic, detailed study of available aerial photography for a two-phase lineament analysis conducted as a part of a comprehensive evaluation of the geologic and seismotectonic conditions in the east-central Colorado Front Range is presented in this paper. The study area encompasses the vicinity of several Denver Water Department proposed dam and reservoir sites considered for east-slope water storage in the Front Range of Colorado. This lineament analysis is a state-of-the-art investigation providing basic data for the regional geologic and seismotectonic evaluation.

The purpose for the lineament analysis is to assist with: 1) the evaluation of all regional geologic structure with an emphasis placed on locations near proposed dam and reservoir sites; 2) providing direction and focus for ongoing and concurrent geologic and seismotectonic investigations that include geologic mapping, fault studies, locations for microseismic monitoring stations, and locations of exploratory drill holes and trenches, and 3) the evaluation of the existence, extent, and characteristics of several mapped faults throughout the area, the questions of possible existence of unmapped faults and the relationship of these faults to the paleoseismicity of the area.

The study area is located west of Denver in the east-central Front Range of Colorado. The area is bounded on the north by the Gross Reservoir area, on the south by Pikes Peak, and it extends west to the Continental Divide and east to the flank of the Front Range. It encompasses approximately 4,500 square miles.

Sets of aerial photographs at five different scales were utilized for the first phase of the lineament analysis including 1:106,000-scale NASA natural color, 1:101,000-scale NASA infrared, 1:76,000-scale USGS black and white, 1:33,000-scale DWD (Denver Water Department) natural color, 1:12,000-scale DWD black and white, and 1:12,000-scale DWD color. The second phase of the study utilized only the USGS 1:76,000-scale black and white aerial photographs. Linear features were plotted on transparent acetate overlays then transferred and compiled on a topographic base map of 1:76,000 scale.

Lineament is defined for the purposes of this study as, "a mappable, simple or composite linear feature of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the pattern of adjacent features and presumably reflects a subsurface phenomenon." The terms "lineament" and "linear feature" are used interchangeably within this paper.

Interpretation of the lineament maps was based on existing geologic maps, current and ongoing detailed and reconnaissance geologic mapping, drill hole and trench log data, aerial reconnaissance geologic mapping, and lineament field checking.

Conclusions based on the lineament analysis that are pertinent to the geologic and seismotectonic investigations are: 1) linear features appearing on aerial photographs generally reflect the regional geologic structure; 2) faults generally appear as zones of discontinuous lineaments suggesting segmented fault zones rather than continuous features as previously mapped; 3) groups of linear features can be correlated with prominent joint sets and foliation trends where rock outcrop is abundant; and 4) field-checked lineaments proved to be a good representative sample for interpretation of all lineaments in the study.

The results of the lineament analysis are consistent with previous lineament studies in that:

1) photo lineaments are not necessarily faults, faults are not necessarily expressed as photo-lineaments;

2) many linear features have no structural significance;

3) distribution and orientation of aerial photo lineaments and structural features on the ground do not always agree;

4) regional geologic structural interpretations for linear features can be made from office photo interpretation, "spot-check" field work, helicopter reconnaissance, reconnaissance geologic mapping and knowledge of regional geology and geography;

5) interpretation of some linear features is impossible, even after complete photo and field evaluation, due to field inaccessibility, vegetative ground cover, colluvial and alluvial cover, topography, and lack of outcrop in certain areas;

6) a great number of the correlations of linear features with specific structural features for a lineament analysis is dependent primarily upon the observer, the scale of the aerial photograph, whether the air photo is black and white, color or color infrared, time of day for the aerial photography, and lightness or darkness of the individual air photo.

INTRODUCTION

Purpose and Scope

This paper presents a systematic, detailed study of available aerial photography for a two-phase lineament analysis conducted as a part of the comprehensive evaluation of the geologic and seismotectonic conditions in the east-central Colorado Front Range. The study area encompasses several Denver Water Department proposed dam and reservoir sites, including the Two Forks project area, under consideration for east-slope water storage in the Front Range of Colorado. The lineament analysis is a critical portion of the ongoing geologic and seismotectonic investigations for the proposed Two Forks and alternate dam and reservoir sites associated with the Systemwide Environmental Impact Statement (SEIS) under preparation by the U. S. Army Corps of Engineers. Both phases of the lineament analysis provide an independent approach for continual direction and focus of the geotechnical investigations for the seismic and geologic evaluations of the proposed Two Forks and alternate dam and reservoir sites.

This paper is based on reports submitted to the Denver Water Department that are included as a part of the comprehensive evaluation of the Geologic and seismotectonic conditions in the east-central Front Range of Colorado (Steele, 1984 and Steele, 1985). These reports contain the compiled lineament base maps and the full-scale drawings from which the reduced-scale figures accompanying this paper were produced.

The lineament analysis is a state-of-the-art investigation providing basic data for the regional geologic and seismotectonic evaluation. The purpose for the lineament analysis is to assist with: 1) the evaluation of regional geologic structure with an emphasis placed on locations near proposed dam and reservoir sites; 2) providing direction and focus for ongoing concurrent geologic and seismotectonic investigations that include geologic mapping, fault studies, locations of microseismic monitoring stations, and locations of exploratory drill holes and trenches; and 3) the evaluation of the existence, extent and characteristics of mapped faults throughout the area, the possible existence of unmapped faults, and the association of these faults to the paleoseismicity of the area.

Prior to and during the study, an extensive literature search of pertinent geologic reports pertaining to air-photo lineament analysis was completed. The principal purposes for the search were to provide information on: 1) lineament analysis methodology and history, 2) previous investigations and their conclusions, 3) developing a sense of the relationship between lineaments and regional geology, particularly structural features, and 4) developing criteria for lineament evaluation.

The definition of lineament used in this report is that of O'Leary and others (1976) based on the usage introduced and amplified by Hobbs (1904; 1912): "A lineament is a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the pattern of adjacent features and presumably reflects a subsurface phenomenon." The definition of lineament supplied by the Glossary of Geology (1980) is comparable: "A lineament is a linear topographic feature of regional extent that is believed to reflect crustal structure."

Also, for further clarification within this paper, the terms "lineament" and "linear feature" are presumed to have the same meaning and are used interchangeably.

Previous and Concurrent Investigations

The air-photo lineament analysis is a part of the ongoing extensive, comprehensive, geologic and seismotectonic investigations directed by the Geotechnical Advisory Committee for the purpose of evaluating Denver Water Department potential sites for additional water storage on the east slope of the Colorado Front Range. Work began on these investigations in 1983 and continues.

Concurrent geologic and seismotectonic investigations include studies on the following topics:

1) regional detailed and reconnaissance geologic mapping
2) exploratory trenches and core holes
3) regional and detailed fault studies

4) Quaternary studies
5) fluvial terrace deposit evaluation
6) air-photo lineament analysis
7) tectonics of the Front Range
8) stress regimes, strain rates and seismic potential in the Front Range
9) seismicity of the Front Range
10) microseismic monitoring
11) seismic design considerations
12) reflection feasibility study
13) gravity feasibility
14) reservoir-induced seismicity
15) seismic risk analysis
16) design earthquakes for the Colorado Front Range

The first phase of the lineament analysis project was started in 1983 and completed in 1984. The second phase of the lineament analysis project began in late 1984 and continued through October of 1985 with air-photo interpretation and data compilation. Field checking of lineaments was completed during late August, September and early October of 1985.

All of the geologic and seismotectonic investigations for 1983, 1984, and 1985 are presented in the Interim Report, Second Interim Report and Third Interim Report (Geotechnical Advisory Committee, 1984; Geotechnical Advisory Committee, 1985a; and Geotechnical Advisory Committee, 1985b; respectively). All of the work is also abstracted in the Summary Report (Geotechnical Advisory Committee, 1986).

Geographic, Physiographic and Geologic Setting

The study area is located west of Denver in the east-central Front Range of Colorado. The area is bounded on the north by the Gross Reservoir area, on the south by Pikes Peak, and extends west to the Continental Divide and east to the flank of the Front Range (Figures 1 and 2). It encompasses approximately 4,500 square miles, including the counties of Clear Creek and Gilpin and portions of Boulder, Douglas, Grand, Jefferson, Park, Summit, and Teller Counties. For the most part, the study area is located within the National Forests of Pike, Arapahoe, and Roosevelt. Several sections of the land are privately owned, particularly in the Evergreen vicinity.

The study area is located in the Southern Rocky Mountain Physiographic Province (Fenneman, 1931), characterized predominantly by rugged mountains and deeply-incised valleys (Harza Engineering Company, 1985). Dominant physiographic features of the area include the hogback of northwest-trending sediments along the east flank of the Front Range, the Continental Divide, South Park and Pikes Peak.

The geology of the lineament-analysis study area is shown on the maps by Bryant and others (1981), Scott and others (1978), Tweto (1979) and summarized by Harza Engineering Company (1985) in the Second Interim Report.

ACKNOWLEDGMENTS

I wish to express appreciation to Dr. Roy Shlemon for his expert guidance and suggestions from the inception of the lineament analysis project, and to Dr. Ernest E. Wahlstrom and V. Q. Hornback for providing technical discussion and

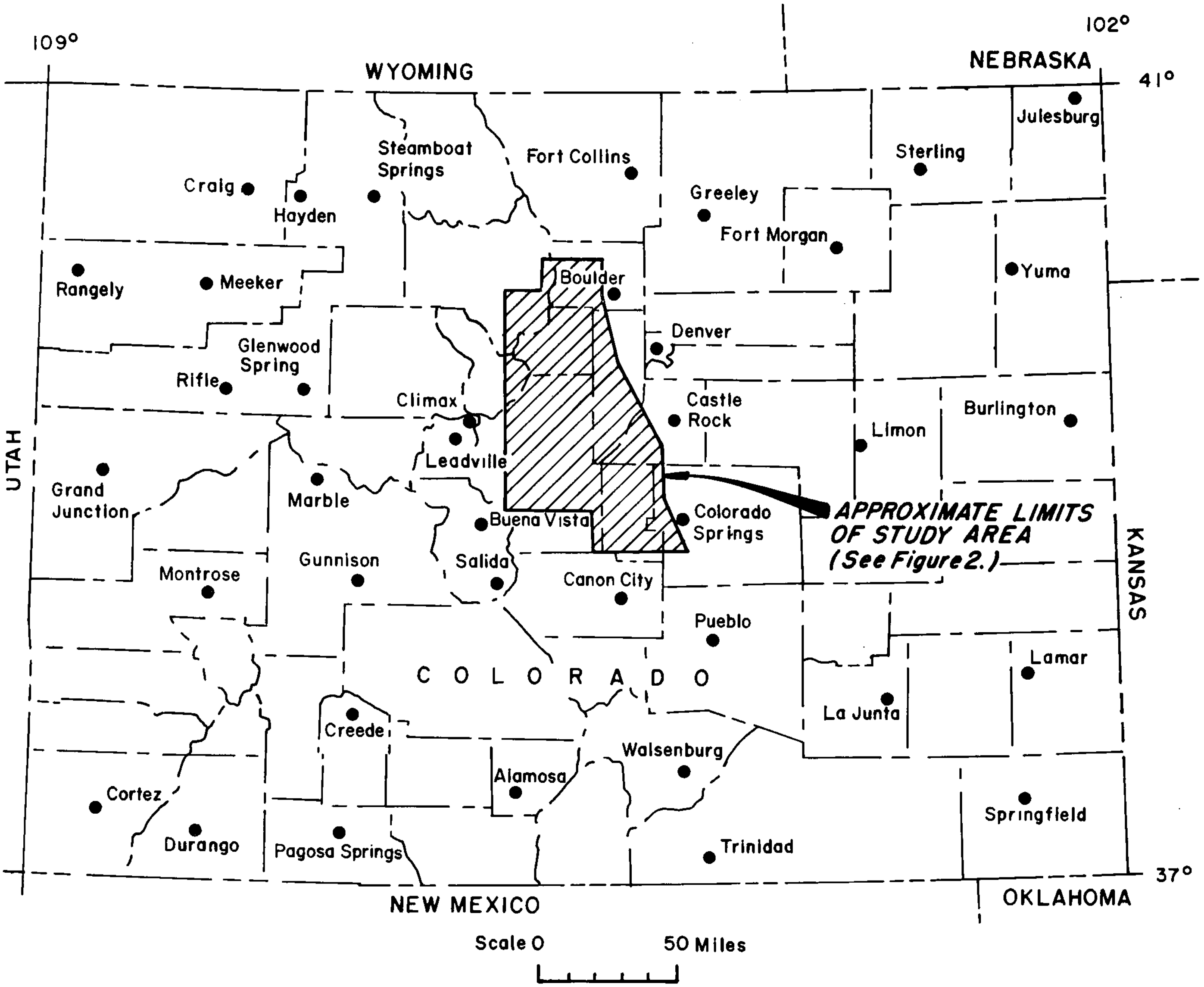


Figure 1. Location map of study area in Colorado, adapted from Kent and Porter (1980).

constructive criticism along with support and encouragement during this project.

A special debt of thanks and appreciation is owed to Dave Hallman and Jeff Leety for their numerous contributions to the field investigations, data compilation, and technical discussions in support of this project.

AIR PHOTO LINEAMENT ANALYSIS

Scope of the First-Phase Study

A systematic, detailed evaluation of available aerial photography at five different scales was made for the first-phase lineament analysis of the study area (Steele, 1984). Much of the information about the first-phase study included below was paraphrased from Steele (1984) for the purpose of continuity and correlation within this paper.

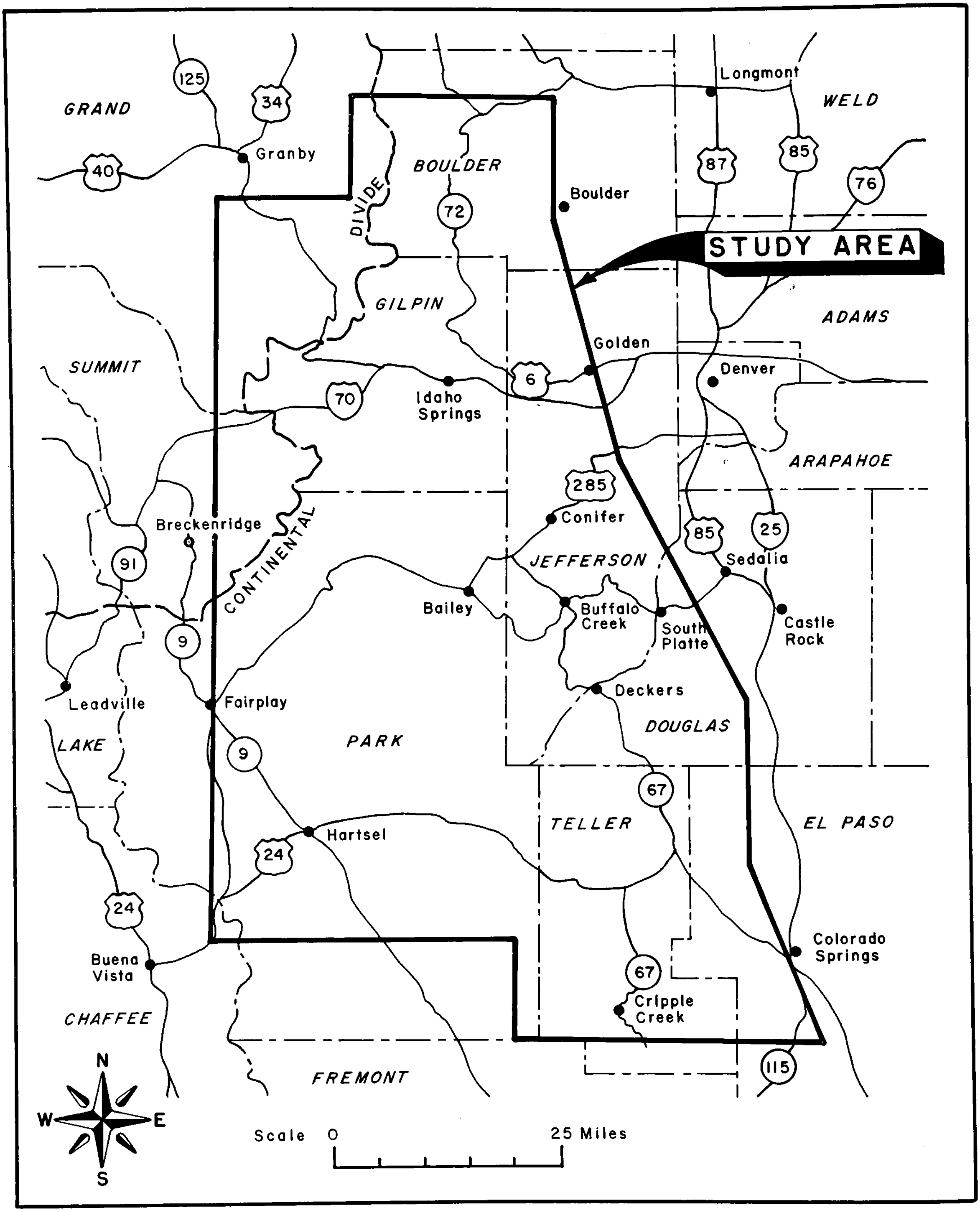


Figure 2. Index map showing air-photo lineament analysis study area, east-central Colorado.

The regional-level study utilized both the 1:106,000-scale NASA natural color aerial photos and the 1:101,000-scale NASA color infrared aerial photos that cover the proposed Two Forks Project area and all the proposed Two Forks alternate sites. Complete coverage of this area was not available at either scale. The local-level study used 1:33,000-scale natural color photos that cover the proposed Two Forks Project area and some of the proposed alternate site areas. The detailed site-specific-level study used 1:12,000-scale natural color photos that cover the proposed Two Forks Project area specifically. A separate photo-lineament analysis was made of the area encompassing the previously mapped Floyd Hill fault system at two different scales. The aerial photos utilized for the Floyd Hill study were 1:76,000-scale USGS black and white and 1:106,000-scale NASA natural color. (The 1:76,000-scale set of aerial photographs was identified as 1:78,000-scale in Steele (1984). However, as a result of a scale survey of the entire set of photographs, it was determined that the average scale of the set of USGS black and white photographs was 1:76,000.) Additionally, an independent site-specific-level study was made of the Two Forks Project area by Harza Engineering Company using 1:12,000-scale black and white aerial photos. Stereoscopic coverage was available at all five scales.

Date Compilation and Photo Evaluation

The linear features on each aerial photograph were traced onto transparent acetate overlays. Mosaic acetate-overlay lineament maps were compiled at the scales of 1:106,000, 1:76,000, 1:33,000 and 1:12,000. Data traced from the 1:101,000-scale aerial photos was reduced in scale to 1:106,000 and combined with the data from the 1:106,000-scale aerial photos. The acetate-overlay lineament maps compiled included indiscriminately all linear features on the photographs regardless of origin.

Lines on the overlays representing linear features on the photographs were roughtly divided into two categories distinguished by line weight. The two categories were: 1) more major linear features that are immediately apparent and characterized by dominance on the aerial photograph based on length and strength; and 2) more minor linear features that are not obviously apparent and characterized by being less linear, more diffuse, short and discontinuous.

Interpretation of these lineament maps was based on existing geologic maps, current and ongoing detailed and reconnaissance geologic mapping, drill hole and trench log data, aerial reconnaissance geologic mapping, reconnaissance lineament field checking and minor amounts of individual-lineament field checking. Existing geologic maps utilized in this study include Bryant and others (1973), Bryant and others (1981), Cochran (1984), Hornback (1984), Peterson (1964), Scott and others (1978), Sheridan and Marsh (1976), Sheridan and others (1972), Shlemon (1984), Taylor (1976), and Tweto (1979).

Conclusions based on the First-Phase Analysis

The first-phase lineament analysis was centered primarily in the vicinity of the proposed Two Forks dam and reservoir site and the alternate sites located relatively near Two Forks, i.e. Ferndale and New Cheesman. This was due to the amount of ground coverage available in certain sets of the aerial photographs utilized for the study. Of primary concern during the evaluation was the relationship of the air-photo linear features with the regionally mapped geologic structural features, particularly faults and/or shear zones.

Emphasis was placed on faults located in proximity to the proposed Two Forks and alternate dam sites that have been categorized as "potentially active" by Kirkham and Rogers (1981). The Kennedy Gulch fault and the Floyd Hill fault are two of these faults categorized by Kirkham and Rogers (1981).

A tentative conclusion resulting from the first-phase lineament study was that Kennedy Gulch is a zone of discontinuous photo-linear expressions suggesting a segmented fault zone rather than a continuous feature as previously mapped (Peterson 1964). It was also tentatively concluded that there is no single through-going or continuous linear expression corresponding to the Floyd Hill fault system as mapped by Sheridan and others (1972) and Sheridan and Marsh (1976). These results suggest that the Floyd Hill fault is also a segmented, discontinuous feature. Concurrent studies involving detailed and reconnaissance geologic mapping of the areas confirm the existence of both the Kennedy Gulch fault and the Floyd Hill fault. Results of this mapping are presented by Harza Engineering Company (1985). Additional concurrent studies along the Kennedy Gulch fault are presented by Cochran (1984), Hornback (1984), Hornback (1985), Shlemon (1984), Shlemon (1985) and Wallace and Friedman (1985).

Evaluation and comparison of the composite acetate-overlay first-phase lineament maps also showed that features appearing as continuous linear patterns on the 1:106,000-scale map become less apparent as linear features on the 1:76,000-scale map, even less apparent as linear features on the 1:33,000-scale map and least apparent as linear features on the 1:12,000-scale map. In general, the lineament maps reflect regional structure, but mapped faults appear as zones of segmented and subparallel lineaments.

Scope of the Second-Phase Study

Initially, sets of aerial photographs at five different scales were utilized for the first phase of the lineament analysis of the study area. The air-photo scales were 1:12,000; 1:33,000; 1:76,000; 1:101,000; and 1:106,000 (Steele, 1984). Upon completion of the first-phase study it was determined to proceed with the lineament analysis study using only one scale of aerial photos rather than partially completing the lineament analysis for the study at five different scales.

Photo Selection

The USGS black and white aerial photos at the scale of 1:76,000 were selected to proceed with the second-phase lineament analysis for two reasons; 1) they were the one scale of photos available that offered complete coverage, including stereoscopic coverage of the study area, and 2) they were an intermediate scale of photos between the large-scale 1:12,000 photos and the small-scale high-altitude 1:106,000 photos.

Complete coverage of the study area at one scale minimizes error in lineament evaluation. Due to the tendency of the high-altitude aerial photos to accentuate linear features and the low-altitude aerial photos to diffuse linear features (Steele, 1984), it was thought that an "intermediate" scale of aerial photos would average these extreme conditions and tend to neutralize the effects of scale on the evaluation and conclusions.

Base Map Compilation

A 1:76,000-scale topographic base map was constructed in order to compile the air-photo linear features (Steele, 1985; plates 1-9). To arrive at the 1:76,000 scale for the base map, an air-photo scale survey of the entire set of USGS black and white photos was completed. Results of the survey indicated that the air photos from the set varied in scale from approximately 1:70,000 to 1:82,000. The base map was constructed at the average scale for the entire set of photos, i.e. 1:76,000, to have as many of the photos be as near the scale of the base map as possible. This allows for more accurate transfer of linear features from photo to base map. For compilation of the base map, USGS 1:50,000-scale topographic county maps were spliced together and reduced in scale to 1:76,000.

Plotting Procedures

Linear features on each aerial photograph were traced onto transparent acetate overlays. Only linear features observed in the central section of each photograph (where coverage permitted) were traced onto the overlays. Planimetric errors are inherent in all aerial photos, particularly those in areas of high relief, as is most of the Front Range area included in this study. These errors increase in all directions from the photo center. Also, care was taken to reject non-tectonic features such as old roads, fence lines, power lines and paths, if possible. If the origin of a linear feature was unknown or questionable, it was mapped. One person, trained in geology and familiar with Front Range geology and geography, completed this portion of the lineament analysis for consistency in selection of linear features. Experience and knowledge of the regional geology and geography proved helpful in reducing the number of man-made lineaments transferred to the overlays.

Lineaments were then transferred from the air-photo acetate overlays and plotted on a 1:76,000-scale topographic base map (Steele, 1985; plates 1-9). Lines on the topographic base map representing linear features on the photographs are roughly divided into two categories distinguished by line weight; they are: 1) more prominent linear features that are immediately apparent and characterized by dominance on the aerial photograph based on length and strength, and 2) less prominent linear features that are not obviously apparent and characterized by being less linear, more diffuse, short and discontinuous. Linear features were placed in the second "less-prominent, less-apparent" category if they were not immediately apparent when first observing the aerial photograph.

Compilation of linear features for the lineament analysis maps included indiscriminately all linear features on the photographs regardless of origin, excluding only the obvious man-made features described above.

Evaluation of Lineaments

Evaluation and interpretation of the lineament maps was based on existing geologic maps, current and ongoing detailed and reconnaissance geologic mapping, regional fault studies, drill hole and trench log data, aerial reconnaissance geologic mapping, and field checking. This evaluation consists of both photo interpretation and field interpretation.

The photo interpretation consists of the tabulation of lineament data and lineament evaluation in preparation for field interpretation of linear features.

For the purposes of lineament evaluation and as a means of sorting data for field checking, a statistical system of lineament counting and sorting was used. The lineament maps were each divided into equal-area rectangles; all lineaments within the rectangles were assigned a numerical designation. This method allowed for a systematized method of lineament location, tabulation and a more manageable number of lineaments to evaluate within a particular group. Lineaments were also classified by length.

Lineaments shown on the maps that measured less than one inch in length were eliminated from the statistical tabulation, however, they are considered in the overall lineament analysis and field investigations. These lineaments were eliminated from the tabulation by the author in order to expedite lineament counting and sorting. Also, the interest of this study gravitates toward correlation of lineaments with structural features of regional significance. It is generally considered by this author and by previous studies that lineaments of longer length represent features with more regional structural significance.

Next, each lineament was evaluated and assigned a most probable associated feature. Careful scrutinizing of regional geologic maps, the 1:76,000-scale set of aerial photographs, geologic quadrangle maps, topographic maps, and 1:24,000-scale photoquads aided in the photo evaluation of linear features. Also, detailed geologic mapping, core logs, and trench logs from concurrent investigations were valuable for the interpretation of linear features. Of particular importance was the correlation of linear features to mapped faults.

Most lineaments from this study represent major or other faults, drainages, rock-unit contacts, rivers or streams and topography, however, for approximately one-fifth of lineaments tabulated, the most probable associated feature was unknown. Due to the elimination of lineaments that measured less than one inch in length from the initial statistical tabulation an anomaly occurred in the tabulated results. After completion of the lineament analysis, including field investigations, it was observed that most of these lineaments measuring less than one inch in length could be correlated with joints or foliation. Therefore, joints and foliation can be added to the list of features that the lineaments in this study most probably represent.

Prominence on an aerial photograph, length, and associated feature are the three methods of evaluating a linear feature to form a basis for field interpretation.

Field Checking and Reconnaissance Mapping

Field investigations for lineament evaluation were accomplished by using four methods: 1) field checking of individual lineaments; 2) field checking of lineaments representing previously-mapped faults utilizing the regional fault study; 3) regional grouping of linear features and assumptions based on known regional geology; and 4) helicopter reconnaissance mapping. Concurrent investigations, including detailed geologic mapping, trenches, drill holes, and Quaternary studies, as well as published regional geology maps aided in all investigation methods.

Locations of lineaments to field check were selected based on proximity to proposed water storage facility sites (Two Forks and alternate sites) and land accessibility. U. S. Forest Service land is widespread in the vicinity of Two Forks and the alternate dam sites offering good access for field studies.

Interpretation of linear features was also accomplished by evaluating groups of lineaments that all seemed to be associated with the same regional feature based on previously-mapped geology, knowledge of the regional geology, and geography. Certain lineaments within one of these groups was then "spot-checked" in the field to verify the existence of joint sets, regional foliation trends or faults. Figure 3 shows two example sections from the lineament study area that exhibit joint-controlled air photo linear features. This illustrates, for the purposes of this region-wide lineament analysis, how groups of lineaments were evaluated and categorized with an appropriate associated feature without actually field checking each lineament individually.

Two helicopter reconnaissance lineament-evaluation trips were completed for this study. Both trips included the areas of the proposed Two Forks and alternate dam and reservoir sites. Also included were areas containing groups of lineaments that could be "spot-checked" from the air and evaluated en masse. These areas were located within wilderness zones and areas of rugged topography where access by foot and vehicle was limited. The helicopter reconnaissance mapping helped to complete the field investigations of linear features that could only be partially evaluated on the ground due to the access problems.

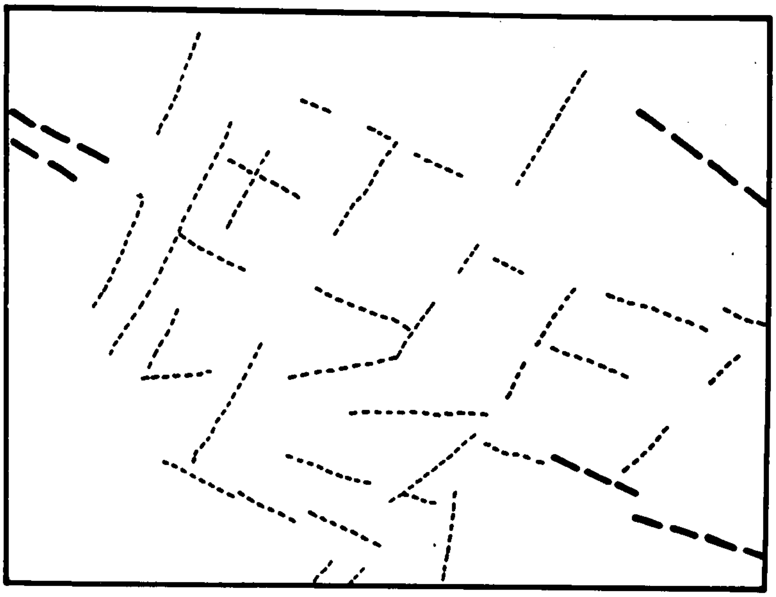
Interpretation of Lineaments

Correlation of mapped lineaments with structural features, particularly faults, is the primary concern of this lineament analysis. The likelihood that a mapped linear feature has a subsurface expression, i.e. reliability of interpretation of linear feature, depends on two different sets of criteria: 1) spatial coincidence with geologically and geophysically mapped structures and 2) morphology of linear features, i.e. linearity, distinctness, continuity, tonal contrasts, stratigraphic or lithologic offset relations, lithologic changes, topographic offsets, and linear geomorphic features including alignment of drainage and landforms (Friedman and Simpson, 1980). Evaluation of lineaments and the assessment of the reliability of lineament interpretation in this investigation is accomplished through photo studies, compilation of lineament data, and a combination of field checking methods.

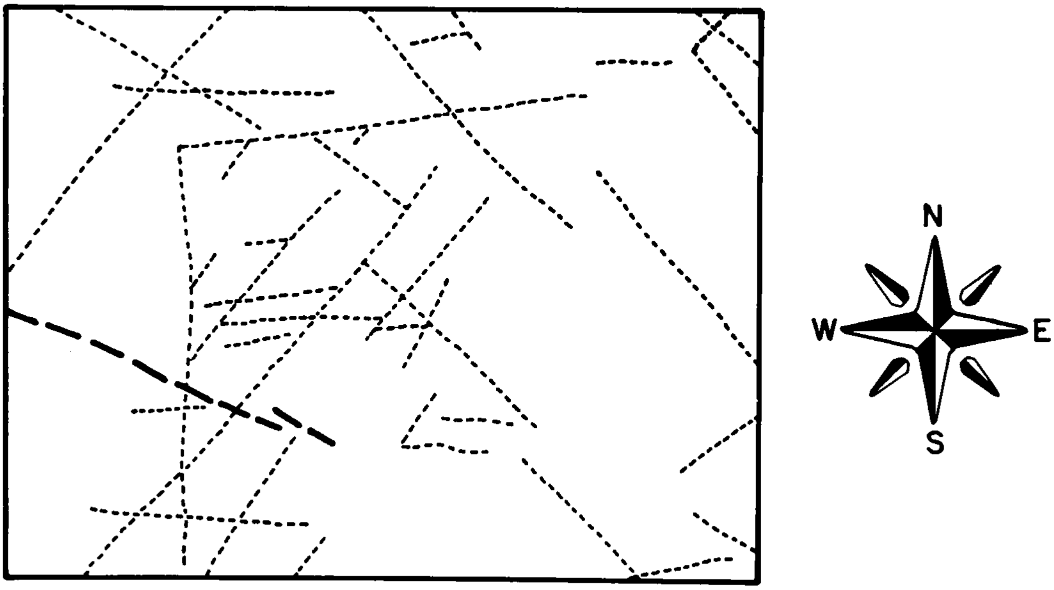
Figures 4 through 9 show the comparison of selected mapped faults with air-photo linear features in two locations from the lineament study area. The Kennedy Gulch area, due to its proximity to the proposed Two Forks dam and reservoir site, is of particular interest for this study. Selected mapped faults in the vicinity of Kennedy Gulch are shown on Figure 5. Figure 4 shows all of the air-photo linear features mapped in the Kennedy Gulch area during the lineament study. Figure 6 shows only those linear features thought to be associated with the mapped faults shown on Figure 5. Figures 4 through 6 show that air photo lineaments reflect regional structure. Also patterns of lineaments show that mapped faults are represented as zones of discontinuous photo-linear expressions suggesting segmented fault zones rather than the continuous features previously mapped.

The same general comparisons, correlation, and conclusions can be observed in the Tarryall Reservoir area shown on Figures 7 through 9.

The Kennedy Gulch and Tarryall Reservoir areas are representative examples of the correlation of air-photo linear features and regional structure present throughout the entire study area (Figure 2).



Area located approximately 10 miles west of Tarryall Reservoir.



Area located approximately 3 miles east of Elevenmile Reservoir.

EXPLANATION

Less prominent air photo linear features.

More prominent air photo linear features.

SCALE 1:76,000

Figure 3. Examples of areas showing joint-controlled air-photo lineaments.

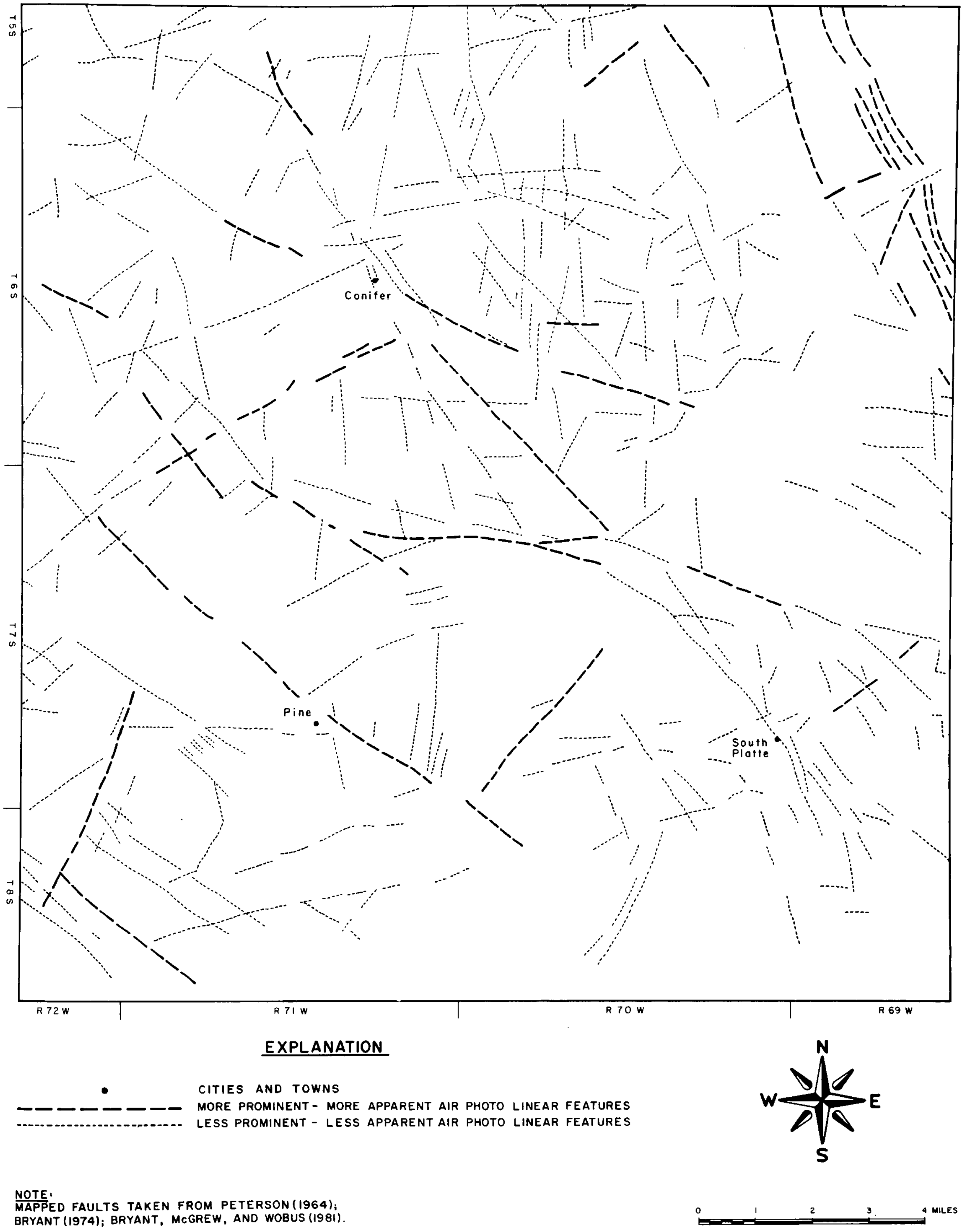


Figure 4. All air-photo linear features in the Kennedy Gulch area.

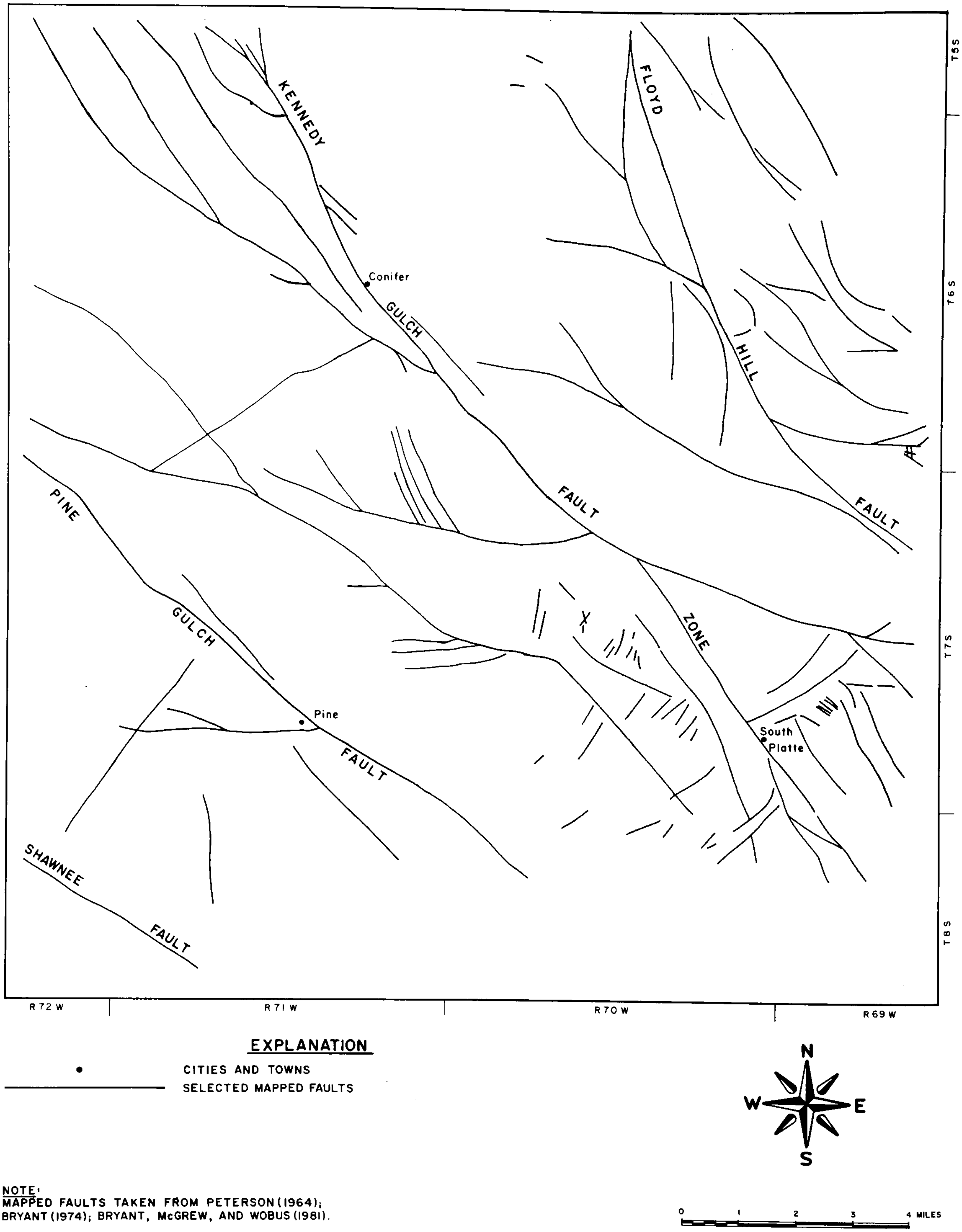


Figure 5. Selected mapped faults in the Kennedy Gulch area.

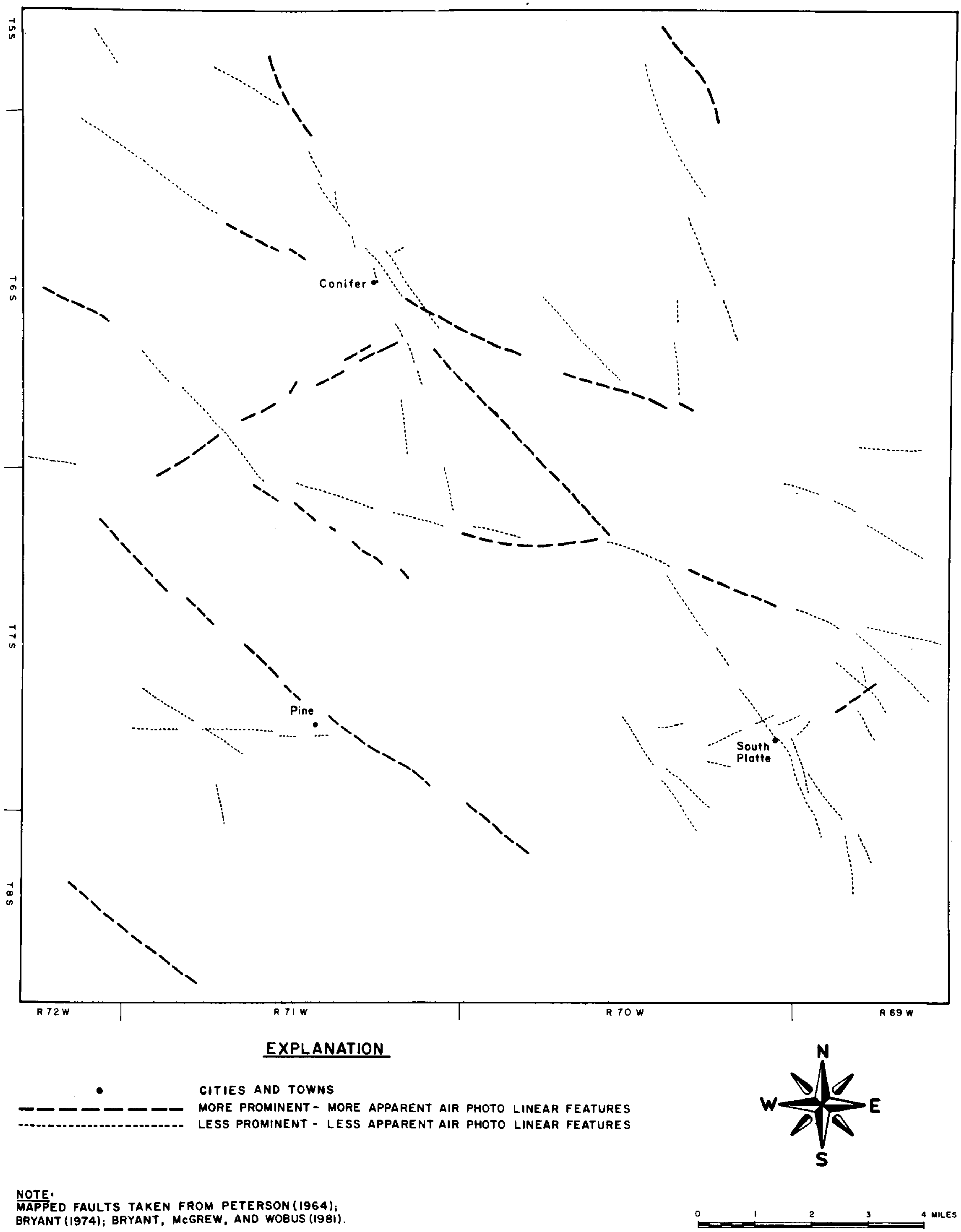
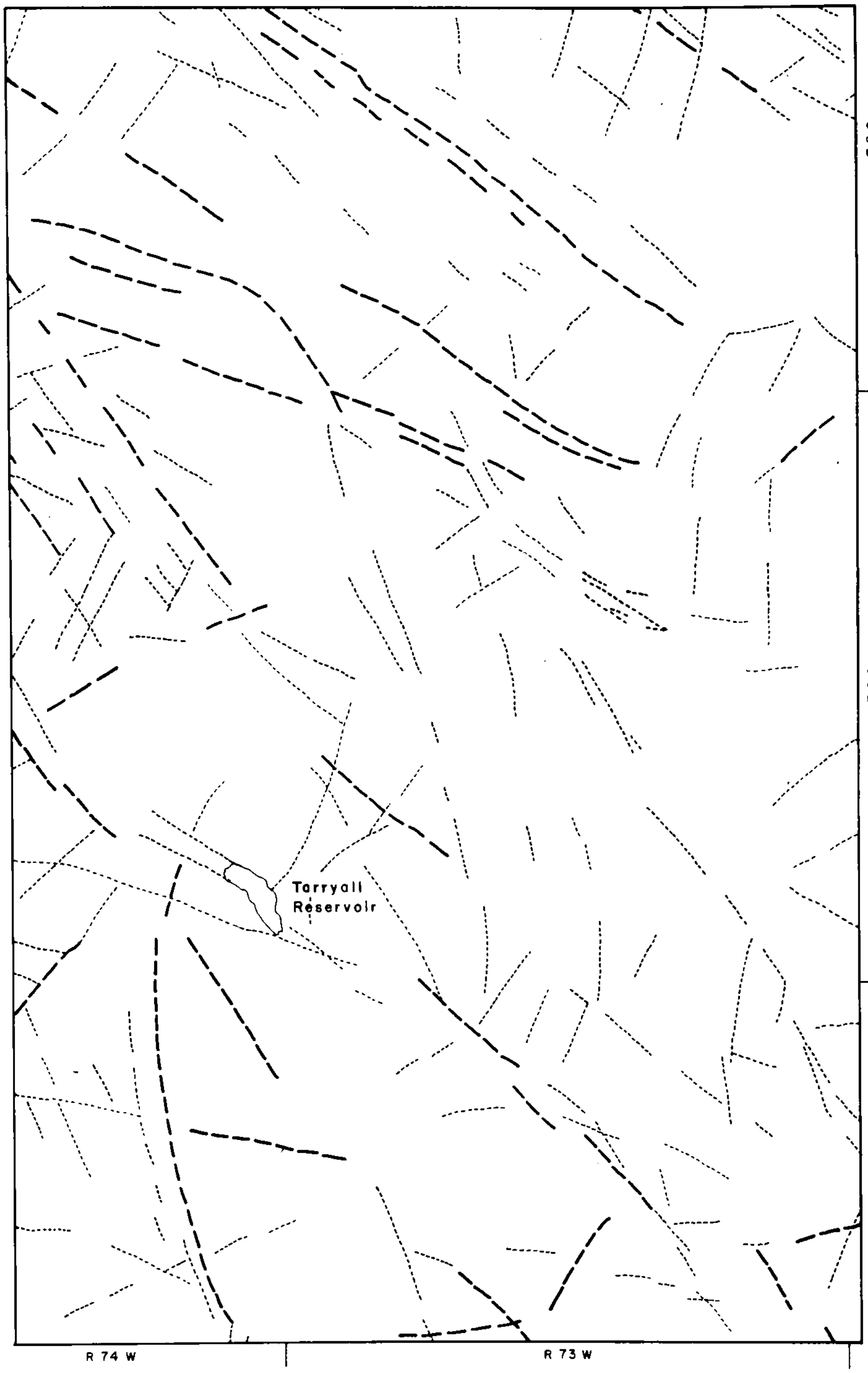
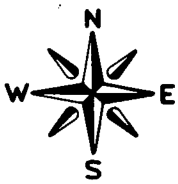


Figure 6. Air-photo linear features associated with selected mapped faults in the Kennedy Gulch area.



EXPLANATION

MORE PROMINENT - MORE APPARENT AIR PHOTO LINEAR FEATURES
LESS PROMINENT - LESS APPARENT AIR PHOTO LINEAR FEATURES
TARRYALL RESERVOIR



NOTE:
MAPPED FAULTS TAKEN FROM BRYANT, McGREW, AND WOBUS, (1981).

0 1 2 3 4 MILES

Figure 7. Air-photo linear features in the Tarryall Reservoir area.

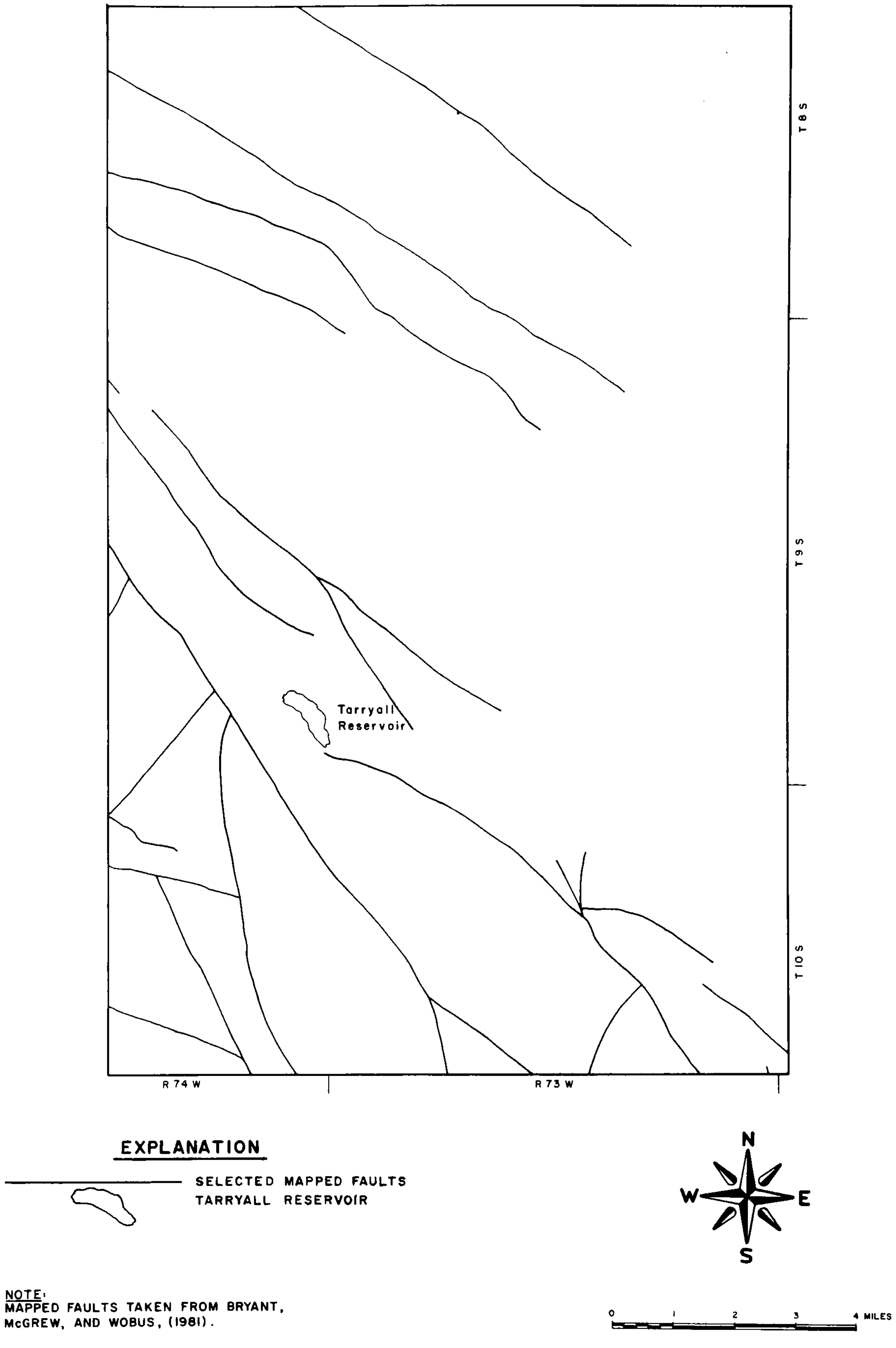


Figure 8. Selected mapped faults in the Tarryall Reservoir area.

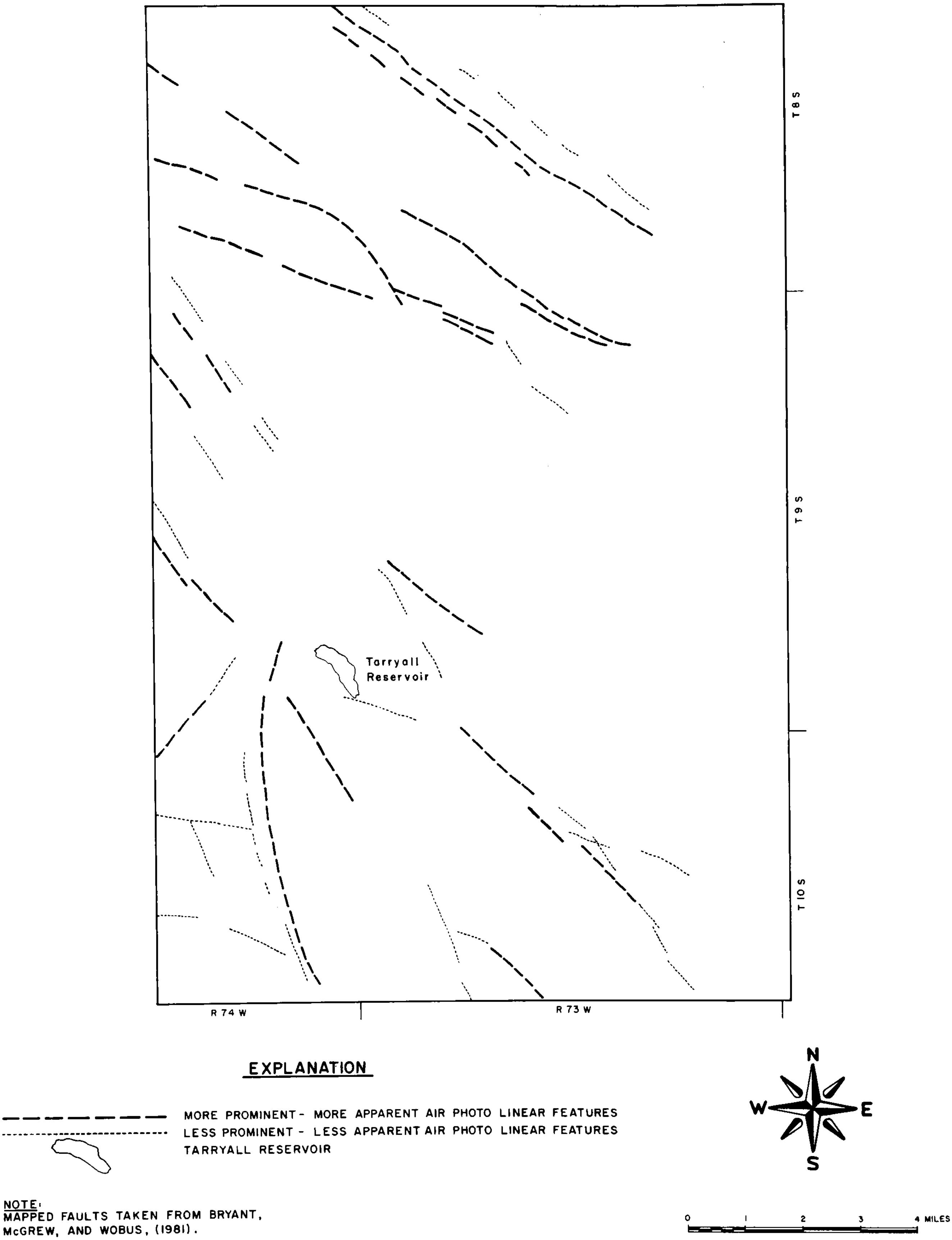


Figure 9. Air-photo linear features associated with selected mapped faults in the Tarryall Reservoir area.

Correlation of air photo linear features with joints is shown on Figure 3. The Tarryall Reservoir and Elevenmile Reservoir areas are used as example-locations of the correlation that exists throughout the study area (Figure 2) between air photo linear features and joints.

The dominant regional joint sets in the area located approximately 10 mi west of Tarryall Reservoir trend predominantly N60°E and N65°W. Trends of joints recorded in the field correlate well with lineament patterns observed on the aerial photos. In the portion of the study area located east of Elevenmile Reservoir the dominant joint sets trend approximately N50°E and N45°W; a secondary set trends approximately E.-W. Again, field measurements correlate well with the lineament patterns observed on the aerial photographs. The relationship between lineaments and joints shown on Figure 4 is another example of linear features reflecting the regional structure.

Correlation of Lineaments with Structural Features

The lineament maps show a strong general correlation between the air photo linear features and the regional mapped geology. Lineaments correlate well with joint sets and foliation within regions where bedrock is readily visible. Faults are represented, for the most part, by zones of segmented lineaments trending along and parallel to the mapped fault trace. A great number of the correlations of air photo linear features with specific structural features for a lineament analysis is dependent primarily upon: 1) the observer; 2) the scale of the aerial photograph; 3) whether the air photo is black and white, color or color infrared; 4) time of day for the aerial photography; and 5) lightness or darkness of the individual air photo. Results from the lineament study involving several different scales of aerial photographs is discussed in an earlier section of this report.

The lineament maps show a comparison between air photo linear features and mapped faults. Of particular interest is the relationship shown in the Kennedy Gulch area due to its proximity to the proposed Two Forks dam and reservoir site. There is definitely a strong zone of northwest-trending linear features that most probably represent the Kennedy Gulch fault zone. The Kennedy Gulch fault and other mapped faults located within the study area are old features that were generated in Precambrian time and reactivated during the Laramide Orogeny. The gentle, more subtle topographic expression of these faults is represented by a zone of segmented air photo linear features on the lineament map.

General correlation of air photo linear features with regional and local joint sets is possible throughout the study area. Lineaments also generally correlate well with foliation trends in areas with good rock outcrop.

Vegetation patterns and differential erosion of contrasting lithologies exhibit strong linear features on the air photo lineament map that suggest the configuration of underlying structure. The linear pattern of structural features is masked by overlying Quaternary colluvium and alluvium; vegetation lineaments on the colluvium and alluvium suggest underlying bedrock structure.

Vegetation lineaments are primarily controlled by groundwater flow associated with abrupt deepening or shallowing of the Quaternary colluvial or alluvial section overlying the bedrock structural feature. Differential erosion of contrasting lithologies exhibit strong air photo linear features, however, these lineaments are a result of a bedrock weathering phenomenon and usually do not represent a fault.

CONCLUSIONS

Conclusions based on the lineament analysis that are pertinent to the geologic and seismotectonic investigations are: 1) linear features appearing on aerial photographs generally reflect the regional geologic structure; 2) faults generally appear as zones of discontinuous lineaments suggesting segmented fault zones rather than continuous features as previously mapped; 3) groups of linear features can be correlated with prominent joint sets and foliation trends where rock outcrop is abundant; and 4) field-checked lineaments proved to be a good representative sample for interpretation of all lineaments in the study.

The results of the lineament analysis are consistent with previous lineament studies in that:

1) photo lineaments are not necessarily faults, and faults are not necessarily expressed as photo lineaments;

2) many linear features have no structural significance;

3) distribution and orientation of aerial photo lineaments and structural features on the ground do not always agree;

4) regional geologic structural interpretations for linear features can be made from photo interpretation, "spot-check" field work, helicopter reconnaissance, reconnaissance geologic mapping and knowledge of regional geology and geography;

5) interpretation of some linear features is impossible, even after complete office and field evaluation, due to field inaccessibility, vegetative ground cover, colluvial and alluvial cover, topography and lack of outcrop in certain areas;

6) a great number of the correlations of linear features with specific structural features for a lineament analysis is dependent primarily upon the observer, the scale of the aerial photograph, whether the air photo is black and white, color, or color infrared, time of day for the aerial photography, and lightness or darkness of the individual air photo.

Comparison of the air photo lineament maps, regional geologic maps, and structural features observed in the field during the reconnaissance fault study mapping (Harza Engineering Company, 1985), reconnaissance geologic mapping of Kennedy/Long Gulch (Cochran, 1984, and Hornback, 1985), and geologic trench logs (Hornback, 1984; 1985) tends to demonstrate that a general correlation can be made between the air photo lineament map and the regional structure. Confidence in the air photo lineament study is enhanced by field check results and the concurrent geologic and seismotectonic investigations.

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ALLUVIAL TERRACE INVESTIGATION ALONG THE NORTH FORK OF THE SOUTH PLATTE RIVER, SOUTH PLATTE RIVER AND HORSE CREEK, EAST-CENTRAL FRONT RANGE, COLORADO

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ABSTRACT

Analysis of alluvial terraces has provided a means for assessing tectonically related displacement. Five Quaternary terraces, Qts (youngest), Qt_1, Qt_2, Qt_3, and Qt_4, that have been mapped along Horse Creek, North Fork South Platte River, and South Platte River are recognized as being significant deposits based on their regional extent and relatively constant elevation above the modern river. Terraces were mapped on the basis of cut tread surface level above the river and degree of cobble weathering.

Detrital charcoal fragments sampled from Qt_1 overbank deposits yielded radiometric ages of 33,650+/-2280 y.b.p. (years before present), 23,730+/-280 y.b.p., 24,020+/-500 y.b.p., and 10,850+/-280 y.b.p. Based on these dates and relative dating methods, the ages of the terraces are tentatively associated with marine isotope stage chronology, Quaternary alluvial sequences dated in the Front Range, and more broadly with classic mid-continental glacial advances regionally recognized. The youngest terrace deposit, Qts, includes sediment within the rivers bed and flood plain. Qts deposits include Holocene deposits, are estimated to be approximately 10,000 years old, and represent Neoglacial time in the Rocky Mountains (isotope stage 1). Next oldest are Qt_1 deposits, which include all terrace deposits that are from the flood plain to 13 ft. above the river level. Deposit thickness for Qt_1 deposits range from 2.5 to 4.5 ft. Deposits of Qt_1 are judged to be 10,000 to 125,000 years old and possibly represent pre-Pinedale, post-Bull Lake glacial and interglacial periods (isotope stages 2, 3, 4, and 5). Qt_2 deposits are 3 to 5 ft thick and have tread surfaces ranging from 15 to 26.5 ft above the river. Qt_2 is perhaps about 125,000 to 190,000 years old and possibly associated with Rocky Mountain glaciation during the Bull Lake (isotope stage 6). Qt_3 deposits are 2 to 4 ft thick and have tread surfaces ranging from 41 to 55 ft above the river. Qt_3 is inferred to be about 250,000 to 360,000 years old, possibly representing several glacial and interglacial periods (isotope stages 8, 9, and 10). Qt_4 deposits are 5 to 20 ft thick with tread surfaces 80 to 130 ft above the river. Deposits of Qt_4 are tentatively judged to be about 425,000 to 550,000 years old (isotope stages 12, 13, and 14), perhaps representing one or more relatively large climatic events.

Where mapped traces of faults projected through a terrace deposit no measurable vertical offset was documented. Tentatively, the last probable surface rupture that can be associated with tectonic activity within the South Platte study area occurred prior to at least 125,000 years ago on the Kennedy Gulch fault, the unnamed splay of the Oil Creek fault, the unnamed fault splay of the Platte River fault, and the Platte River fault.

INTRODUCTION

Critically important to the evaluation of regional and local seismicity is the study of paleoseismic data; that is, the probable frequency and magnitude of earthquakes that occurred before the availability of historical and instrumental records (Allen, 1975; Shlemon, 1984). Accordingly, to assist in the on-going investigation by the Denver Water Department (DWD) of the earthquake potential proximal to the proposed Two Forks and alternate dam sites, the DWD initiated a study of Quaternary alluvial terrace deposits in the vicinity of Kennedy Gulch and other faults in the east-central Front Range, Colorado (Figure 1).

This paper is based on tentative conclusions presented in a previous report (Wallace and Friedman, 1984) and additional data obtained during the 1985 field season. The 1984 report contains the complete detailed maps and figures from which the figures accompanying this paper were produced.

Purpose and Scope

The major purpose of this study is to evaluate the paleoseismic activity along the Kennedy Gulch and other faults near the proposed Two Forks and alternate dam sites. To accomplish this, a program including field investigations and laboratory analyses began in the early summer of 1984. The objectives were to:

1) determine the presence and extent of the alluvial terrace deposits as potential morpho-stratigraphic markers;

2) determine the age of the alluvial terrace deposits;

3) construct a late Quaternary chronology of the South Platte study area;

4) determine if any terrace deposits are tectonically displaced; and if so, the approximate age of that displacement.

These objectives were achieved by:

1) mapping alluvial terrace deposits to show height above the present river, thickness, dissection, and regional extent;

2) reconnaissance mapping of terrace and alluvial deposits outside the study area for regional correlation;

3) studying pertinent literature and discussing Quaternary geology with U.S. Geological Survey geologists knowledgeable of the regional Quaternary geology and with Roy J. Shlemon, consulting Quaternary geologist;

4) trenching and surveying to determine terrace heights, gradients, and relative soil profile development;

5) determine the age of terrace deposits by radiocarbon and relative dating techniques, e.g.;

   A) sampling terrace soil profiles to determine grain-size distribution, $CaCO_3$ content, and pH;

   B) determining degree of cobble weathering by hammer-blow test;

   C) sampling detrital charcoal fragments from terrace deposits for radiocarbon assay;

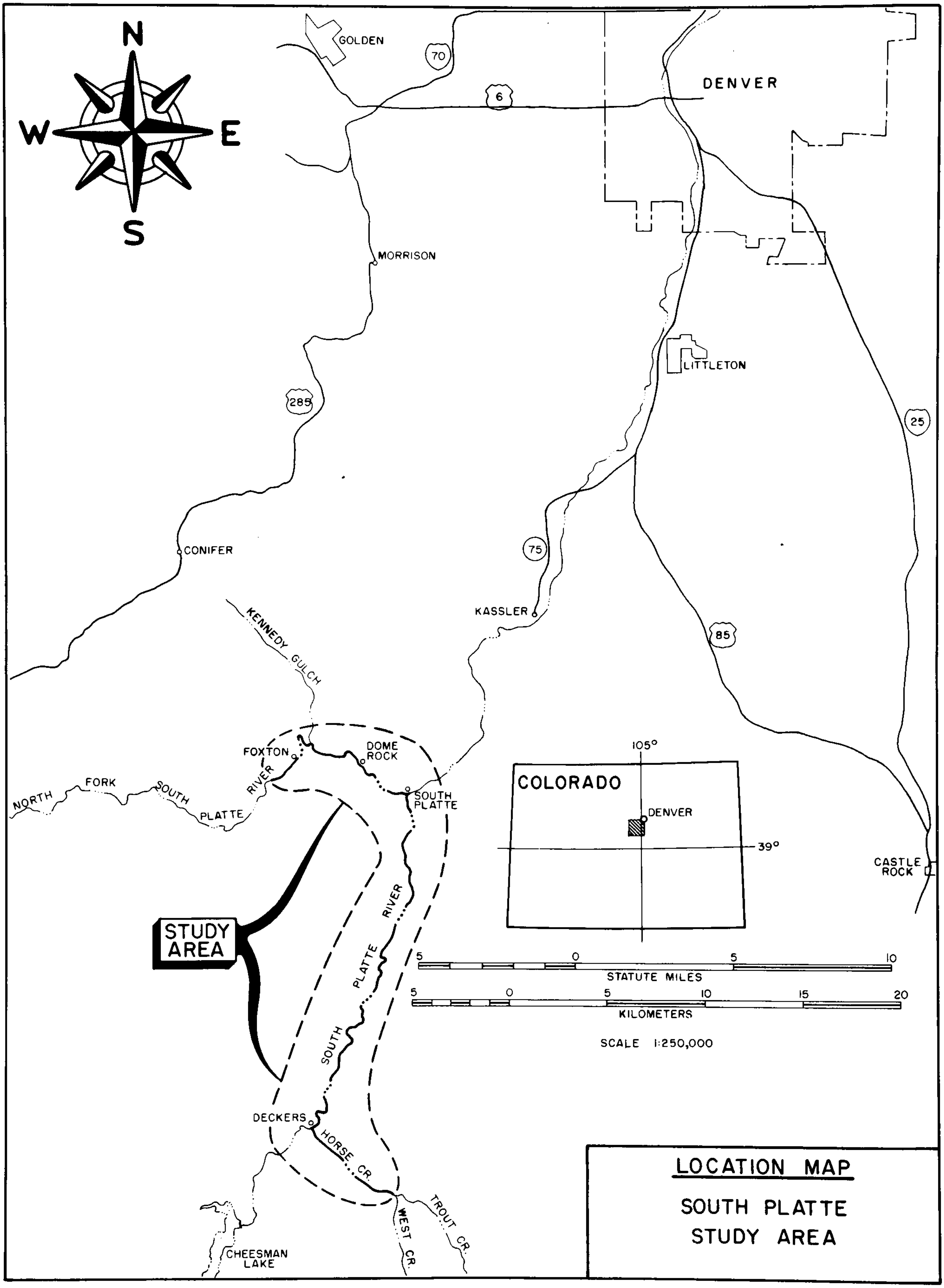


Figure 1. Location map South Platte study area.

6) tracing terrace deposits and surveying the tread surfaces crossing the Kennedy Gulch, Oil Creek, Platte River, and other faults mapped by Bryant and others (1981) and Peterson (1964); this report summarizes the research, laboratory results, and tentative interpretations of the alluvial terrace study.

ACKNOWLEDGMENTS

Much appreciation to Roy Shlemon for his expert guidance and technical contributions; to Richard Madole who provided valuable insight to soil classification and timing of Quaternary glacial events; to Margaret Barry for helpful discussions of relative dating techniques and references; and to Quent Hornback, Susan Steele, Ernest Wahlstrom, and Duane Zavadil for providing discussions and constructive criticism. Greg Wallace, co-author of the original report, was very instrumental to the completion of the final manuscript.

ALLUVIAL TERRACE DEPOSITS

Much work has been done in the Front Range correlating terrace sequences to Pleistocene glacial events (Scott, 1963; Pearl, 1973; Machette, 1975; Van Horn, 1976). Even though these terraces are laterally continuous from the mountain front eastward, the terraces within the mountains are much more discontinuous and often non-existent. Because physical connection between the glacial outwash deposits and Front Range terraces has not been demonstrated at this time, correlation must rely on alternate methods. Generally, the occurrence and extent of glacial outwash and alluvial terraces relates to major change of climate and sedimentation during the Pleistocene.

The three rivers studied are the North Fork South Platte, the South Platte, and Horse Creek. Specifically, the segments investigated and mapped parallel the rivers from the Junction of Trout and West Creeks to 1.3 mi upstream from Foxton (Figure 1). The two major rock types in the area are the Pikes Peak granite and the metamorphic Idaho Springs Formation.

"River terrace" is used to describe the step-like topographic embankments lining river valleys marking former higher elevations where the river once flowed. Many of the step-like topographic features, however, are masked, buried, or mantled by slope wash, fan deposits, or colluvium, leaving little or no evidence of the original deposit. The term "tread" describes the relatively flat bedrock surface beneath the terrace, and the term "riser" refers to the slope separating terrace treads. The formation of a terrace results from lateral cutting and/or aggradation to produce the tread, followed by later downcutting to form the riser.

Two discrete terrace types are best described by riser characteristics. A "fill terrace" is composed entirely of sediment deposited as the result of aggradation. The terrace develops as the river downcuts. A "rock-cut terrace" develops from the erosion of bedrock where the riser is composed wholly of bedrock, often with a veneer of fluvial gravel capping the cut surface. A rock "slip-off-slope terrace" is a local terrace deposit on the inside of a meander spur, formed by a brief halt during the irregular incision by a meandering stream. As the stream migrates laterally, channel gravel equal in thickness to the depth of flood scour are deposited on the inside of the meander bend. Fill terraces are usually much thicker and generally form paired terraces (Moss, 1974).

The terrace deposits within the three river valleys are not paired. Evidence of a major episode of aggradation favoring preservation of paired terraces was not observed. The terraces studied are the result of laterally migrating waters which have 1) cut and beveled the bedrock, 2) reworked and deposited alluvium, and 3) subsequently downcut to lower levels.

Inspection of a longitudinal section illustrates consistent morpho-stratigraphic positions and the regional extent of the terrace deposits. Paleo river gradients of all terraces are generally equal and seem to parallel present day river gradients (Wallace and Friedman, 1984).

Terraces deposits within the study area are informally designated Qts, Qt_1, Qt_2, Qt_3, and Qt_4. "Q" refers to Quaternary, "t" to alluvial terrace, and "s" to present stream deposits and flood high-water level deposits. Numerical subscripts refer to the order which significant morpho-stratigraphic units occur above the river (Figure 2).

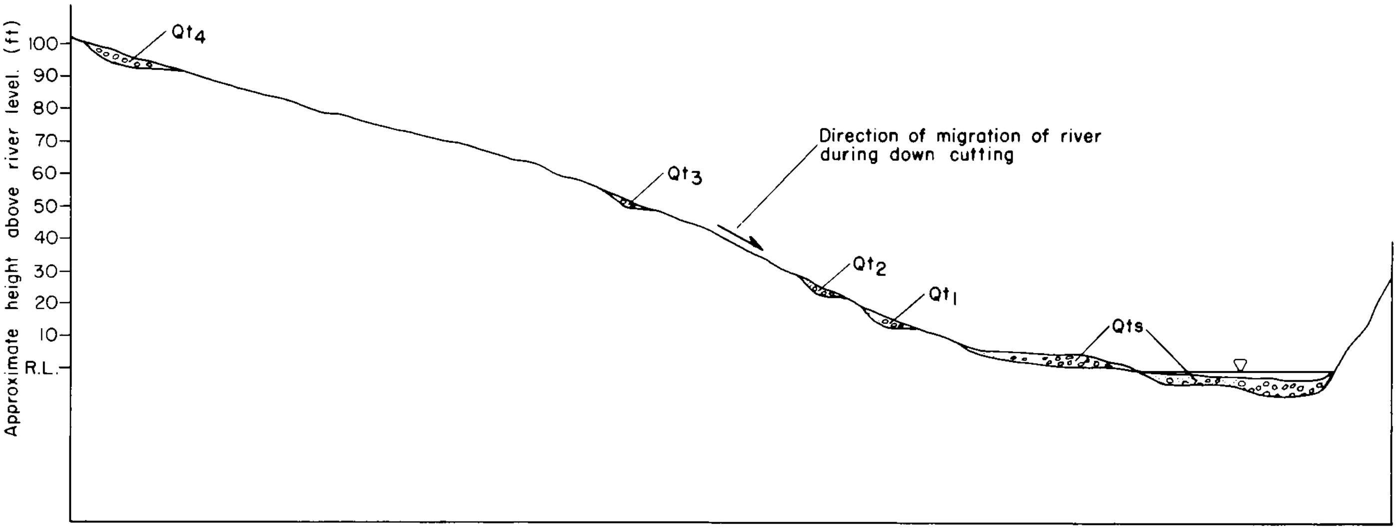


Figure 2. Generalized cross section showing Quaternary alluvial terrace sequence (Qts thru Qt_4) along the North Fork South Platte River; in vicinity South Platte, Colorado.

Variations in the height above the river within each terrace deposit occur because of 1) undulating and beveled bedrock surfaces, 2) fluctuating channel gradients, and 3) the extended length of time represented by each terrace level. Undulating bedrock surfaces result from differential erosion across varying bedrock lithologies, a shift in channel direction, and transverse channel migration. Fluctuations in channel gradients are a result of localized incision and aggradation.

The terrace sediments generally consist of sub-rounded to well-rounded gravels, cobbles, and boulders with a sand-silt matrix. Deposited on many tread surfaces is a fining-upward sequence of cobbles and boulders in some instances overlain by sand, silt and clay strata. In other instances little or no evidence exists of either the coarse or fine sequence. Alternating clay and sand layers are often found within the finer sequence.

Mapping Procedures

Terrace deposits were mapped on a 1:2,400 topographic base with a contour interval of 10 ft. Terrace elevations were determined by hand-leveling and in some cases by surveying equipment. The elevations of terrace deposits were surveyed at the base of the cut bedrock surface. The majority of the terraces are visible from the roads paralleling the rivers, except for Qt_4 and several Qt_3 deposits which are concealed by vegetation. A deposit was mapped as a terrace only if a visible concentration of fluvially-reworked clasts had been preserved on a flat or beveled bedrock cut surface. Aerial photographs were of limited use because of scale and obscuring colluvium.

Alluvial Terrace Characteristics

Originally, Qts deposits included the present sediment in the rivers, the rivers flood plain, and terraces that have developed less than 5 ft above the river level. Qt_1 deposits were originally assigned as terraces that had developed between 8.5 ft to 13 ft above the river level. Revisions resulting from new data and additional field study have assigned Qts deposits to include sediment within the rivers bed and flood plain and Qt_1 terrace deposits now include all terrace deposits that have developed above the flood plain up to thirteen feet above the river level.

Qts is the most abundant of the five terrace deposits recognized in the study area. Qts deposits include sediments within the present river bed and flood plain. It is estimated Qts deposits are found along at least 40 percent of the length of the rivers in the study area.

Qt_1 deposits include terraces that have developed up to 13 ft above the present flood plain. Qt_1 deposits are found along 6.6 percent of the length of the present river valleys. Terrace thickness ranges from 2.5 ft to 4.5 ft. with the longest continuous deposit length being 850 ft.

Qt_2 deposits express the greatest lateral extent of the upper terraces. One continuous deposit exceeds 1800 ft. It is interesting to note that Qt_2 deposits are predominately located at but are not limited to the inside of rock slip-off slope meander bends. The range in height above the river that Qt_2 deposits are found is from 15 to 27 ft and terrace thickness ranges from 3 to 5 ft. Deposits of Qt_2 line 13.8 percent of the length of the rivers studied.

Deposits of Qt_3 are less continuous and preservation is very limited. The range in height above the river that Qt_3 deposits are found is from 41 to 58 ft. Qt_3 deposits line 8.1 percent of the length of the river valleys studied. The longest continuous deposit is approximately 500 ft in length and terrace thickness ranges from 2 to 4 ft.

Atop spurs and ancient rock slip-off meander slopes are several Qt_4 deposits. The height of these deposits range from 80 to 130 ft above the present stream level and they are 5 to 20 ft thick. They are found along less than 0.9 percent of the length of the entire river valleys in the study area. The longest single deposit is 330 ft in length.

Generally, the degree of terrace disection increases as terrace height above the river increases. More evident is the modification in terrace form from lower to upper levels. The upper level terraces have an increasing amount of colluvium masking their treads and risers. Numerous deposits consist only of remanent cobbles that are exposed at the surface and it is likely several terraces are buried beneath slope wash and colluvium. Field observations indicate, for the most part, that geomorphic expression of the five terraces illustrates an increasing degree of modification due to the progressive age of each terrace deposit.

AGE CLASSIFICATION

Age determination for the terrace gravel deposit sequence within the South Platte River study area relied on four radiocarbon dates, relative dating, associations with regional chronologies established elsewhere in the Rocky Mountains, and the marine isotope stage sequence. Accordingly, the ages of the terrace deposits are tentatively dated by 1) evaluating radiometric ages of detrital charcoal from Qt_1, 2) separating and assessing morpho-stratigraphic levels based on cobble (clast) weathering, and terrace height above the river, and 3) tentatively correlating terrace levels (Qts, Qt_1, Qt_2, Qt_3, Qt_4)with the Rocky Mountain glacial sequence, the eastern Front Range alluvial sequence, and the marine isotope stage chronology. The approximate terrace-deposit ages result from a comprehensive evaluation of all of the above.

Various soil age indicators (i.e., $CaCO_3$, color, pH, clay content) have also been used to subdivide Quaternary sediments in other studies. A relative age classification utilizing these techniques could not be adapted to the terrace soils. A total of 15 soil samples were collected along with being measured, described and analyzed. Results were variable and deemed generally inappropriate for correlation with other work in the Front Range.

Radiocarbon Dates

Several terrace deposits were inspected for material that could be dated radiometrically; unfortunately, most materials were too small for adequate dating. However, adequate amounts of detrital charcoal were discovered by backhoe trenching. Four samples were collected and dated from three sample locations.

It is stressed, for the purposes of this report, that less emphasis be placed on the absolute dates obtained from the detrital charcoal fragments sampled from terrace overbank deposits. The radiocarbon dates are used as guidelines, not definitive criterion and a reasonable degree of scatter in dates is to be expected. Many factors may contribute to the apparent disparity in absolute dates and they include 1) fault related offset, 2) local channel scouring, 3) variations in bedrock lithologies, 4) localized channel fill, 5) large scale events that post date original deposit (i.e., 100 year or 500 year floods), 6) sample contamination, 7) poor sampling procedures, and 8) inefficient laboratory analysis. However, as the result of this and other studies (ESA, 1984; Hornback, 1984; Harza, 1985), it has been determined that no alluvial terrace within the study area has been offset by faulting.

Two of the sample sites are 5 ft apart, located along the North Fork South Platte River approximately 0.25 mi north of the confluence at South Platte. In this area, the dateable charcoal samples were imbedded in a horizontally-bedded fluvial overbank deposit preserved by a younger debris flow deposit. The three separate samples of detrital charcoal fragments and their enclosing sediments sampled along the North Fork, yielded ages of 33,650 +/-2280 y.b.p., 23,730 +/-280 y.b.p., and 24,020 +/-500 y.b.p. The tread surface elevations for this deposit is approximately 5 ft above the river.

The third sample site is located 0.4 mi south of the confluence along the South Platte River. At this locality a road cut slope has exposed a fining upward sequence of at least two distinct facies (ESA, 1984). The samples of detrital charcoal fragments and their enclosing sediments sampled along the South Platte were also imbedded in a horizontally bedded fluvial overbank deposit preserved by younger slope wash and colluvial deposits. This sample yielded an age of 10,850 $\pm$ 280 y.b.p. It is inferred that this date represents a minimum age of overbank deposits within Qt_1. The tread surface elevation for this deposit is some 10 ft above river level.

The regional terrace investigation has illustrated the variable elevation of individual terrace-bedrock contacts. These elevation differences are most generally caused by differential erosion across varying bedrock lithologies and by local channel scouring. Hence, elevation inconsistencies do occur and are particularly apparent for the Qt_1-bedrock contact (R.J. Shlemon personal communication, 1985).

Assuming these cut surfaces represent a previous major glacial period, based on marine isotope stage chronology, the age would be approximately 10,000-60,000 years old (marine isotope stages 2 and 3). However, a glacial advance associated with stage 3 is generally not recognized in Colorado.

Relative Dating Methods

Relative dating is based upon the premise that certain weathering parameters are time dependent, and can therefore be used to delineate episodes of deposition (Burke and Birkland, 1979). Moreover, if environmental factors that influence weathering rates are similar, then comparison of this kind can be made.

The degree of cobble (clast) weathering is influenced by several variables including climate, lithology, vegetation, position in the weathering profile, and time (Jenny, 1941; Burke and Birkeland, 1978; Colman, 1977). Of these variables, Colman (1977) found that lithology appears to be the most important factor. Accordingly, weathering data were collected only from coarse-grained granite fluvial cobbles derived from the Pikes Peak intrusive complex. This lithology was chosen because of its abundance and consistent mineralogy.

Clasts were sampled below the B horizon wherever possible. Many times, however, samples were taken from the horizon directly on top of the tread surface and at least 1 ft below the ground surface.

The weathering ratio and weathering index were derived from the hammer-blow weathering test used by Burke and Birkeland (1978). At each sampling site at least 50 cobbles, ranging from 3 to 6 in. in diameter, were struck with a 4 lb. hammer and classified as either fresh, weathered, or grussified. A cobble was deemed fresh if a crisp ring was heard and the cobble broke into a few pieces after several sharp blows. It was designated as weathered if a dull thud was heard and the cobble broke into several pieces with a moderate blow. It was called grussified if it disintegrated when struck.

This procedure was repeated for 19 different sample sites at various terrace deposits. Particular emphasis was directed towards sampling terrace deposits at various heights above the present day river.

The amount of fresh, weathered, and grussified samples at each site are expressed as a ratio. Percent fresh cobbles and percent grussified cobbles at each site are plotted against height of the sampled terrace deposit (Figure 3). For ease of illustrating data points, only average values and range of values are shown on each plot. The amount of fresh cobbles decreases with increase in terrace height above the river with minor overlap of percentage values. Opposite to this, the percentage of grussified cobbles increases with increase in height of terrace deposits above the river.

It is possible in the analysis of cobble weathering-time relationship that the cobbles can be redistributed from higher terrace levels to lower terrace levels. However, an important assumption in this type of analysis is that

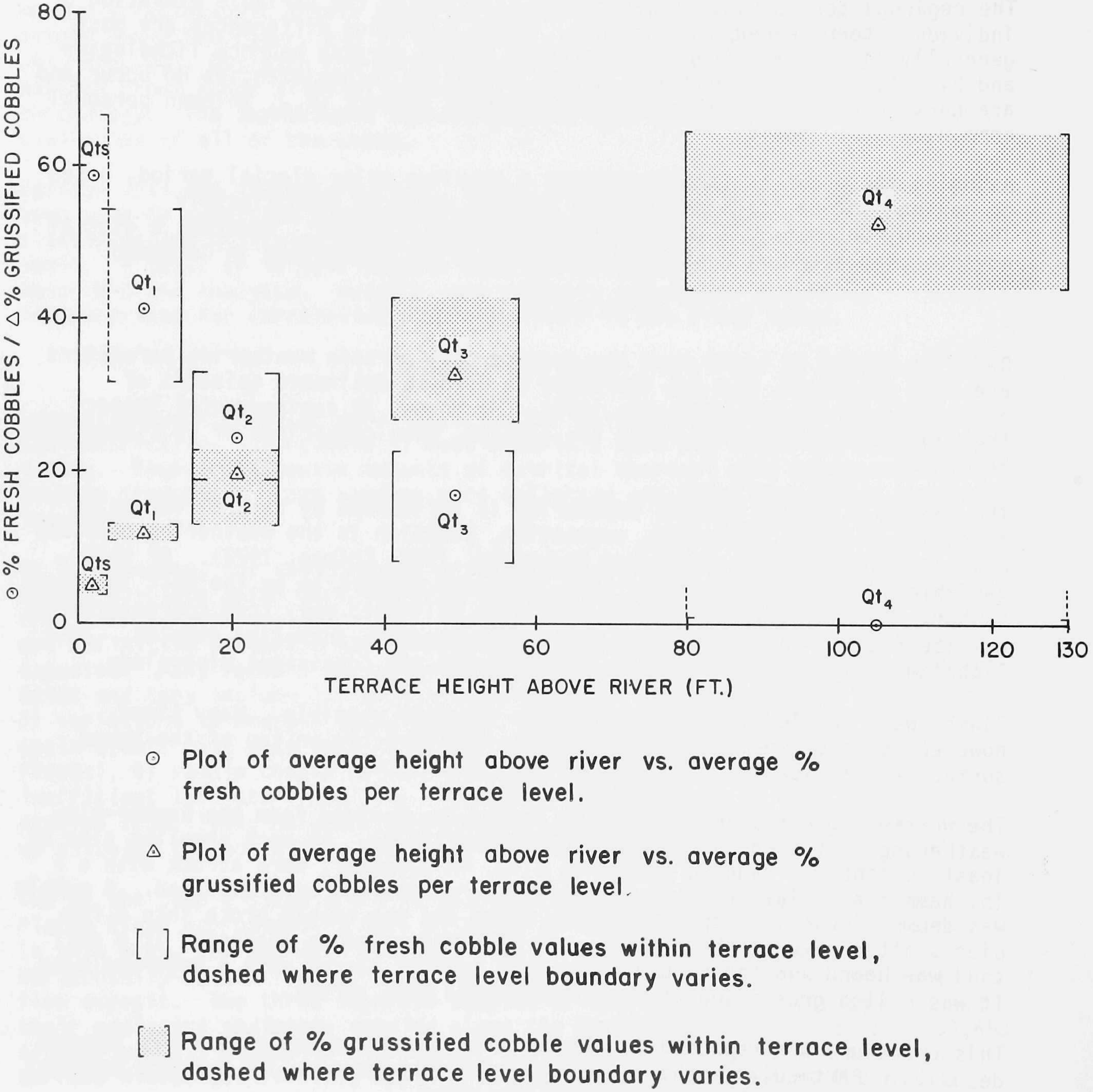
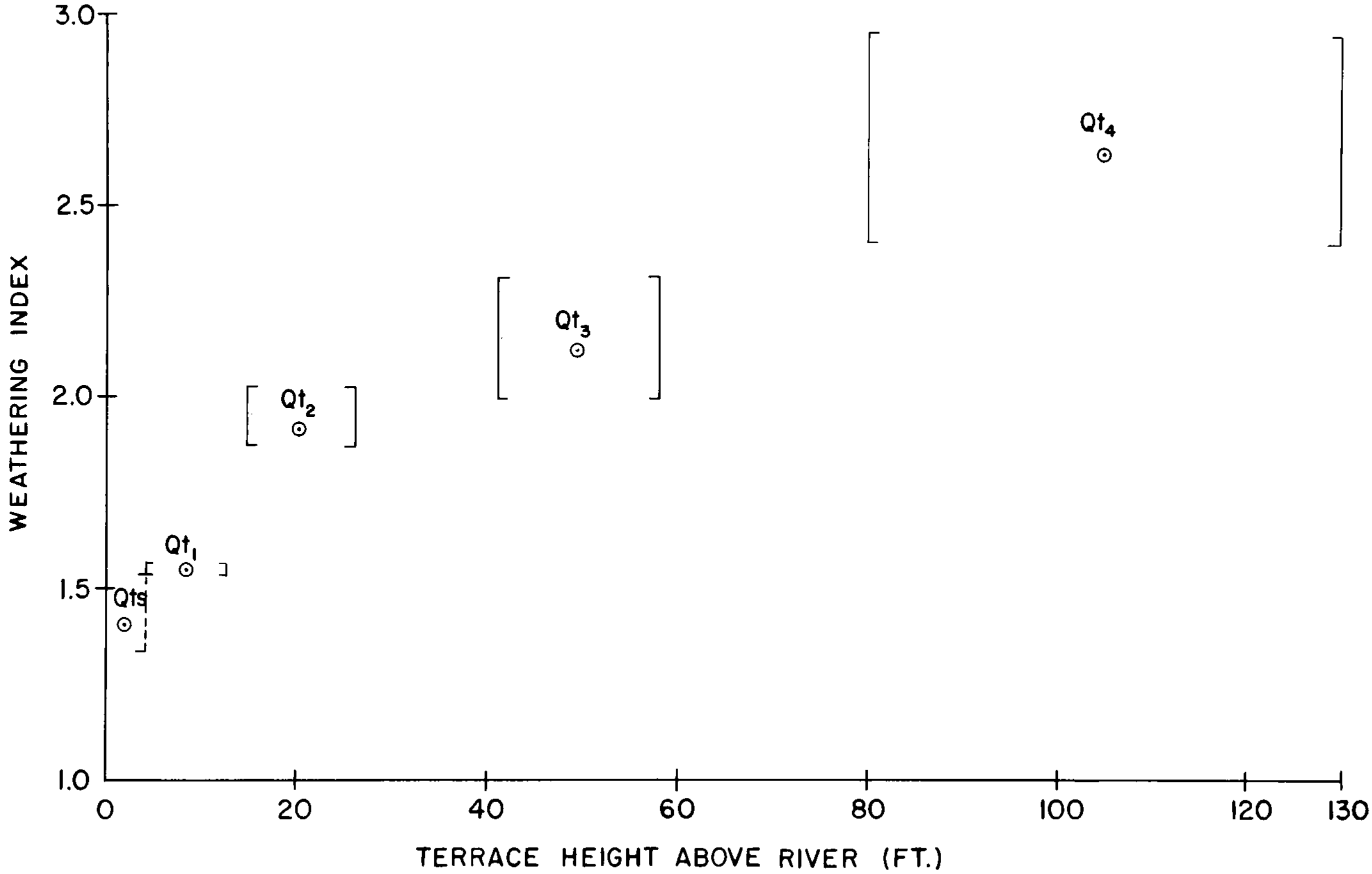


Figure 3. Variation in percent of fresh/grussified cobble samples between alluvial terrace levels.

highly weathered stones have been decimated during transport from higher to lower terraces and that the cobbles were deposited relatively fresh. Hence, the relationship probably represents in-situ weathering.

Cobble weathering index values were also obtained from the hammer-blow data. The method used was modeled after procedures of Piety (1981). At each site, the number of fresh rocks are multiplied by 1, the number of weathered rock by 2, and the number of grussified rocks by 3. The products are summed and then divided by the total number of rocks counted. The result is weathering index number between 1 and 3.

These weathering-index data are plotted against associated terrace heights above the river in the same format used with weathering ratio plots. This plot shows an increase in weathering index with increase in height of terrace deposit above the river (Figure 4).



⊙ Plot of average height above river vs. average weathering index.

[ ] Range of weathering index values within terrace level.

Figure 4. Variation in weathering index between alluvial terrace levels.

The weathering ratio and weathering index plots indicate a clear separation in degree of weathering development of cobbles between the five terrace levels in the study area. With an increase in terrace height above the river, the amount of grussified cobbles increases and the amount of fresh cobbles decreases, indicative of an increase in relative age of the deposits with increasing height above the river. Based on the observable degree of weathering development of the cobbles, no further subdivision within each terrace level, and therefore each age group, could be made.

CHRONOLOGICAL SEQUENCE

Previous work in Colorado has demonstrated a regional correlation between Pleistocene and Holocene climatic events with eastern Front Range alluvial sequences. (Hunt, 1954; Malde, 1958; Scott, 1963; Van Horn, 1972; Machette, 1975). A summary of these glacial and alluvial sequences together with marine isotope stage chronology and the South Platte study area terrace sequence is shown in Table 1.

The ages of the marine isotope stage boundaries shown in Table 1 are taken from data compiled by Colman and Pierce (1981; see also Figure 5). More recent work by Johnson (1982) suggests that some stage boundaries estimated from sedimentation rates by Shackleton (1977) are subject to revision based on magnetic reversal dates by marine-astronomical correlations.

Classical mid-continental sequence terminology presented in Table 1 is the result of recent work in the midwest. The "classic" Kansan-Nebraskan of the mid-continental sequence have been reclassified as pre-Illinoian by Hallberg and Boellstorff (1978). Analysis of the stratigraphic sequence in the midwest shows that these terms have been miscorrelated (Hallberg, 1980).

Approximate age boundaries assigned to the Rocky Mountain glacial sequence are based on the following:

1) Pinedale terminal moraines at West Yellowstone, Montana have obsidian hydration dates of 20,000 to 35,000 y.b.p. Assuming that glaciation in the Front Range and at West Yellowstone was synchronous, then the Pinedale Glaciation probably began in the Front Range prior to 35,000 years ago. However, to illustrate the apparent general correlation of isotope stage 2 with the Pinedale, the upper boundary is conservatively placed at 25,000 y.b.p. Radiocarbon ages for sediments from kettles on the Pinedale terminal moraine in the upper valley of the Colorado River on the west side of the Front Range suggest that the outermost moraines, at least in places, are no younger than 13,000 y.b.p. and may be older than 14,600 y.b.p. (Madole, 1976b). Three radiocarbon ages from LaPoudre Pass, located at the head of the Colorado River at an altitude of about 10,263 ft, suggest that Pinedale Glaciation in the Front Range ended before about 10,000 y.b.p., and possibly before 11,000 years ago (Madole, 1979).

2) Uranium-trend dating of Bull Lake till near Allens Park, Colorado, yielded an age of 130,000 +/- 40,000 y.b.p. (Shroba and others, 1983). This date is in agreement with the 130,000 to 155,000 y.b.p. age assigned to Bull Lake till near West Yellowstone, Montana (Pierce and others, 1976). The Bull Lake age boundaries correlate with isotope stage 6.

Table 1. Tentative correlation chart of Quaternary deposits.

y.b.p. x 10³	Marine Isotope Stage Chronology (1)	Classic mid-Continental Sequence (2)	Rocky Mountain Sequence (3)	Eastern Front Range Alluvium (non-glacial) (4)	South Platte Study Area Terrace Sequence (5)
	1	post-Wisconsin	Neoglacial	Piney Creek	Qts
10	2	late-Wisconsin	Pinedale	Broadway	
25	3	mid-Wisconsin			
60	4	early-Wisconsin			Qt_1
75	5	Sangamon		Louviers	
125	6		Bull Lake	Slocum	Qt_2
190	7	Illinoian and pre-Illinoian			
250	8				
275	9				Qt_3
335	10				
360	11		pre-Bull Lake		--?---?--?--
425	12				--?---?--?--
460	13				Qt_4
≈ 505	14				
≈ 550	15				--?--?---?--
≈ 595	16 (600)	Pearlette	ash type 'O' (4a)	--?---?--?-- Verdos	
≈ 630					

(1) Shackleton and Opdyke, 1973; Shackleton, 1977; Coleman and Pierce, 1981.
(2) Hallberg and Boellstorff, 1978; Hallberg, 1980; Shlemon, 1984 (Personal communication).
(3) Madole, 1976b; 1979; Pierce and others, 1976; Shroba et al, 1983.
(4) Machette, 1975 (Uranium series and radiocarbon dates).
(4a) Machette, 1976a; 1976b; Van Horn, 1976.
(5) Wallace and Friedman, 1985.

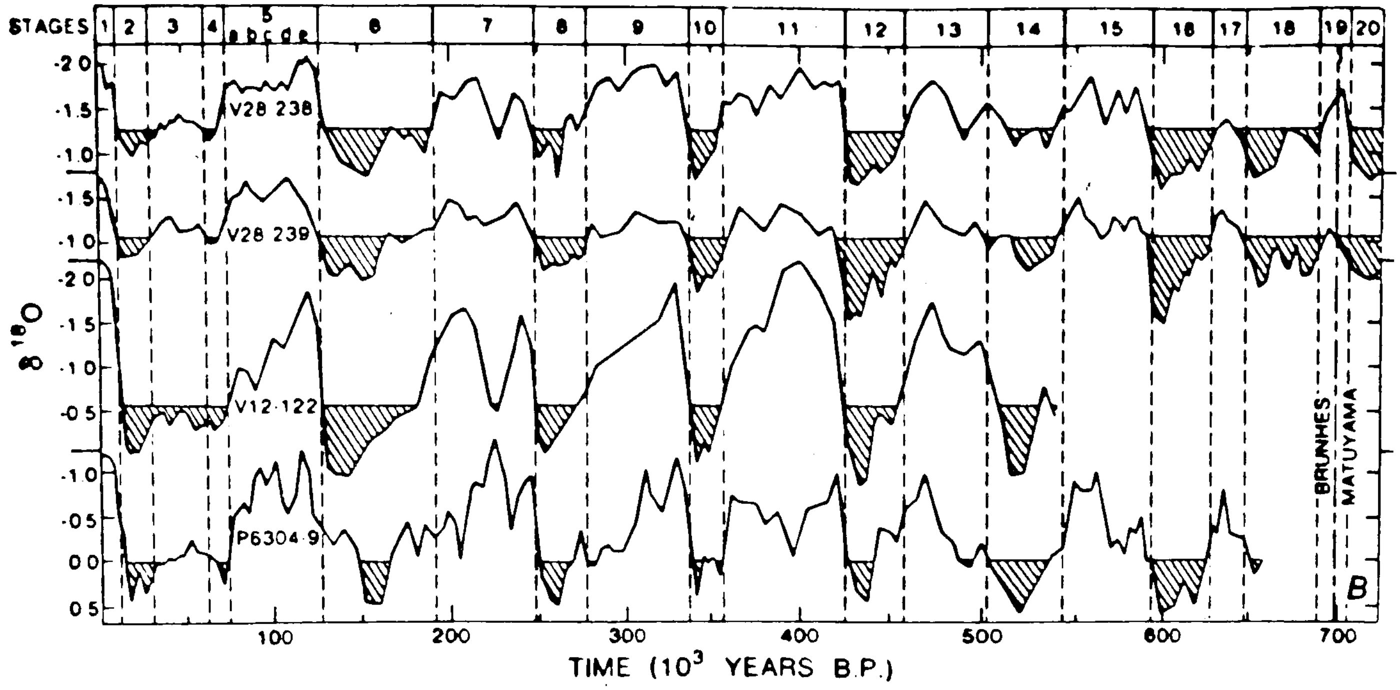


Figure 5. Oxygen-isotope records of four deep sea cores.

The alluvial terrace sequence of the eastern Front Range that was observed seemingly correlates well with glacial events. Radiocarbon dates from Broadway and Piney Creek Alluvium fall within the assigned ages of Pinedale and Neoglacial advances. The older Slocum and Louviers alluvium sequences are less definitively dated by uranium series dates correlative with glacial periods, fossils, and pedologic evidence. The age of the Verdos Alluvium is about 600,000 years old, based on the Type "O" Pearlette Ash found within a deposit along Ralston Creek (Machette and others, 1976a, 1976b) and Bear Creek (Hunt, 1954).

Uranium-series dates from the Slocum Alluvium suggest that this deposit may correlate with Bull Lake Glaciation (isotope state 6). The age range of the Louviers Alluvium suggests it may not have a Rocky Mountain glacial equivalent. However, two minor glacial advances, isotope stages 5b and 5d, have been recognized in the Yellowstone area.

Alluvial terrace deposits in the study area have been subdivided into five levels. Four radiocarbon dates were obtained from Qt_1 and provide a tentative minimum age of the surface from which they were sampled. Based on these dates it is tentatively estimated that Qts probably represents Neoglacial equivalent deposits. This association also tentatively correlates Qts with Piney Creek and post-Piney Creek Alluvium.

The higher terrace levels (Qt_1 through Qt_4) are tentatively dated by association with the 'Rocky Mountain' glacial sequence, the 'eastern Front Range' alluvial sequence, and the marine isotope stage chronology. Qt_1 deposits are estimated to be Broadway and Louviers equivalents and probably associated with glacial advances during marine isotope states 2, 4, 5b, and 5d. For the purpose of this report no attempt was made to subdivide Qt_1 further. Qt_2 deposits are estimated to be the Slocum equivalent and probably associated with Bull Lake Glaciation (isotope stage 6). The significance of this association is the apparent abundance and lateral extent of Qt_2, and the oxygen-isotope data from marine sediments that indicate a period of pronounced glacier growth occurring during isotope stage 6.

Deposits Qt_3 and Qt_4 are probably pre-isotope stage 7. Based on marine isotope stages, the next probable earlier glacial advance occurred during stage 8. However, the next 'Front Range' alluvial deposit is the Verdos, and based on Type "O" Pearlette Ash is isotope stage 16. If Qt_3 and Qt_4 represent one or more glacial advances during stages 8, 10, 12, or 14, then they would represent events recognized in the 'Front Range' sequence. Until further dates are available, Qt_3 is estimated to include sediment of isotope stages 8, 9, and 10. From the world-wide isotope stage data (Figure 5), it is apparent stages 8 and 10 produced relatively small climatic events. If this is true, then it is likely that Qt_3, because of the relative abundance and wide range of height above the river, could have extended over such an interval. Qt_4 tentatively represents stage 12 and/or 14. The high position and considerable thickness of Qt_4 indicate antiquity and a large scale event(s).

EVIDENCE OF TECTONIC DISPLACEMENT

Recency and amount of fault movement can be determined by cross-cutting relationships between faults and the terrace deposits and can provide a means for quantitatively estimating approximate age and magnitude of displacement of Quaternary faulting (Kirkham and Rogers, 1981). Detecting offset where the trace of a mapped fault projected directly through a terrace deposit necessitates exposing and surveying tread surfaces across the fault.

Faults located in the study area, as mapped by Bryant and others (1981), and Harza (1985) are represented on the 1:150,000-scale map by dashed lines (Figure 6). This approach of representing the mapped faults as dashed lines on the map was taken for two reasons: 1) the difficulty in accurately transfering data from a small (1:500,000) to a large (1:150,000) scale map, and 2) the location of the faults represent specifically the work depicted by others.

Oil Creek Fault

Evidence of displacement on the Oil Creek fault is seen in an exploratory mine pit located approximately 0.3 mi southwest of West Creek and 6.5 mi southeast of Deckers. The fault is the northern extension of the Oil Creek fault which strikes N-S and dips 56° W. The fault is high-angle normal and offsets colluvial/debris flow material (Figure 7). It is believed that the colluvial/debris flow material probably post dates an alluvial terrace of West Creek that is scarcely preserved at its toe. This alluvial terrace deposit is located more than 200 ft above West Creek. The colluvial/debris flow caps a bedrock spur which suggests that a topographic reversal has occurred. The relative position of this deposit above the creek and degree of geomorphic expression suggests that the colluvial/debris flow is at least older than Qt_4.

Unnamed Splay of Oil Creek Fault

Immediately east of Fletcher Ranch along Horse Creek, a presently unnamed splay of the Oil Creek fault trends north-northwest crossing the Horse Creek Valley. A Qt_3 deposit overlies the trace of the mapped fault. No

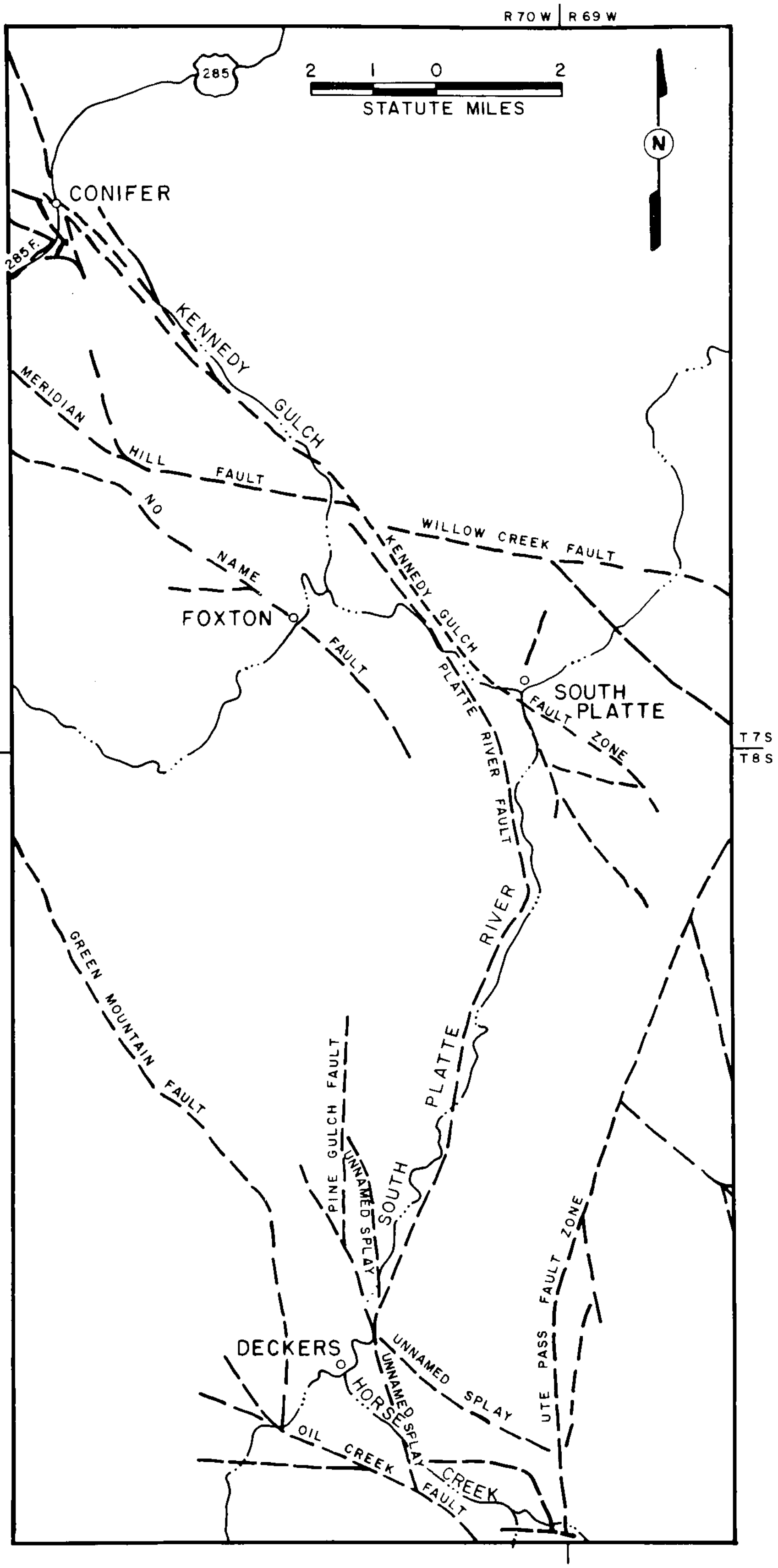


Figure 6. Map showing approximate trace of faults taken from Bryant et al (1981) and Harza (1985).

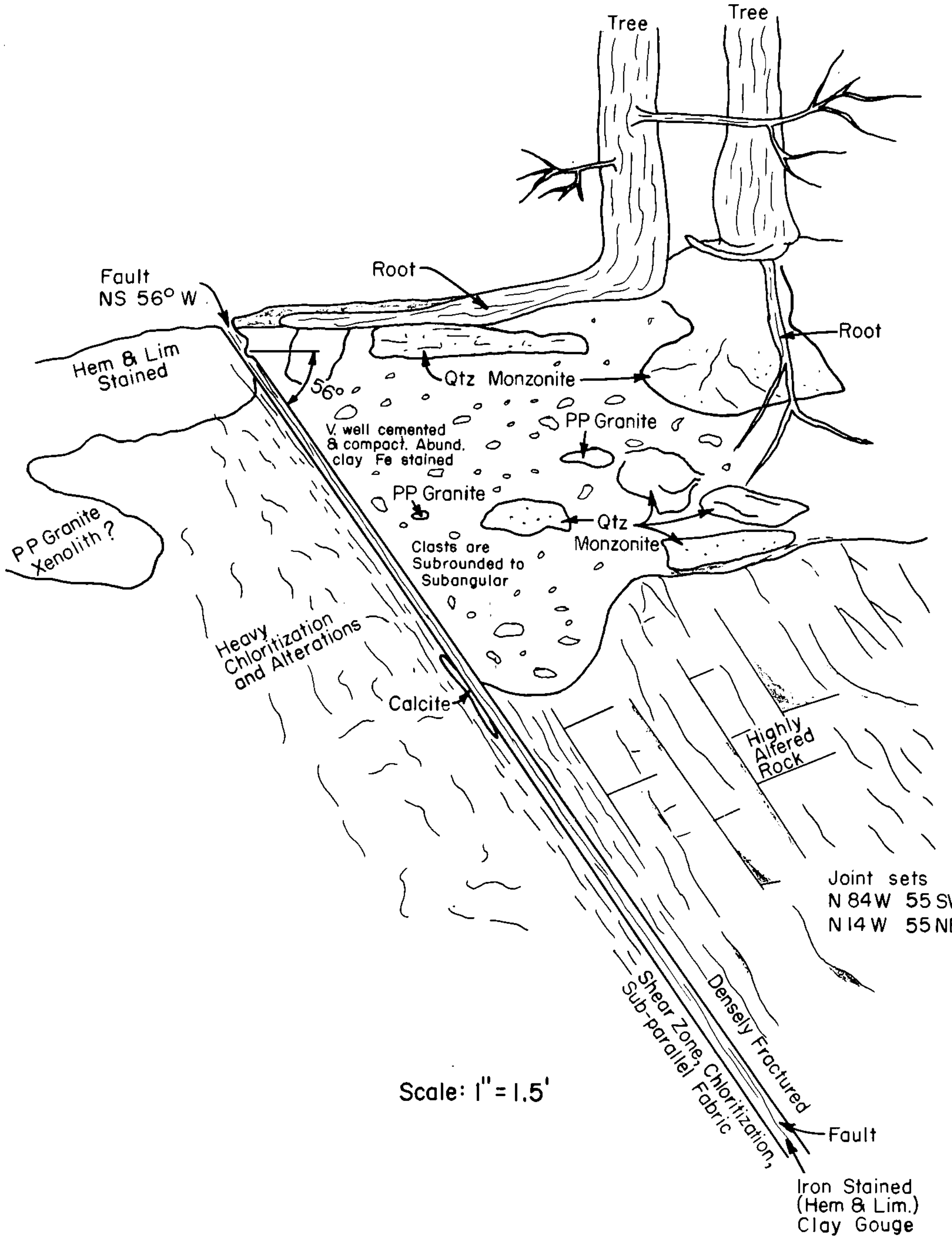


Figure 7. Cross section illustrating normal movement along northern extension of Oil Creek fault located in a mine pit near West Creek, Colorado.

displacement of the Qt_3 terrace is discernable, thus suggesting that the last surface rupture on the fault occurred at least 250,000 y.b.p.

The same unnamed splay of the Oil Creek fault extends further north into the Trumbull area. Here a projection of the fault crosses a Qt_2 deposit. No displacement is observed, thus corroborating that last surface displacement probably occurred before about 125,000 y.b.p.

Unnamed fault splay

Another unnamed fault that connects Pine Gulch fault and the Platte River fault trends north through Snow Water Springs. An unbroken Qt_2 deposit overlies the fault. This relationship suggests the age of last surface rupture along this fault occurred prior to 125,000 y.b.p. Further to the north this same fault exhibits no displacement of a Qt_3 deposit. This indicates the age of last surface rupture took place prior to 250,000 years ago.

Platte River Fault

The southern extension of the Platte River fault is mapped at Snow Water Springs. No apparent displacement occurs in this vicinity along the Platte River fault. A Qt_2 deposit overlying the fault is apparently not displaced, indicating that last surface rupture took place prior to about 125,000 years ago.

No apparent displacement of three Qt_2 deposits overlying the fault was observed in the vicinity of Oxyoke and Longview. This indicates the last possible movement along the Platte River fault in this area probably occurred prior to 125,000 y.b.p.

Kennedy Gulch Fault Zone

The Kennedy Gulch fault, as mapped by Bryant and others (1981) and Peterson (1963), appears to have not displaced overlying Qt_3 deposits near South Platte. This indicates that the last surface rupture in this area along Kennedy Gulch fault is prior to 250,000 y.b.p.

In summary it can be tentatively stated that movement along any of the faults in the study area occurred prior to at least 125,000 y.b.p.

CONCLUSIONS

As part of the on-going seismotectonic assessments, mapping Quaternary alluvial terrace deposits located along the North Fork South Platte River, South Platte River, Horse Creek, and 1.3 mi upstream from Foxton to the junction of West Creek and Trout Creek, provided a means for assessing possible tectonic displacement along faults in the area. Five Quaternary terrace formation levels, Qts (youngest), Qt_1, Qt_2, Qt_3 and Qt_4, are recognized based on their regional extent at relatively constant elevations above the modern river. These terrace deposit sequences were observed along portions of all the above mentioned rivers and represent an ancestral course of each. Their ancient river courses entrenched Precambrian bedrock and shifted laterally to produce unpaired terraces. The terraces were formed during climatic events that produced influxes of discharge and sediment load greater than the present. Terrace levels are composed of cut bedrock (tread surface) overlain by a fining-upward sequence of fluvially-reworked cobbles, channel sands, and finer-grained flood plain silts and clays. In most places, however, complete deposit sequences are not present due to erosion.

Alluvial terrace levels were distinguished and mapped by degree of cobble weathering and cut-tread surface level above the river. Detrital charcoal fragments, sampled from Qt_1, yielded ages of 33,650 +/-2,280 y.b.p., 23,730 +/-280 y.b.p., 24,020 +/-500 y.b.p. and 10,850 +/-280 y.b.p. Based on these "calibration" dates and relative weathering characteristics, the ages of older terraces were inferred by association with Quaternary sequences dated elsewhere in the Rocky Mountains and with the marine isotope stage chronology. The youngest terrace, Qts, is judged to be Holocene in age and represents Neoglacial time in the Rocky Mountains (isotope State 1). The next oldest, Qt_1, is judged to be about 10,000 to 125,000 years old, possibly associated with regional glaciation and interglaciation (isotope stages 2, 3, 4, and 5). Qt_2 is inferred to be about 125,00 to 190,000 years old, associated with major regional glaciation during Bull Lake time in the Rocky Mountains (isotope stage 6). Qt_3 is tentatively judged to be approximately 250,000 to 360,000 years old, perhaps representing several glacial and interglacial periods (isotope stages 8, 9, and 10). This association is based on the comparatively wide range that Qt_3 tread surfaces are found above the modern river. Qt_4 is tentatively judged to be about 425,000 to 550,000 years old (isotope stage 12, 13, and 14) representing one or more relatively large climatic events. This association is based on Qt_4 thickness (approximately 15 ft) and height (80 plus ft) above the river.

The traces of faults where projected through a terrace deposit exhibited no measurable offset. Based on probable age range of the terrace deposits, it is thus inferred that last probable surface rupture within the South Platte study area occurred prior to at least 125,000 years ago along the Kennedy Gulch fault, Oil Creek fault, the unnamed splay of the Oil Creek fault, the Platte River fault, and the unnamed fault splay of the Platte River fault.

The terrace ages and related heights above the river suggest that little downcutting by the river has occurred within this area during late Pleistocene. Furthermore, the consistent morpho-stratigraphic position of the terrace levels suggests also that there has been insignificant tectonic uplift in this area over the last 350,000 years.

All Quaternary alluvial terrace deposits mapped are undisplaced or otherwise unaffected by underlying mapped faults in the study area. If, in fact, there was movement during Quaternary time, then last displacement along the Kennedy Gulch fault, Oil Creek fault, unnamed splay of the Oil Creek, the unnamed splay between Pine Gulch and Platte River faults, and the Platte River fault most likely occurred prior to at least 125,000 years ago.

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LATE QUATERNARY STRATIGRAPHY, SOUTH PLATTE RIVER, TWO FORKS AREA, EAST-CENTRAL FRONT RANGE, COLORADO

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INTRODUCTION

The study of late Quaternary stratigraphy is becoming increasingly important for seismotectonic investigations. Of particular interest is the need to identify and date Quaternary sediments that lie across aerial-photographic lineaments or projections of known or inferred faults. Determining whether or not these sediments are displaced can provide important data about paleoseismicity, information particularly useful for design of dams and other large engineered structures.

In Colorado the presently best-dated Quaternary sections are glacial deposits in the mountains and fluvial terrace sediments flanking most major streams in the piedmont (Scott, 1960, 1962, 1963; Richmond, 1965; Machette and others, 1976; Madole, 1976, 1980; Van Horn, 1976; Mahaney and Fahey, 1978; Porter and others, 1983; Colman and others, 1985). Unfortunately, often there is no direct physical correlation between the mountains and the piedmont, for high-gradient streams in the intervening canyons have usually eroded most geomorphic and stratigraphic markers. A major exception, however, is now known to occur along the South Plate River near Two Forks in the east-central Front Range (Figure 1). Here, near the junction of the North Fork and the South Fork of the South Platte River, deep backhoe trenches exposed a remarkably-complete late Quaternary stratigraphy which has now been logged in detail (Earth Sciences Associates [ESA], 1984). This trenching program, commissioned by the Denver Water Department as part of regional seismotectonic investigations, was intended to locate and date Quaternary sediments and hence to assess the relative activity of possible faults in the area. The initial two trenches were placed across projections of the Kennedy Gulch fault, as previously projected into this area (Peterson, 1964; Scott, 1975; Bryant and others, 1981; Kirkham and Rogers, 1981). These trenches, accordingly, are designated the "Kennedy Gulch Trench" (KGT) after the fault system of that name. The KGT exposed the first-known, significant, late Quaternary stratigraphy in the South Platte Canyon area; namely, terrace deposits, covering alluvial-fan sediments (debris and mudflows), and enclosing relict and buried paleosols. The trench logs and stratigraphic interpretations were initially documented as unpublished consultants' reports (ESA, 1984; Shlemon, 1984), and have since been supplemented by a radiocarbon date (J. Friedman and D. Zavadil, pers. commun., October 1985; Shlemon, 1985). The original discovery of the KGT Quaternary stratigraphy led to further investigations which have since documented the approximate age and regional extent of terrace deposits flanking the South Platte and other major drainages in the east-central Front Ranges (Wallace and Friedman, 1985; Geotechnical Advisory Committee, 1985, 1986).

This paper describes the late Quaternary stratigraphy bordering the South Platte River near Two Forks as deduced from the KGT study area. It utilizes, generally, the stratigraphy exposed in the trenches and adjacent roadcuts. It focuses, particularly, on three Quaternary stratigraphic assemblages

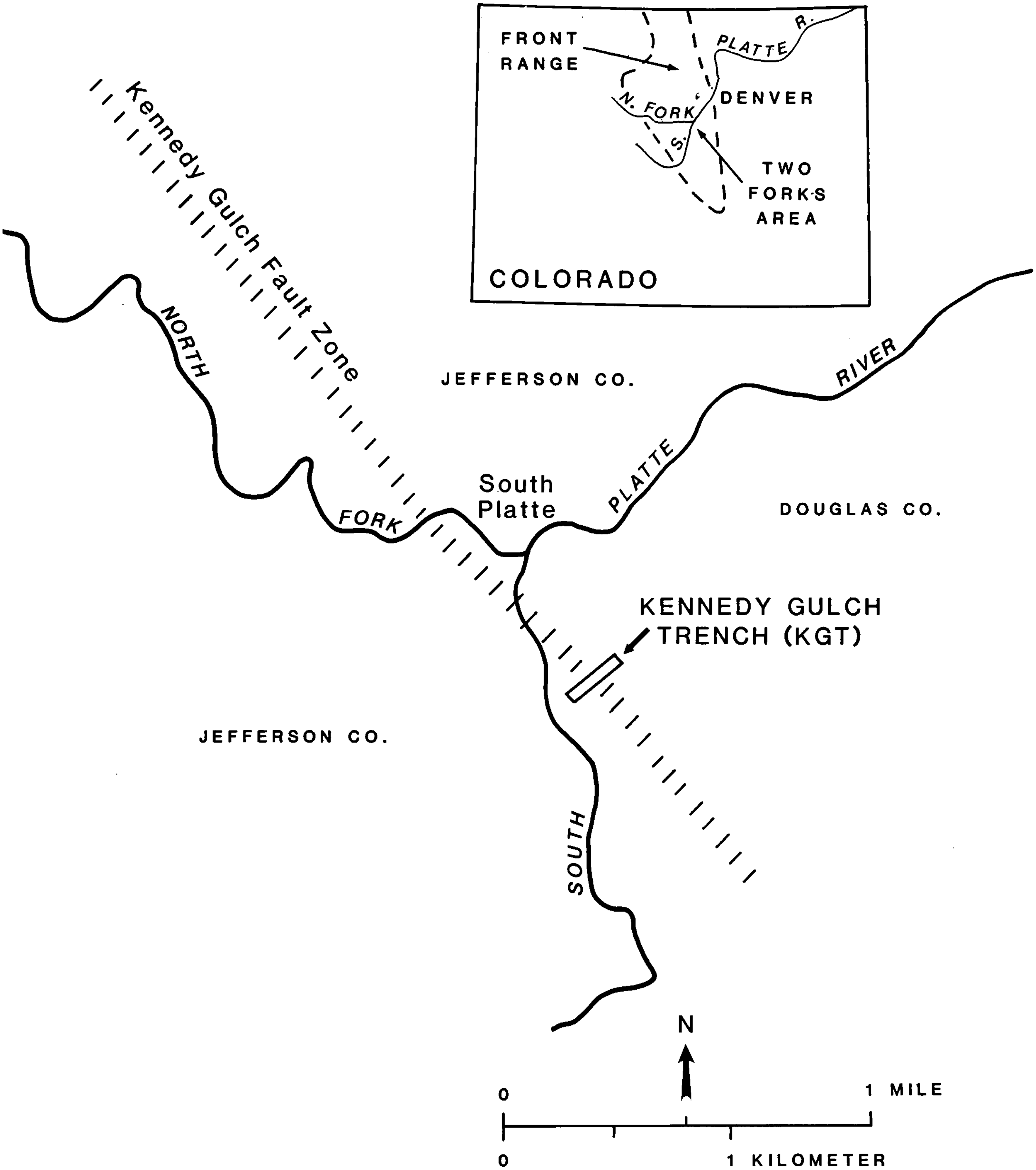

Figure 1. Map showing location of the Kennedy Gulch Trench (KGT) site in the Two Forks area, central Front Range, Colorado.

relatively dated by paleo-environmental reconstruction and by association with regional, climatically-controlled epochs of landscape erosion, deposition and stability; namely: (1) fluvial terrace deposits laid down by ancestral channels of the South Platte River; (2) covering alluvial fan and related debris and mudflow deposits; and (3) capping and intercalated relict and buried paleosols.

ACKNOWLEDGMENTS

Authorization and logistical support for the trenching program and interpretations of Quaternary stratigraphy was provided by the Denver Water Department (DWD) as part of on-going seismotectonic investigations in the Front Range of Colorado. Gratefully appreciated is the support provided by the DWD Geotechnical Advisory Committee and geotechnical staff, particularly that given by J. Friedman, Q. Hornback, J. Parsons, S. Steele, E. Wahlstrom, G. Wallace, and D. Zavadil. The KGT was excavated and logged by Earth Sciences Associates, Fort Collins, under contract with the DWD. Engineering-geological documentation of trench stratigraphy was provided by ESA geologists D. Yadon and D. Hunt. Field commentary and reviews were also generously given by G. Scott, U.S. Geological Survey, and by E. Komie and P. Dickson, Harza Engineering Company, Chicago.

THE KENNEDY GULCH TRENCH (KGT)

Two trenches and a roadcut exposure comprise the KGT study area: an upslope, northeastern trench, approximately 75 m long, a middle and lower slope, southwestern trench about 180 m long, and several 1-meter wide and 3-4 m deep excavations along a bordering roadcut (Figure 2). The trenches range in depth from about 2 m upslope in bedrock to some 5 m downslope in terrace and alluvial fan deposits (ESA, 1984).

The KGT exposes bedrock consisting mainly of the Precambrian Pikes Peak Granite and the Idaho Springs metamorphic assemblage, and a complex cover of Quaternary deposits ranging from fluvial channel gravels to overlying alluvial fan sediments and buried paleosols. Numerous shears and small faults occur in the bedrock; none, however, cut the overlying Quaternary sediments (ESA, 1984; Geotechnical Advisory Committee, 1986).

QUATERNARY STRATIGRAPHY

A generalized schematic of the major Quaternary stratigraphic units in the KGT area is shown in Figure 3. Identified are two, and a probable third (intermediate-age) channel gravels laid down by an ancestral South Platte River, and three overlying alluvial fan sequences, some replete with buried paleosols. The Quaternary deposits are dated relatively by their weathering characteristics (relict and buried paleosols), by geomorphic expression (nested cut and fill sequences), by a radiocarbon date, and by association with regional, climatically-controlled epochs of sedimentation dated elsewhere in Colorado.

Channel Deposits

The oldest channel gravels were exposed in the central part of the trench. Here, at an elevation of about 20 m above present river level, the gravels form a stratigraphic unit about 4 m thick and consist of well-rounded granitic

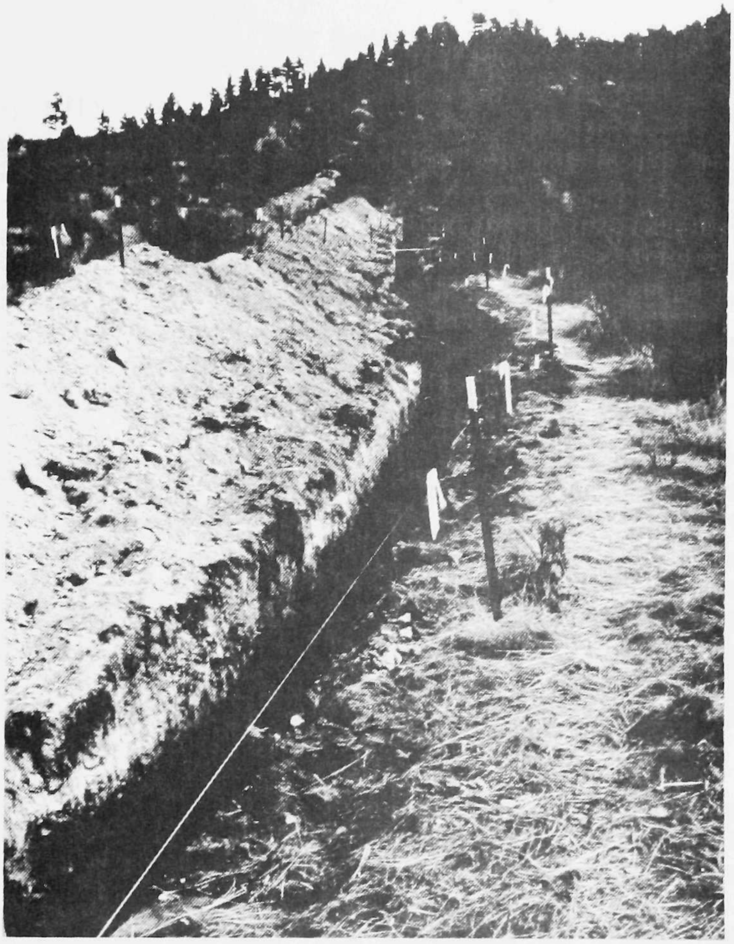

Figure 2. Upper part of the 255-m long, Kennedy Gulch trench system exposing Quaternary stratigraphy, Two Forks area, Colorado.

and metamorphic clasts up to 15 cm in diameter. The gravels directly overlie Precambrian bedrock with basal channel relief in the order of 4 to 5 cm.

The intermediate-age channel is but a few meters thick, occurs about 15 m above the South Platte floodplain, and is less well defined than either the older or younger deposits (Shlemon, 1984, 1985). However, it likewise consists of well-rounded cobbles and a few boulders, rests directly on bedrock, and has been truncated by younger deposits on its western margin (Figure 3). Confirmation that the intermediate-age channel is regionally extensive has since been verified in other seismotectonic studies carried out by the Denver Water Department (Wallace and Friedman, 1985; Geotechnical Advisory Committee, 1985, 1986).

The base of the youngest channel gravel exposed in the KGT occurs approximately 3 meters above the South Platte floodplain. These deposits, about 3 m thick, are also typified by well-rounded metamorphic and some

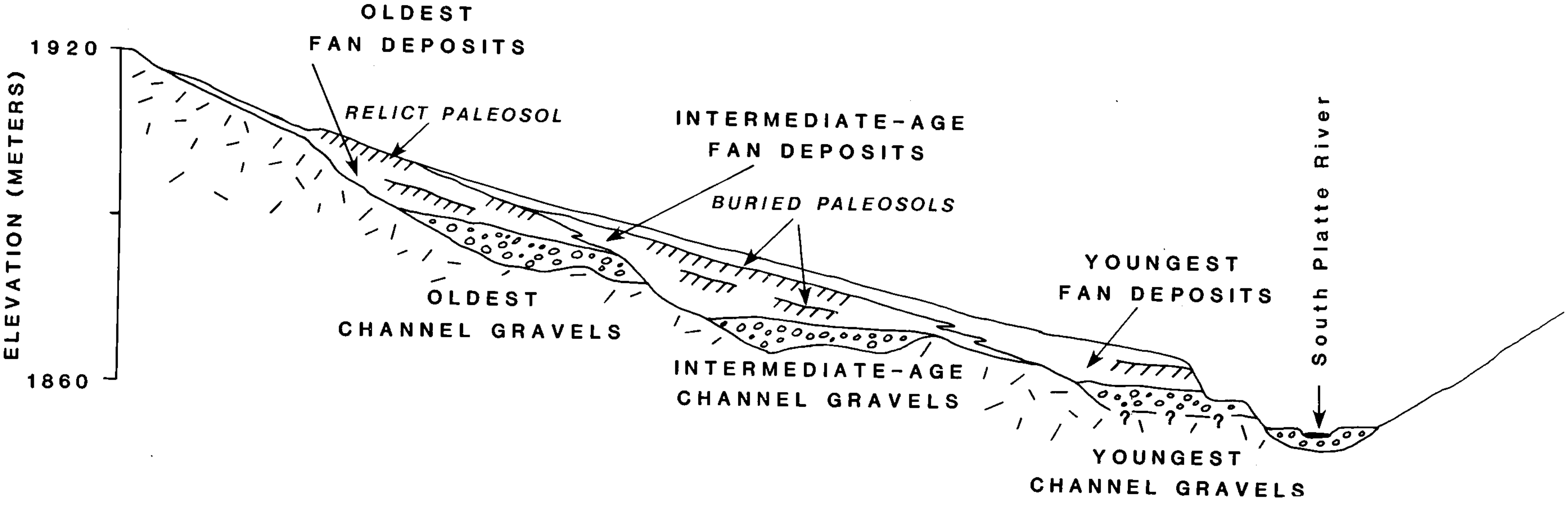

Figure 3. Schematic cross-section of the KGT stratigraphy showing
(a) ancient terrace gravels of the South Platte River,
(b) overlying fan deposits (coluvium, mud- and debris flows), and
(c) surficial and intercalated relict and buried paleosols.

granitic clasts. The gravels are also exposed in adjacent roadcuts and rivercuts where they form the base of a generally fining-upward sequence of sandy cobbles overlain by overbank, fluvial fine sands and silts, terminated by a buried paleosol (Figure 3).

Fan Deposits

The oldest fan deposits overlie channel gravels in the northeastern part of the KGT at elevations of about 25 to 45 m above present river level (Figure 3). These deposits are mainly angular bedrock clasts in a carbonate-rich, clayey-silt matrix. The deposits are crudely stratified and appear to have been laid down mainly as mud and debris flows intermixed with local lenses of colluvium. Lenticular, moderately-developed buried paleosols also occur within this section, indicating intermittency of fan deposition. Upslope, the old fan deposits are overlain by up to a meter of recent talus. Downslope, the deposits are partially stripped, for their general southwesterly dip is truncated by the more steeply-dipping modern slope (Figure 2).

The intermediate fan deposits overlie both the older- and intermediate-age channel gravels. These deposits consist mainly of locally-derived stringers of angular clasts in a sandy clay or silt matrix. Carbonate rinds coat many rounded clasts in the lower part of the fan deposits, well below an intercalated, buried paleosol. This indicates that the carbonates probably formed during an earlier stage of pedogenesis (older fan time ?) and were later transported with their host clasts during intermediate-age fan time. Like the older fan deposits, the surface of the intermediate-age fan is likewise degraded, for it is truncated by the present slope and is covered by a veneer of modern colluvium.

The topographically lowest and youngest nested alluvial fan deposits generally overlie or grade into the youngest channel gravels as exposed in roadcuts and in the southwestern part of the KGT (Figure 3). These deposits are somewhat better stratified than their older counterparts, consisting of reworked angular and rounded clasts derived from the "uphill," older fan and channel deposits, respectively. Also, several slightly-developed buried paleosols occur within the young fan deposits, marking times of local landscape stability. These paleosols are often truncated by stonelines and record local unconformities with the fan section (Figure 3).

Paleosols

Numerous buried and relict paleosols occur in the KGT area. Moderately- to strongly-developed relict paleosols typify an approximately 20-degree slope in the northeastern part of the KGT (Figures 2 and 3). Here, despite modern surface erosion, a moderately-developed paleosol is still present, characterized by a dark, reddish-brown argillic horizon with fine, angular blocky structure and common, thin, illuvial clay films on ped faces. Additionally, a stage III to IV calcic horizon is present, likewise indicative of moderate to strong pedogenic development (Machette, 1978).

Buried paleosols with varying degree of profile development occur throughout the intermediate and younger alluvial fan deposits. Some are of local extent, recognized primarily by their reddish-brown calcic and weak argillic horizons and their stage I - II calcic horizons. Other buried soils are intercalated markers, extending for almost the entire length of the fan deposits, apparently formed during short-lived epochs of landscape stability. A representative, slightly-developed (Holocene) buried paleosol is well exposed in roadcuts bordering the KGT, where it has formed on overbank, fluvial silts covering the youngest channel gravels (Figures 4 and 5).

AGE AND CORRELATION OF KGT QUATERNARY STRATIGRAPHY

The presence of three nested and progressively younger South Platte River channel gravels and covering fan sediments suggests that these deposits were laid down in response to regional, climatically-controlled changes in hydrology and sedimentation. These changes are well documented in the glacial

Figure 4. Roadcut exposure, southwest end of KGT, showing fining-upward stratigraphic sequence of estimated 12,000-15,000 year-old South Platte River gravels (near feet of observer), charcoal-bearing sands and silts, and overlying fan deposits with weakly-developed buried paleosols.

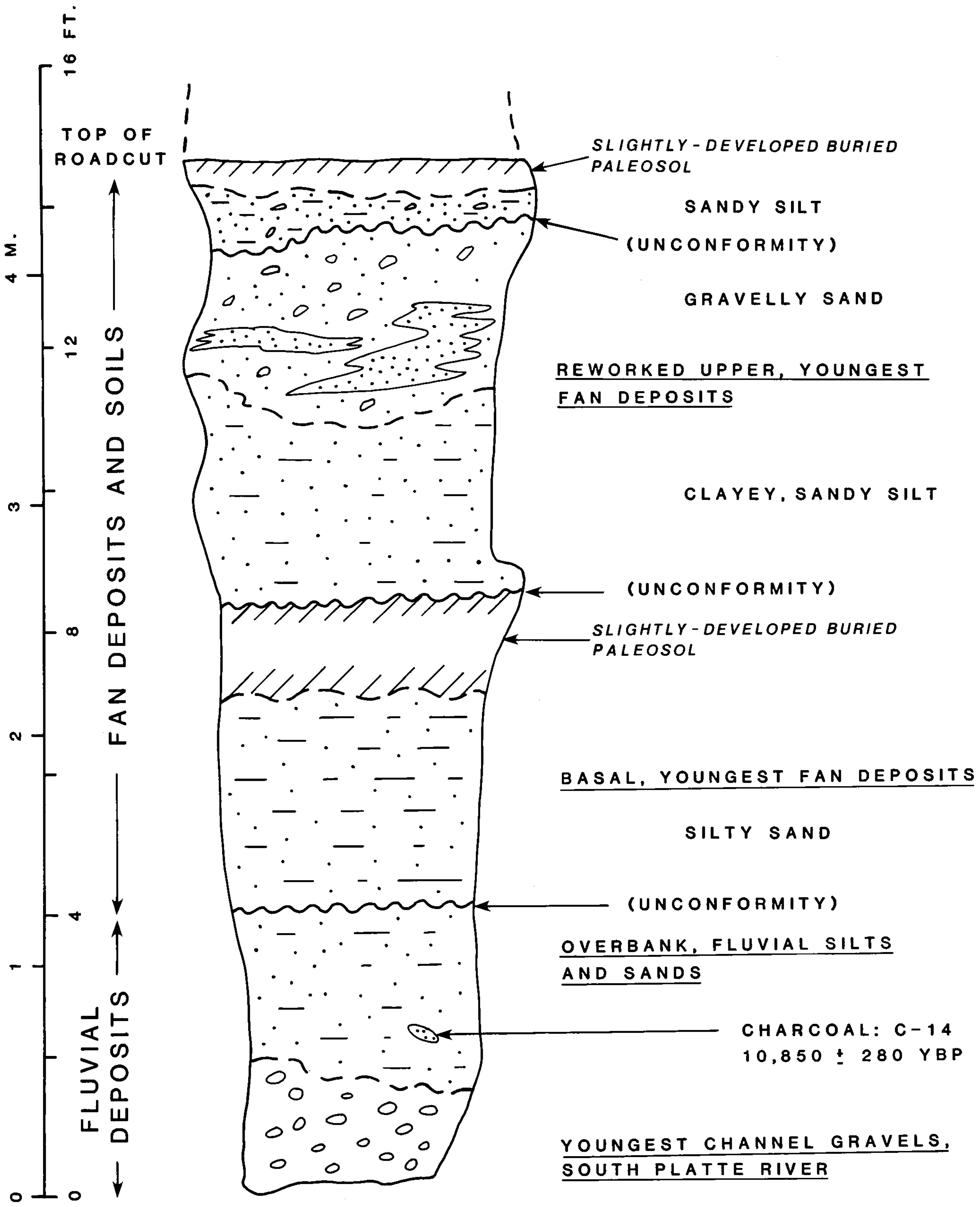

Figure 5. Generalized log of roadcut exposure, southwest end of KGT, showing basal channel gravels, overbank fluvial deposits bearing 10,850 year-old, radiocarbon-dated charcoal fragments, and overlying "youngest fan deposits" and buried paleosols. Log modified from ESA (1984); charcoal collected by J. Friedman and D. Zavadil, Denver Water Department.

history of the Colorado mountains (Richmond, 1965; Madole, 1976, 1980; Nelson, 1976; McCalpin, 1982; Porter and others, 1983).

An approximate age for the gravel and fan deposits is afforded by their relative stratigraphic position and paleo-environmental setting. In general, full glacial events are recorded in "downstream" canyons and piedmont stratigraphy by initial channel incision and by later deposition of extensive channel gravels. Because extensive mud- and debris-flow (fan deposits) cover the ancient channel gravels, regional fan deposition seemingly mostly ensued in "late glacial" time. Such fan deposition was not likely continuous, however, for local epochs of relative landscape stability also took place, as recorded by numerous slightly- to moderately-developed buried paleosols. In contrast, interglacial epochs were likely characterized by relative landscape stability with resultant regional soil formation (relict paleosols), except on steep slopes and on floodplains where erosion and deposition, respectively, essentially continued (Ruhe, 1969; Morrison, 1978; Shroba and Birkeland, 1983).

An approximate age for the KGT stratigraphy is also provided by association with the marine, oxygen-isotope stage chronology (Shackleton and Opdyke, 1973, 1976; Bloom and others, 1974; Bloom, 1983). Applying this chronology to terrestrial sequences is not yet wholly conclusive, but it does provide an independent assessment for dating the South Platte fans and gravels. Inferentially, therefore, at least the upper part of the lowest channel gravels exposed in roadcuts and the southwestern part of the KGT would likely have been laid down by an ancient South Platte River some 12,000 to 15,000 years ago (isotope stage 2), a time of world-wide lowered sea levels and regional glaciation in the Colorado mountains (Madole, 1976; Colman and Pierce, 1981; Porter and others, 1983). This inference has recently been borne out for the KGT area by a radiocarbon date obtained from charcoal in overbank silts immediately overlying the youngest channel gravels (Figure 5). Here, an age of 10,850 +/- 280 years (Beta-13821) confirms that, for the most part, the youngest channel gravels at this locality are probably associated with the last regional glaciation in the Colorado mountains (late Pinedale) and to equivalent-age Broadway alluvium in the piedmont (Machette and others, 1976; Madole, 1976, 1979; Pierce and others, 1976; Wallace and Friedman, 1985).

The absolute age of the intermediate-age channel is not yet known, but is inferred to be associated with a similar, regional climatic event. Based on stratigraphic position, this event is judged to be an earlier glaciation, tentatively equated mainly to the early Pinedale and to the Louviers alluvium in the Colorado mountains and piedmont, respectively. Such regional changes in climate and sedimentation may well be recorded by stage 4 of the marine, isotope-stage chronology, occurring some 60,000 to 70,000 years ago (Shlemon, 1984).

The oldest channel gravels, also based on stratigraphic position and to a lesser degree on weathering characteristics, are deemed associated with an even earlier regional glaciation, presumably the Bull Lake, in the Colorado mountains, and inferentially the Slocum alluvium in the Colorado piedmont (Wallace and Friedman, 1985). Such a glaciation has been dated elsewhere by obsidian hydration and other techniques as pertaining mainly to isotope stage 6, about 125,000 to 195,000 years ago (Pierce and others, 1976; Colman and Pierce, 1981).

The three KGT fan deposits are not radiometrically dated, but approximate age ranges are inferred based on stratigraphic relationship to the channel gravels, and on general weathering characteristics (mainly soil profile development).

The oldest fan sequence, occurring stratigraphically between the intermediate and older channel gravels, bears a moderately- to strongly-developed relict paleosol. Although not directly correlated to Quaternary soils elsewhere in Colorado because of differences in parent material grain-size and soil climate, relative paleosol development suggests formation during a long epoch of regional landscape stability (interglacial), here judged to be isotope stage 5 (late Sangamon), approximately 80,000 to 125,000 years ago. The underlying fan deposits are older and inferentially were thus laid down mainly during the latter part of the preceding isotope stage 6, about 125,000 to 195,000 years ago (Shackleton and Opdyke, 1973; Bloom and others, 1974).

An approximate age for the intermediate KGT fan is deduced from its stratigraphic position; that is, it overlies and hence is younger than the probable 60,000 to 70,000 year-old intermediate-age gravels. Accordingly, these fan deposits, with their intercalated paleosols, are inferred to be about 20,000 to 60,000 years old, in part equated to stages 3 and 4 of the isotope stage chronology.

The youngest fan system includes some recent colluvium and, for the most part, overlies or grades into the probable 12,000 to 15,000 year-old channel gravels. Weakly-developed buried paleosols, with cambic and incipient argillic and locally stage I or II calcic horizons, occur within this fan sequence. These weathering characteristics, plus the 10,850 year-old radiocarbon date, attest that these deposits were laid down within about the last 12,000 years.

CONCLUSIONS

Two trenches (KGT), in aggregate some 255 m long, emplaced across projections of the Kennedy Gulch fault, have provided the first exposures of a remarkably complete, late Quaternary stratigraphy in a canyon area of the east-central Front Range. Faulting is confined to bedrock and no displacement of overlying Quaternary sediments was observed. The Quaternary stratigraphy generally consists of two and a probable third discrete channel gravel laid down by ancestral courses of the South Plate River, of three fan systems typified mainly by mud and debris flows, and of several relict and buried paleosols.

The KGT Quaternary stratigraphy is provisionally dated and correlated by stratigraphic position, by paleo-environmental setting, by association with the marine, oxygen-isotope stage chronology, and locally by a radiocarbon date. The channel gravels were probably mostly laid down during major glacial epochs and reflect changes in regional climate, hydrology and sedimentation. The covering fans, inferentially, were mainly deposited during waning glacial times. Buried and relict paleosols, ranging in relative development from weak to very strong, mark times of relative landscape stability and record breaks in deposition from hiatuses to probable interglacial epochs.

The channel gravels are tentatively dated by association with the marine isotope chronology, and are thus inferred to have been laid down on the order of 12,000-15,000, 60,000-70,000, and 125,000-195,000 years ago, or during stages 2, 4, and 6, respectively. A minimal age of about 12,000 years for the youngest channel is borne out by a 10,850-year radiocarbon date for charcoal obtained from immediately-overlying overbank sands and silts. The channels are also provisionally correlated with the late (younger) and early Pinedale glaciations and with Bull Lake glaciations in the Colorado mountains, and with the Broadway (younger), Louviers, and Slocum alluvial sections in the Colorado piedmont, respectively.

The three KGT fan sequences are inferentially dated by stratigraphic position with respect to the channel gravels. These deposits, and their capping and intercalated paleosols, are postulated to have been laid down mainly during isotope stage 1 and the latter part of stage 2 (youngest), during stages 3 and 4 (intermediate), and during stage 6.

Future investigations will undoubtedly refine the age and correlation of Quaternary sediments in Colorado. In the meantime, however, the KGT site documents that Quaternary successions are indeed preserved in at least some canyon areas, and that these sediments can provide important information for stratigraphic correlation and for fault dating in the central Front Range of Colorado.

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GEOLOGIC EVIDENCE OF QUATERNARY FAULTING NEAR CARBONDALE, COLORADO, WITH POSSIBLE ASSOCIATIONS TO THE 1984 CARBONDALE EARTHQUAKE SWARM

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ABSTRACT

An earthquake swarm which struck Colorado's Roaring Fork Valley in spring 1984, centered west-southwest of the town of Carbondale, and focused attention on the area from geologists and seismologists seeking causative mechanisms and tectonic structures to relate to the unusual swarm of earthquakes. Regional surficial mapping studies conducted during 1982 and 1983 in the Carbondale area of southern Garfield County resulted in recognition and mapping of several faults which offset Early to Late Quaternary deposits. This paper briefly describes the locations and geology of some faulted Early to Late Quaternary debris flows, landslides, and terrace gravel deposits known in the Carbondale area. Further study of these faults may determine whether or not any are related to the mechanisms responsible for the 1984 earthquake swarm.

INTRODUCTION

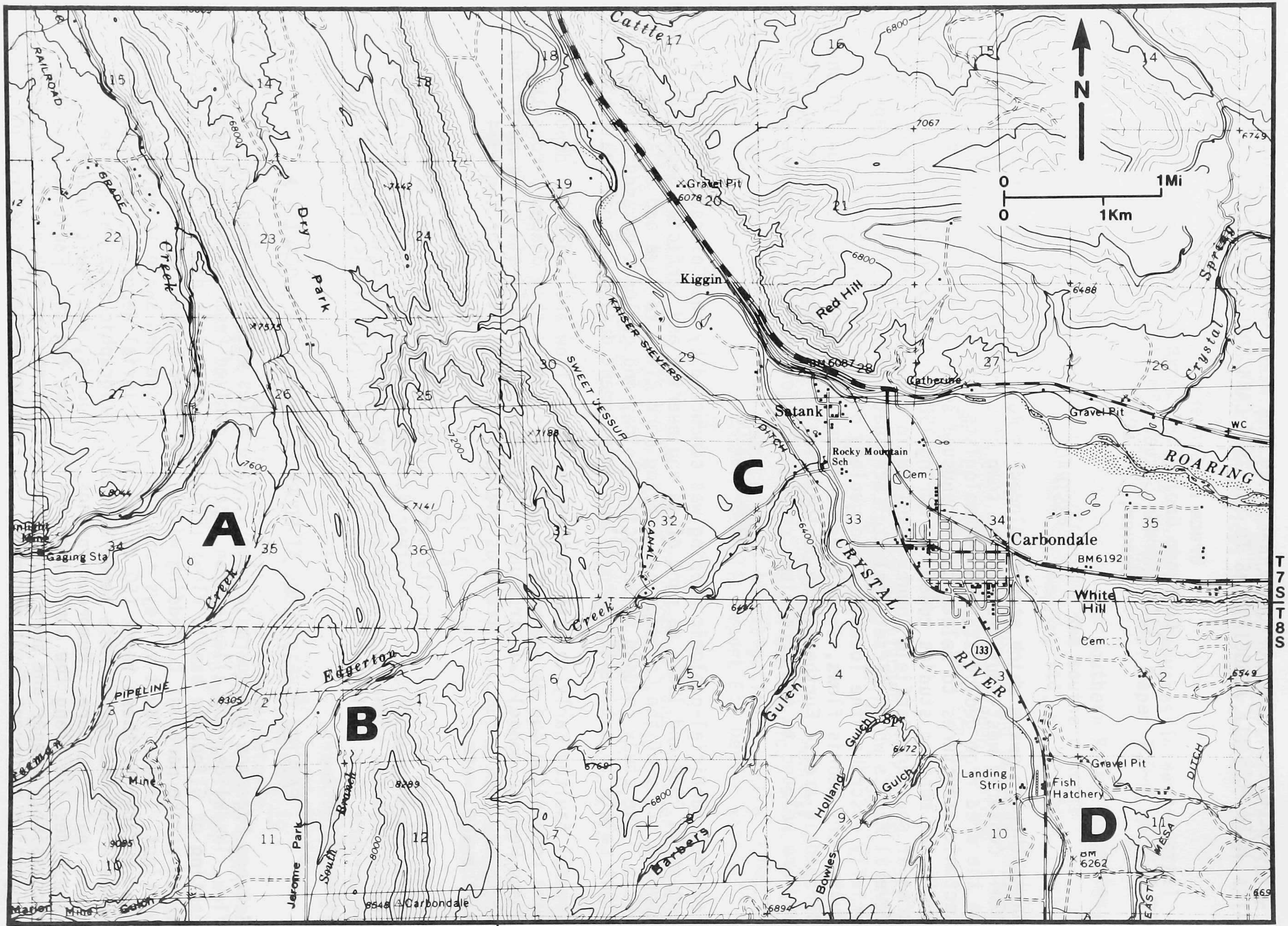
Regional surficial-geologic mapping was conducted by the Colorado Geological Survey in 1982 and 1983, as part of an engineering and surficial geologic mapping study of the Colorado and Roaring Fork River Valleys and adjacent areas. The study focused on surficial geology and geologic hazards as they might relate to anticipated growth and development during the oil-shale boom.

Several faulted Early to Late Quaternary debris flow and landslide deposits were recognized and mapped west of Carbondale, where they draped across the Grand Hogback monoclinal structure. This area is roughly six miles north and along the same structural trend as the epicentral locations of the 1984 earthquake swarm.

These faulted surficial deposits were studied and mapped in detail, and are herein briefly described. Two other faulted, and several deformed terrace gravel deposits known in the Carbondale area are also described, as is the occurrence of a spring which became active during the May 14, 1984, M_L 3.2 event (Figure 1).

FAULTED DEBRIS FLOWS AT FOURMILE CREEK AREA (LOCALITY A)

Between Edgerton and Fourmile Creeks, five miles west of Carbondale, debris flow, landslide, and alluvial fan deposits derived from erosion and mass wasting of Oligocene basalt flows (Figure 2), have been disrupted by faults which strike parallel to bedding within the Grand Hogback monocline. Distinct, linear fault valleys form unusual ridge and swale topography across the surfaces of these thick (50 to 175 ft) colluvial deposits, where they overlie the Cretaceous Mesa Verde-Mancos stratigraphic interval in the monoclinal structure. Numerous springs, sag ponds, and fault induced (?) landslides lie along the surface traces of these faults. Fault valleys are successively deeper and more pronounced with increasing age of the surfaces, suggesting recurrent fault movement. Surface expressions range from 100 ft



Base from U.S.G.S. R 89 W R 88 W

Figure 1. Location map showing localities discussed in text; (A) faulted debris flows, (B) Edgerton Creek Spring and landslide, (C) faulted terrace deposit, (D) faulted terrace deposit "Fish Hatchery Fault".

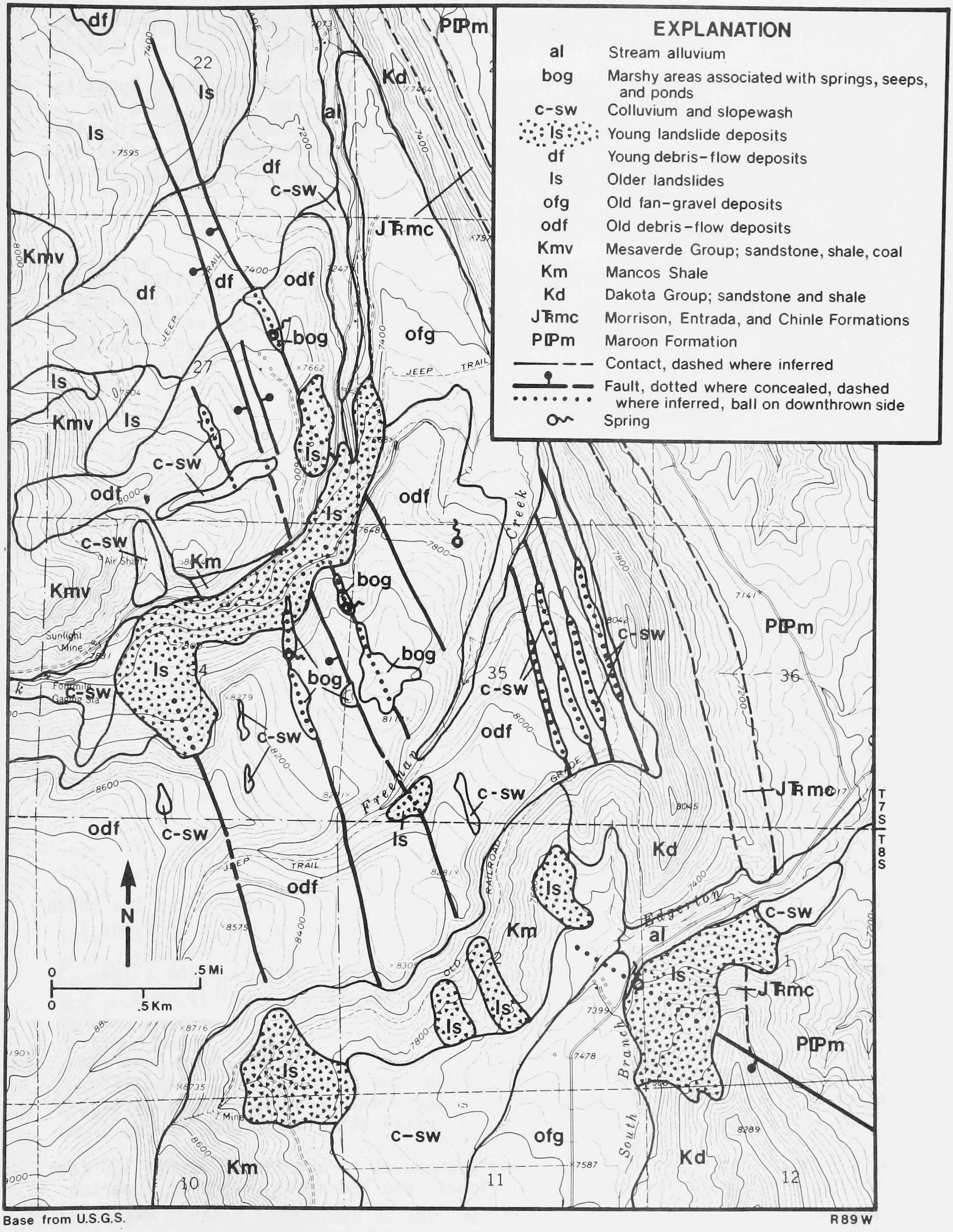


Figure 2. Geologic map of the Fourmile and Edgerton Creek areas, Garfield County, Colorado.

wide, 30 to 50 ft deep linear swales up to three-quarter miles in length, to subtle lineations across the youngest debris-flow deposits.

Oligocene (Larson, et al, 1975) basalt flows six miles north of this locality at Glenwood Springs are faulted in a similar manner where they overlie the same stratigraphic interval (Murray, 1966; Kirkham and Rogers, 1980). Faults in the basalt caprock and the debris flow deposits strike parallel to the axis of the monoclinal structure beneath. The fault valleys in the basalt caprock are more pronounced in expression, and over twice as deep as those in the oldest colluvial deposit at Fourmile Creek. Activity on these faults appears to have been intermittent from Oligocene through Pleistocene time.

Murray (1966) first noted faulting of the oldest debris-flow deposits between Fourmile and Edgerton Creeks. He recognized a series of faults paralleling the strike of the underlying Cretaceous beds within the monoclinal structure, and proposed a flexural-slip mechanism to account for the observed character of the faulting here, and in the basalt caprock six miles to the north (Murray, 1969). Murray did not recognize faults in younger deposits, and considered all of the older debris-flow deposits to be Tertiary in age.

Stratigraphic, pedologic, and sedimentologic evidence indicate that the disrupted debris-flow deposits are significantly younger than the Oligocene basalts from which they are derived. Petrocalcic soil development and topographic position suggest that the oldest debris flows may be on the order of 500 to 700 thousand years old (Machette, 1982).

The youngest debris flow affected by faulting lies 25 to 40 feet above the present level of Fourmile Creek, suggesting a Late Quaternary or possibly Holocene age for latest faulting.

Offset along fault scarps in the debris flow sequence is successively greater with increasing age of the flow lobes, as interpreted from stratigraphic relations. This suggests that flexural slip and associated faulting has continued through Quaternary time at this locality. More importantly, it also suggests that this same mechanism may be associated with other tectonically active areas along the Grand Hogback, such as the area of the 1984 earthquake swarm, where younger rocks, or surficial deposits are not present across structural strike to indicate recurrent movement between beds.

EDGERTON CREEK SPRING AND LANDSLIDE (LOCALITY B)

Tweto (1978) mapped a fault offsetting the Dakota-Mancos Interval on the south bank of Edgerton Creek at the water gap in the Dakota Hogback in sections 1 and 2, T.8S., R.89W. The fault strikes N65°W, dips southwest, and is partially covered by a landslide of Quaternary age (Figure 2). The slide overlies gravels adjacent to the present stream, and may possibly be a seismically induced landslide.

Mr. William Perry, who lives adjacent to the Dakota watergap along Edgerton Creek, reported that a spring began flowing from the base of the landslide after the May 14, 1984 earthquake rocked the area. A stock tank was set up to utilize the water; initial flows were estimated at 25 to 30 gpm.

Clear water issued from bouldery landslide deposits and flowed across 100 feet of dry, grass and sagebrush covered slopes into the south branch of Edgerton

Creek. The spring was still flowing an estimated 10 gpm when visited on October 8, 1985, but had all but dried up by April 11, 1986.

Although the spring is on strike with faults which offset older debris flows as described above, an extensive field reconnaissance did not turn up evidence of surface rupture or cracking along these faults, or in the vicinity of the spring and landslide. More study is necessary to determine how the spring and fault beneath the landslide may relate to the 1984 earthquake swarm.

FAULTED TERRACE GRAVEL WEST OF CARBONDALE (LOCALITY C)

A faulted terrace gravel deposit 140 ft above the valley of the Crystal River is exposed in a roadcut one mile west of Carbondale in section 33, T.8S., R.88W. (L.A. Piety, oral communication, 1981). The fault strikes N14°W, and dips 70°W., offsetting river gravels against gypsiferous units of the underlying Eagle Valley Evaporite Formation.

Adjacent surficial mapping (Soule and Stover, 1985) indicates numerous sink-holes within the surface of the terrace related to collapse of solution cavities or passages within the underlying gypsum strata. This suggests that the "fault" is probably a feature related to collapse of gravel beds into a large sink-hole; however, more work needs to be done before the possibility of tectonics relating to diapirism associated with the underlying Eagle Valley Evaporite can be ruled out.

The presence of halite at depth beneath the Roaring Fork Valley between Carbondale and Glenwood Springs, and gypsum near the surface, is suggested to be responsible for associated deformed gravel terraces several miles north of this fault locality (Mallory, 1966 and 1971) in sections 1 and 2, T.7S., R.89W. Deformation features associated with these terraces, which are tilted back away from the river suggest, but do not prove, Quaternary movement of the terraces (Piety, 1981).

FISH HATCHERY FAULT (LOCALITY D)

A faulted terrace gravel is exposed in a roadcut 1/2 mile east of the Carbondale Fish Hatchery in the SE1/4, NW1/4, T.8S., R.88W. The gravel is 80 ft above the level of the Crystal River, and is probably no more than 20,000 years old (Piety, 1981). The roadcuts through a knob-like hill composed of tuffa cemented gravel, in which the fault is exposed. Underlying bedrock is Eagle Valley Evaporite Formation.

This reverse fault strikes N52°E, and dips 86°N. It offsets tuffa cemented gravel beds 12 feet against a fine-grained whitish-tan sandy unit. Gravel beds on the downthrown side are tilted away from the fault at an angle of 25°, and gravel clasts can be observed dragged up along the fault itself. Carbonate cementing the gravels and parts of the sandy unit is believed to be of groundwater origin.

This fault is probably related either to sink-hole collapse mechanisms, or to evaporite diapirism as discussed above. More detailed study of this locality could better determine the faulting character.

CONCLUSIONS

There are several localities in the Carbondale area where faulted Quaternary deposits have been observed. Faulted Pleistocene-aged colluvial deposits five miles west of Carbondale between Edgerton and Fourmile Creeks, and a newly active spring associated with a fault in the same area, suggest that recurrent slippage along bedding planes in Cretaceous sediments within the Grand Hogback monoclinal structure has occurred intermittently during the Quaternary. This type of tectonic mechanism may possibly be associated with the 1984 earthquake swarm which occurred in the immediate area.

Several faulted terrace gravel exposures and deformed alluvial terraces along the Roaring Fork and Crystal River Valleys lend support to a tectonic model of active diapirism or disolution associated with gypsum and anhydrite of the Eagle Valley Evaporite Formation, which underlies the region. This tectonic driving mechanism for flexural slip along the Grand Hogback may be associated with the 1984 earthquake swarm (Murray, 1969).

Further study of the features briefly described here, as well as the discovery of any other localities in the Carbondale area where Quaternary movement is evident, may refine knowledge of the mechanics of seismicity in the Roaring Fork and Crystal River Valleys.

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