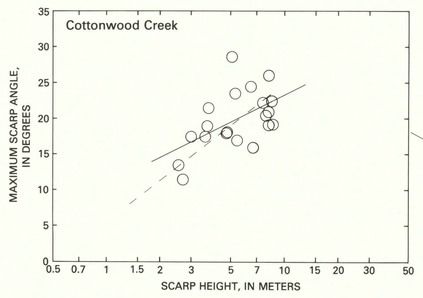
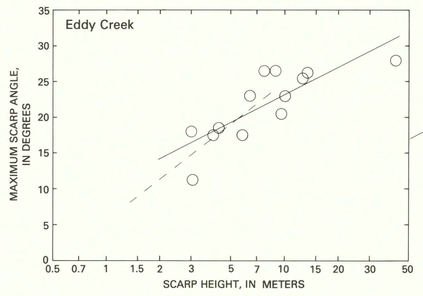
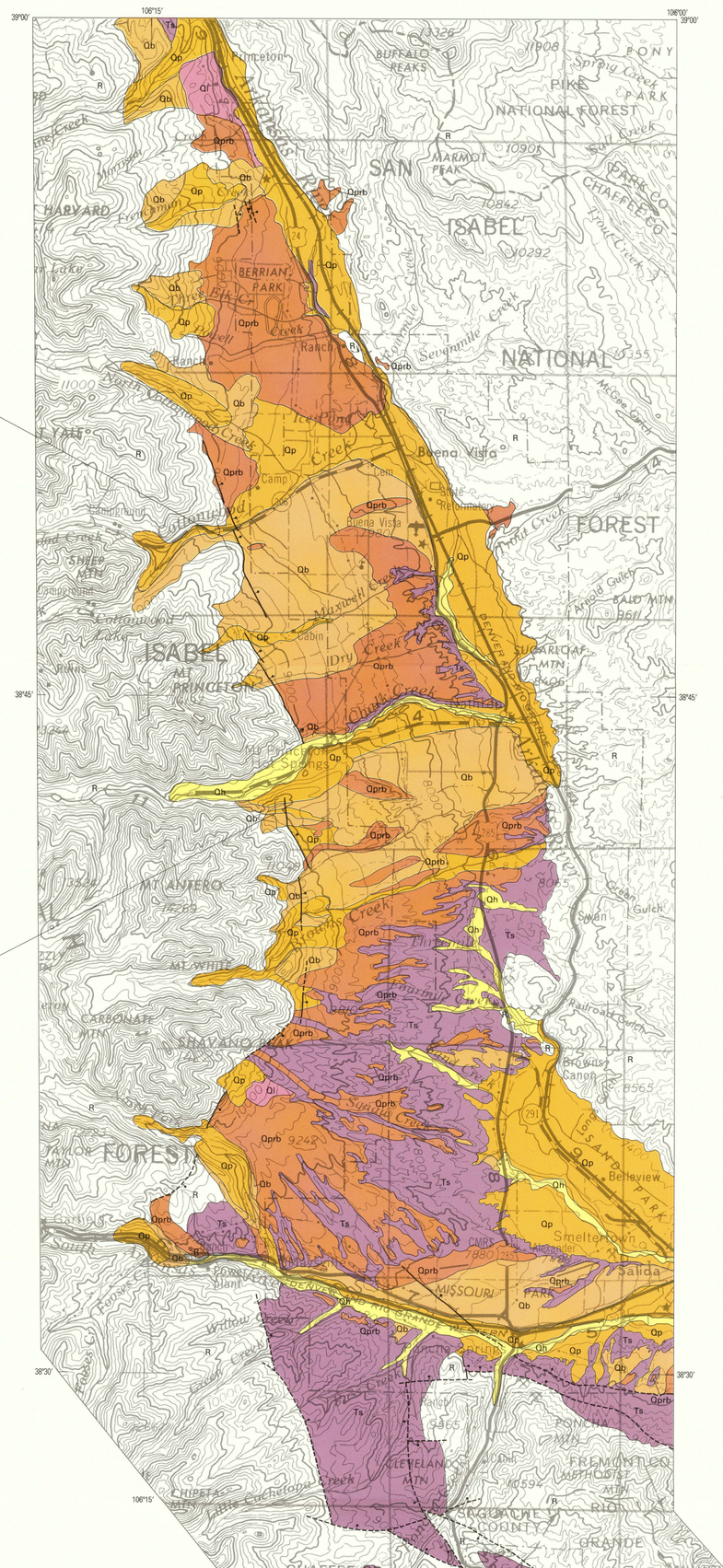
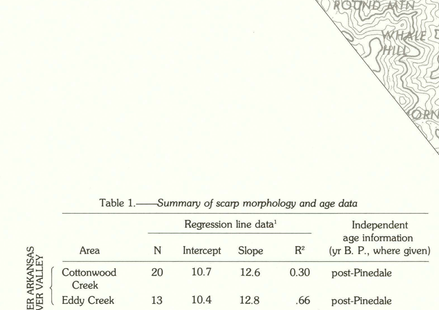
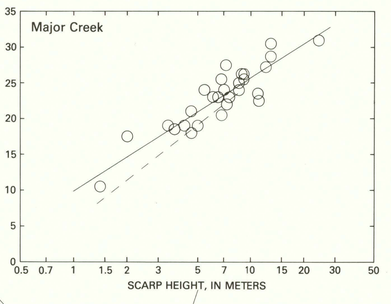
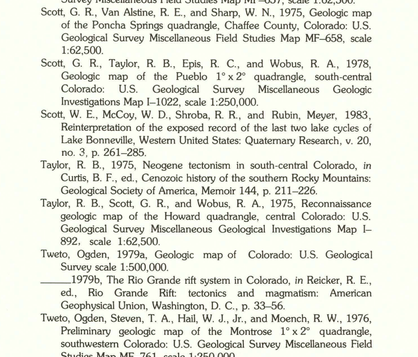




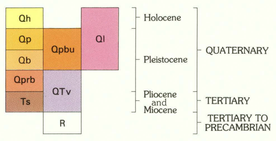








CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

(Small areas of Quaternary deposits within mountain ranges are not shown.)

Qh STREAM AND FAN ALLUVIUM AND EOLIAN DEPOSITS (HOLOCENE, <10,000 years)—Generally <1 to about 3 m thick, but eolian deposits near Great Sand Dunes National Monument are more than 100 m thick. Generally contain very weakly developed soil profiles characterized by A/C horizon sequences

Qp DEPOSITS OF PINEDALE AGE (UPPER PLEISTOCENE)—Stream and fan alluvium, eolian deposits, till, and outwash. Deposits one to several tens of meters thick. Generally contain weakly developed soil profiles characterized by A/weak-B/C horizon sequences. Pinedale deposits range in age from about 11,000 years to perhaps more than 40,000 years (Colman and Pierce, 1981; Porter and others, 1983)

Qb DEPOSITS OF BULL LAKE AGE (UPPER TO MIDDLE PLEISTOCENE)—Stream and fan alluvium, eolian deposits, till, and outwash. Deposits one to several tens of meters thick. Generally contain moderately to well-developed soil profiles characterized by A/Bt/C horizon sequences. Bull Lake deposits are not well-dated, but may range in age from about 70,000 to 150,000 years (Pierce and others, 1976; Colman and Pierce, 1981)

Qpbu Deposits of Bull Lake and Pinedale age, undifferentiated

Qprb DEPOSITS OF PRE-BULL LAKE AGE (LOWER TO MIDDLE PLEISTOCENE)—Stream and fan alluvium, eolian deposits, till, and outwash. Deposits one to several tens of meters thick. Generally contain very well-developed soil profiles characterized by A/strong-Bt/C or K horizon sequences. Deposits range in age from several hundred thousand to more than a million years old

Ql LANDSLIDE DEPOSITS (HOLOCENE AND PLEISTOCENE)—Large deposits of earthflow, slump, debris slide, or rockfall origin. Includes deposits of a variety of ages. Shown only where extensive deposits occur in areas mostly occupied by other Quaternary deposits

QTv VOLCANIC ROCKS (QUATERNARY TO MIOCENE)—Consists primarily of basalt flows, with local vent materials such as those around cinder cones. Includes Pliocene Servilletta Basalt and younger rocks such as those forming Mesita Cone

Ts SEDIMENTARY ROCKS (PLIOCENE AND MIOCENE)—Consists of poorly consolidated sands, silts, gravels, and minor volcaniclastic debris that form basin-fill materials of the late Tertiary Rio Grande rift. Sediments as much as 3,000 m thick in upper Arkansas River Valley and as much as 5,000 m thick beneath Quaternary sediments in San Luis Valley. Includes rocks of Santa Fe and Dry Union Formations

R OLIGOCENE TO PRECAMBRIAN ROCKS, UNDIFFERENTIATED

——— CONTACT—Dashed where Quaternary deposits extending into mountainous areas are arbitrarily terminated and not shown

———T——— NORMAL FAULT—Bar and ball on down-thrown side. Only faults that are known or inferred to displace Quaternary deposits, or which bound units QTv and Ts, are shown. Faults shown as solid lines are all associated with distinct scarps or topographic anomalies. Two types of faults are shown as dashed lines: (1) faults inferred to cut Quaternary deposits on the basis of indistinct topographic anomalies, steep contacts (in most cases against bedrock along mountain fronts), and/or continuity in trend with faults known to cut Quaternary deposits, and (2) faults bounding units QTv and Ts

SCARP MORPHOLOGY DATA

Graphs on map show maximum scarp angle plotted against log of scarp height for each scarp profile measured along scarp segment indicated by leader and bracket. Solid line is least-squares regression line through solid-line points (table 1); points not included in regression are dashed (see text). Dashed line is regression line for the Bonneville shoreline in Utah (Bucknam and Anderson, 1979), a well-defined, single event scarp of known age (table 1), used as a reference line for each plot. Data sets are named for local features, some of which do not appear on this map.

Table 1.—*Summary of scarp morphology and age data*

	Area	N	Regression line data[1] Intercept	Slope	R^2	Independent age information (yr B. P., where given)
UPPER ARKANSAS RIVER VALLEY	Cottonwood Creek	20	10.7	12.6	0.30	post-Pinedale
	Eddy Creek	13	10.4	12.8	.66	post-Pinedale
	Villa Grove	64	8.2	12.8	.61	post-Pinedale
	Major Creek	29	9.9	15.8	.81	Holocene (1) 7,660 (2) 10,100[2]
NORTHERN SAN LUIS VALLEY	San Isabel Creek	9	15.0	12.9	.81	post-Pinedale
	Great Sand Dunes	13	17.0	12.7	.92	post-Pinedale
	Uracca Creek	19	9.6	13.8	.69	Holocene 5,640[2]
SOUTHERN SAN LUIS VALLEY	Ikes Creek	6	7.4	20.5	.64	post-Pinedale
	Willow Creek Reservoir	8	3.6	15.3	.79	Holocene
	Rito Seco	16	2.6	14.7	.79	Holocene 1,940–4,115[3]
	Culebra Creek	8	12.3	9.8	.10	Holocene
	Bonneville shoreline	16	5.6	19.4	.90	late Pleistocene 14,000–15,000[4]

[1]For least-squares regression of maximum scarp angle on the log of scarp height; N, number of scarp profiles; R^2, coefficient of determination.
[2]Last two fault events occurred shortly before dates given (McCalpin, 1982).
[3]Last fault event occurred between dates given (Kirkham and Rogers, 1981).
[4]Scarp data from Bucknam and Anderson (1979); age estimate from Scott and others, (1983).

INTRODUCTION

This map shows the faults and faulted rocks and deposits in the tectonically active part of the Rio Grande rift in Colorado, with particular emphasis on faults and deposits of Quaternary age. The Rio Grande rift in Colorado has been the subject of considerable recent geologic investigation. General compilations of the late Cenozoic tectonic features of the state of Colorado have been made by Wittkind (1976), Kirkham and Rogers (1981), and Colman (1985). More detailed work used in compiling the map is shown in figure 1. Additional work pertinent to the tectonic history of the Rio Grande rift includes Scott (1970, 1975a), Epis and Chapin (1975), Lipman and Mehnert (1975), Taylor (1975), Epis and others, 1976), Huntley (1976), Knepper (1976), and Tweto (1979b). The following brief overview of the tectonic setting and history of the Rio Grande rift is summarized from the work of these authors. Individual reference citations have been omitted for the sake of clarity.

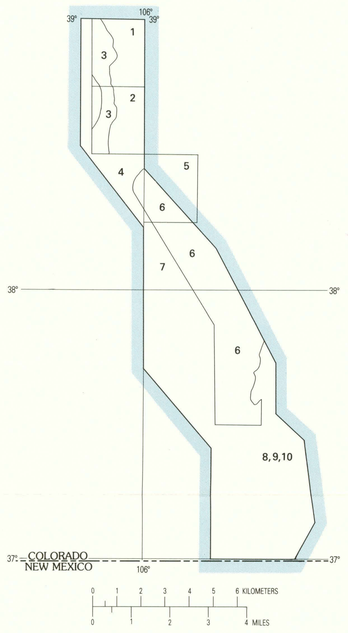


Figure 1.—Index map showing sources of information for map compilation: 1, Scott, 1975b; 2, Scott and others, 1975; 3, Ostenaa and others, 1982; 4, Tweto and others, 1976; 5, Taylor and others, 1975; 6, McCalpin, 1982; 7, Scott and others, 1978; 8, Johnson, 1969; 9, Tweto, 1979a; 10, Colman, S. M. unpublished reconnaissance. General information was also gathered from Witkind, 1976; Kirkham and Rogers, 1981; and Colman, 1985.

The Rio Grande rift has been the most tectonically active area in Colorado in late Cenozoic time. The active part of the rift in Colorado is composed of two major units which 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, whereas the San Luis Valley is a half-graben, with the main fault zone on its eastern side and downwarp on its western side. Numerous secondary faults offset the major structures and form secondary horsts and graben structures. The two main grabens are separated by a complex zone of normal faults in the area of Poncha Pass. Late Cenozoic fault displacements generally decrease northward and gradually die out north of the upper Arkansas River Valley. Quaternary faulting probably occurred north of and within the northern 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 along the west side of the southern part of the upper Arkansas River Valley and at the foot of the Sangre de Cristo Range along the east 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. During this stable period, Eocene 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 and 29 m.y. ago, although some sort of 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 Santa Fe Formations accumulated. Graben faulting and regional uplift apparently accelerated in late Miocene and Pliocene time, and a total of as much as 3,000 m of sediment in the upper Arkansas River Valley and 5,000 m in the San Luis Valley was deposited. 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, and scarp heights become progressively higher in older Quaternary deposits, indicating a history of recurrent faulting through the Quaternary. Deposits as young as a few thousand years are faulted, suggesting that the late Cenozoic period of faulting continues to the present.

FAULTS AND UNITS SHOWN ON THE MAP

The certainty with which late Cenozoic movement of faults in the Rio Grande rift in Colorado is known ranges considerably. Late Cenozoic movement is well-documented for some faults, such as those with distinct scarps in late Quaternary deposits, whereas late Cenozoic movement on other faults, such as those buried by Quaternary deposits or those entirely in Precambrian rocks, is tentatively inferred from regional structural relations. Several previous compilations have attempted to show all faults known or suspected to have moved in late Cenozoic time (Witkind, 1976; Tweto, 1979b; Kirkham and Rogers, 1981; Colman, 1985). For these reasons, the emphasis of this map is on faults which are known or inferred to displace Quaternary deposits. The only other faults shown on the map are those that bound pre-Quaternary rift-related sedimentary and volcanic rocks.

Virtually all known or inferred Quaternary faults in the Rio Grande rift of Colorado are documented by their topographic expression; 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 at depth by continuous fault zones. All faults that cut upper Quaternary deposits in the Rio Grande rift in Colorado show evidence of recurrent movement. The most common type of evidence for recurrence is fault scarps whose heights increase in successively older deposits. In addition, trenches dug across some of the faults invariably showed stratigraphic evidence of multiple fault movements (McCalpin, 1982; Ostenaa and others, 1981).

The map units are designed primarily to show the general pattern of the late Cenozoic sedimentary basins associated with the rift, and to show the age relations between Quaternary deposits and the faults that cut them. Quaternary deposits have been subdivided by age to the extent possible at the map scale.

SCARP MORPHOLOGY

Age estimates of Quaternary fault movements are critical for deciphering the neotectonic history of an area and for assessing seismic 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 commonly do not closely bracket the ages of faulting.

Because of these difficulties, any method that can be used to estimate the actual ages of Quaternary faulting can be valuable. Recent research on fault scarps has shown that their morphology changes systematically with time. Fault scarps in environments similar to those in the Rio Grande rift in Colorado are created with steep faces, called free faces, that vary in steepness from vertical to as little as 50° (Wallace, 1977). The free face is rapidly removed by slumping and other mass movement processes, which lead to a rounded scarp profile. 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 in which the scarp is developed.

For single-event scarps, the maximum scarp angle is a function of both scarp height and age of faulting (fig. 2) (Bucknam and Anderson, 1979; Nash, 1980b; Colman and others, 1981). Regression lines relating maximum scarp angle to the logarithm of scarp height generally form a set of subparallel lines whose relative positions are empirically 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, although the affect of these variables 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). Nash (1980a, b) and Colman and Machette (1981) showed that degradation of scarps with time could be modeled by a diffusion-type equation, and provided a theoretical basis for the empirical maximum-scarp-angle versus log-height relation.

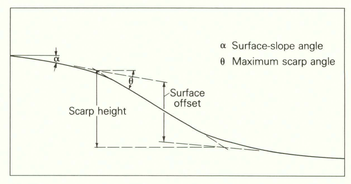


Figure 2.—Diagrammatic definition of the morphological variables (maximum scarp angle and scarp height) plotted for scarps on this map.

Scarp morphology data (maximum scarp angle and the log of scarp height), along with corresponding regression lines, are plotted on the map for several segments of Quaternary faults in the Rio Grande rift (see Description of Map Units for details). Also plotted for reference and comparison is the regression line for the Bonneville shoreline in Utah (Bucknam and Anderson, 1979), a well-defined, single-event scarp of known age (14,000–15,000 yrs; Scott and others, 1983). All else being equal, data for scarps younger than the Bonneville shoreline should plot above the line for the Bonneville shoreline, with the converse being true for scarps older than the Bonneville shoreline. These comparisons are complicated by the fact that lines for multiple-event scarps have lower slopes than those for single event scarps (fig. 3), other factors being equal. Regression lines for multiple-event scarps are actually composite lines through groups of points related to each fault event (fig. 4). In practice, however, different fault events can rarely be distinguished in the data unless the last event is very young or unless the first event is much older than the others. Examples of the latter case are shown as dashed points in the plots for Culebra Creek and Ikes Creek.

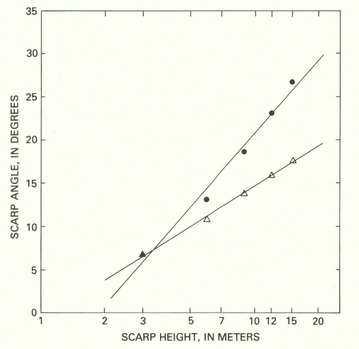


Figure 3.—Morphological data for scarps whose degradation was simulated according to a diffusion-equation model (Colman and Machette, 1981). Filled circles represent a scarp with varying height formed by a single fault event. Open triangles represent a scarp of varying height formed by multiple 3-m fault 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 equal in both data sets. The linear relation of maximum scarp angle to log height is a good fit to the diffusion-equation model for most of the range of angle and height, but breaks down at low heights and at high angles.

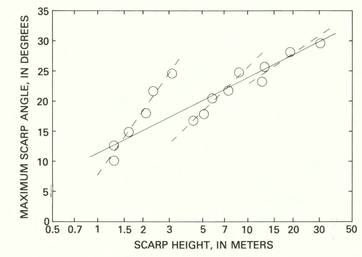


Figure 4.—Hypothetical data set for a multiple-event fault scarp. Each group of points associated with a dashed regression line represents a single fault event of varying displacement. Such groups of points can rarely be separated from each other in real data (see text). Solid line is the regression line for all the data.

Compared to the data for the Bonneville shoreline and data for other scarps in Utah (Bucknam and Anderson, 1979), the ages suggested by data for the scarps in the Rio Grande rift in Colorado are consistent with independent estimates of their ages (see data plots on map and independent age estimates in table 1.). Multiple-event scarps whose last fault event is about the same age as the single-event Bonneville shoreline should have regression lines that are mostly below that for the Bonneville shoreline, but which intersect the line for the Bonneville shoreline near its lower end (fig. 3). Most of the lines for scarps in the upper Arkansas River Valley and northern San Luis Valley are above this position. This suggests that the last movements of the associated faults are younger than 14,000–15,000-year-old Bonneville shoreline, and is consistent with independent evidence that the last movements of these faults occurred about 7,000–11,000 years ago (table 1). In addition, scarps that are known to have similar histories, such as the Eddy Creek and Cottonwood Creek scarps (Ostenaa and others, 1981, 1982), or scarps that are close to each other and are in similar materials, such as the Major Creek and San Isabel Creek scarps, 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 between Utah and the northern part of the Rio Grande rift.

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 much younger than the Bonneville shoreline (table 1), but their regression lines plot below that for the 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 in loose, relatively well sorted, sandy alluvial fan deposits derived from the Santa Fe Formation, and thus probably degrade much faster than the other scarps, which are formed in coarse, poorly sorted, cohesive deposits derived from competent bedrock. These two scarps, then, have a deceptively old appearance. In contrast, the nearby scarp at Culebra Creek is formed in terrace deposits of that stream, which drains large areas of crystalline bedrock. The regression line for the Culebra Creek scarp plots near where expected in relation to that for the Bonneville shoreline.

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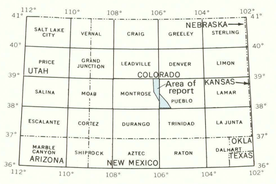
1:250,000, Montrose, 1956 and Pueblo 1954

Montrose revised 1977
Pueblo limited revision as of 1962

APPROXIMATE MEAN DECLINATION, 1985

SCALE 1:125 000
2 1 0 2 4 6 8 10 MILES
2 1 0 2 4 6 8 10 KILOMETERS
CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS
NATIONAL GEODETIC VERTICAL DATUM OF 1929



Geology mapped 1978-81

MAP SHOWING UPPER CENOZOIC ROCKS AND DEPOSITS AND QUATERNARY FAULTS, RIO GRANDE RIFT, SOUTH-CENTRAL COLORADO

By

Steven M. Colman, James P. Mc Calpin[1], Dean A. Ostenaa[2], and Robert M. Kirkham[3]

[1]Utah State University
[2]U.S. Bureau of Reclamation
[3]Colorado Geological Survey

1985

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