SUMMARY OF CENOZOIC GEOMORPHIC, VOLCANIC ANDTECTONIC FEATURES OF CENTRAL COLORADO AND ADJOINING AREAS

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ABSTRACT

Withdrawal of the Late Cretaceous sea from Colorado marked the end of a long history of marine events and the start of a shorter, but eventful, Cenozoic continental history. Laramide uplift started about 70 million years ago; streams eroded the sedimentary cover, and deeply beveled Precambrian rocks. Erosion generally kept pace with uplift so that few mountains stood very high above adjacent aggrading basins. A widespread, late Eocene surface of general low relief developed on Precambrian rocks during about 10 million years of tectonic and magmatic quiescence. Eocene basin-fill clastic deposits accumulated in structural basins and small grabens that formed during the bevelling, and in channels of the fluvial system that drained the area.

In Oligocene time, the late Eocene surface was covered by volcanic and lesser alluvial deposits. Locally, channels were cut into the surface, and these channels also were filled and covered by alluvial and volcanic material. Drainages that developed as early as Laramide time and were firmly established in Eocene time were extensively disrupted by Oligocene volcanism. The Florissant Lake Beds and the Antero Formation accumulated behind dams formed by volcanic deposits.

In early Miocene time, uplift and faulting caused further disruption of the drainage system and fragmentation of the late Eocene surface. Regional block faulting of basin-and-range style in Miocene and Pliocene time resulted in offsets of the surface of 1,500 to possibly 5,000 m (4,900 to 16,400 ft) (Davis and Keller, 1978), and resulting grabens were deeply filled with tectonic sediments. Volcanism continued until at least 19 million years ago, but most of the alluvial and volcanic channels had been segmented in early Miocene time. Trends of these channels can be reconstructed only by piecing together segments that lie on exhumed portions of the late Eocene surface or have been preserved in down-faulted blocks.

Late Pliocene canyon cutting exceeded that during any other part of the Cenozoic; accelerated uplift caused erosion of canyons 180–300 m (590–980 ft) deep at mountain flanks. Resulting sediments are not abundant, but they can be found in upper parts of graben fills.

Quaternary surfaces are narrow and confined to valleys and are not more than 140 m (459 ft) above streams. Surfaces can be dated precisely only where overlying deposits furnish direct evidence of age.

Major modern geomorphic elements are post-Laramide and are related to middle and late Cenozoic volcanism, uplift, basin-and-range-style block faulting and attendant erosion.

INTRODUCTION

The information for this summary of Cenozoic geomorphic, volcanic and tectonic features of central Colorado is taken in part from recent articles by the authors (Epis and Chapin, 1975; Scott, 1975; Taylor, 1975; and Epis and others, 1976). Earlier major articles on Cenozoic structural geology, volcanic fields and erosion surfaces were written by Hills (1888, 1900), Cross (1894), Lee (1917), Van Tuyl and Lowering (1935), Rich (1935), Wahlstrom (1947), Knight (1953), Chapin and Epis (1964), Epis and Chapin (1968), Steven and Epis (1968), Scott and Taylor (1975), and Steven (1975).

The area considered here contains many of the major geomorphic elements of the southern Rocky Mountains (Figs. 1 and 2). These include the Front Range, Rampart Range, North, Middle and South Parks, southern Mosquito Range, upper Arkansas River Valley, southern Sawatch Range, northern San Luis Valley, northern Sangre de Cristo Range, Wet Mountain Valley, Wet Mountains, and Great Plains to the east. Most of the documentation and interpretation of the Cenozoic features discussed here is based on our recent geologic mapping in the Pueblo 1° x 2° Quadrangle (Scott, and others, 1978) where volcanic rocks, faults and geomorphic surfaces are well preserved. Figure 3 and several others that follow attempt to illustrate interrelations of volcanism, tectonism and geomorphology and derive primarily from this work. We believe, however, that the general sequence of events is applicable to most of the Southern Rocky Mountain Province. Much of the information and interpretation regarding north-central Colorado is taken from Scott (1975).

LARAMIDE UPLIFT, EROSION AND DEPOSITION

Active geomorphic development of the Southern Rocky Mountains started in Late Cretaceous time and is still in prog-
ress. The Laramide orogeny began in Late Cretaceous time, about 70 million years ago, when the mountains began to rise and the sea began to withdraw. Laramide, as used here, is the time of orogenic activity between Late Cretaceous and middle Eocene. Laramide events pertinent to the Cenozoic history of central Colorado include intrusion of plutonic rocks, volcanism, uplift, erosion, and deposition and deformation of orogenic sediments. Laramide igneous activity began about 72 million years ago, but most of the intrusives are 70 to 50 million years in age (Tweto, 1975). The mountains were elevated enough to lift Precambrian rocks above sea level. Much of the sedimentary rock cover was eroded from these uplifts, and fine-grained, coal-bearing beds equivalent to the Laramie formation and overlying coarse-grained beds equivalent to the Dawson Formation were deposited in basins adjacent to the uplifts. In Paleocene time, major stream systems, some of them 120 km (72 mi) long, developed in the rising mountains and carried debris from sources in the mountains to form sedimentary rocks and volcaniclastic deposits in bordering basin fills (Fig. 4). Deposits containing volcanic detritus at the distal ends of these stream channels are preserved on the plains near Golden (Denver Formation), near Colorado Springs (two zones in the Dawson Formation), and south of Canon City (in the Poison Canyon Formation). Other equivalent basin fills lie in South Park (South Park Formation), Middle Park (Middle Park Formation), and North Park (Coalmont Formation). Cretaceous and Paleocene volcanic flows and lahars also contributed to filling of the Denver basin and South and Middle Parks. Erosion processes stripped the sedimentary cover from Precambrian rocks along these major channels and then worked laterally. Locally, parts of pre-Paleozoic and pre-Mesozoic surfaces were exhumed and still are preserved with small outcrops of sedimentary rocks on them, but generally erosion cut below these old surfaces.

DEVELOPMENT OF THE LATE EOCENE EROSION SURFACE

Continued erosion in Eocene time, accompanied by a generally stable base level, culminated in a single, well formed, widespread montane surface—the late Eocene surface. Most of the surface is a broad plain, but, locally, it has relief of a few hundred meters along major channels bounded by ridges and where monadnocks escaped planation. Cutting of the late Eocene surface occurred during a period of post-Laramide tectonic and magmatic quiescence ending before deposition of the Wall Mountain Tuff in early Oligocene time (35 million years ago).
Figure 2. Composite of Army Map Service plastic relief maps (2° quadrangles) showing major geomorphic elements of central Colorado. Dashed line is approximate location of schematic structure section shown in Figure 22 (after Epis and Chapin, 1975).
<table>
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<tr>
<th>AGE</th>
<th>PRESERVED DEPOSITS</th>
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<td>Mountains and South Park</td>
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<td>Andesite of Waugh Mtn. (19 m.y.)</td>
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<td>29</td>
<td>Gribbles Park Tuff (29 m.y.)</td>
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<td>Thorn Ranch Tuff</td>
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<td>East Gulch Tuff</td>
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<td>Badger Creek Tuff (32 m.y.)</td>
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<td>Florissant &amp; Balfour Lake Beds &amp; Antero Fm. (33 m.y.)</td>
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<td>Oligocene</td>
<td>Thirtynine Mile Andesite (34 m.y.)</td>
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<td>Tallahassee Creek Conglomerate</td>
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<td>37.38</td>
<td>Wall Mountain Tuff (35-36 m.y.)</td>
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<td>Pierre Shale</td>
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* Harland & Others, 1964; Gill & Cobban, 1966

Figure 3. Late Cretaceous and Cenozoic volcanic and sedimentary deposits
### Summary of Cenozoic Geomorphic, Volcanic and Tectonic Features

<table>
<thead>
<tr>
<th>Igneous Activity</th>
<th>Event</th>
<th>Tectonism</th>
<th>Geomorphology</th>
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<td>Slight differential uplift</td>
<td>Terrace formation</td>
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<td>Extrusion of basaltic andesite</td>
<td>Major uplift</td>
<td>Beginning of strong uplift, block-faulting &amp; formation of local basins</td>
<td>Major canyon cutting and inception of present drainage system</td>
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<td>Intrusion &amp; extrusion of phonolite Extrusion of rhyolite</td>
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<td>Partial diversion of drainages into local grabens; parts of late Eocene surface reused for transportation and deposition of detritus</td>
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<td>Extrusion of silicic ash-flow tuffs</td>
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<td>Northward and northeastward restriction of ash flows. Construction of Guffey volcano; lakes filled with tuffaceous beds. Drainage eastward to Great Plains. Disruption and damming of drainages</td>
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<td>Deposition of andesite, quartz latite, ash-flow, air-fall &amp; water-laid tuffs</td>
<td>Voluminous eruption of andesite</td>
<td>Stability of mountain blocks and faults</td>
<td>Drainage system of late Eocene surface reused. Drainage eastward to Great Plains. Silicic ash flows spread over late Eocene surface.</td>
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<td>Extrusion of silicic ash-flow tuff</td>
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<td>Magmatic quiescence</td>
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<td>Alluvial filling of paleo-valleys and local grabens. Major erosion of Laramide uplifts and aggradation of adjacent basins; development of widespread surface of low relief.</td>
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<tr>
<td>Eruption of andesite</td>
<td>Uplift of Laramide ranges &amp; formation of basins</td>
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<td>Erosion of sedimentary rocks overlying Precambrian basement. New surface cut into Precambrian rocks; locally surface beneath sedimentary rocks exhumed.</td>
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<td>Intrusion of Whitehorn Granodiorite (70 m.y.)</td>
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and related tectonic and geomorphic events of central Colorado (after Epis and others, 1976).
During formation of the surface, erosion apparently kept pace with uplift so that very few areas in the mountains stood very high above adjacent aggrading basins. Paleontologic and geomorphic evidence indicates that the surface formed at elevations less than 900 m (2,920 ft) in a warm, subhumid climate, conditions which are dramatically different from those of today (Epis and Chapin, 1975; MacGinitie, 1953 and 1969; Leopold and MacGinitie, 1972).

This late Eocene surface is the only widespread Cenozoic surface of low relief in the mountains (Fig. 5). It was cut in many areas along the eastern front of the Rocky Mountains from the Greenhorn Mountain in the Wet Mountains northward along the Front Range to Wyoming where it was reported by Knight (1953). It possibly correlates with an Eocene surface described by Soister (1968), Harshman (1968) and Denson and Harshman (1953). It possibly correlates with an Eocene surface described by Soister (1968), Harshman (1968) and Denson and Harshman (1953). Epis and Chapin (1975) suggested that the surface is probably traceable southward into New Mexico and possibly southern Arizona. The surface is overlain in many places by Eocene, Oligocene, or Miocene alluvial and volcanic deposits. In Eocene time, sediments that formed the Huerfano Formation, Echo Park Alluvium, and equivalent formations were carried in channels and across a developing pediment surface on the flanks of the uplifts, where local veneers still remain, and were deposited to thicknesses of hundreds or locally more than 1,000 m (3,280 ft) in the deepening grabens and basins (Fig. 6).

Deposition kept pace with basin development; therefore, the deformation apparently did not appreciably disrupt throughgoing streams. Using the late Eocene surface as a structural datum, it is clear that most of the modern geomorphic elements of the region post-date the Laramide orogeny and are related to younger tectonic activity.

Large segments of the late Eocene surface are preserved only beneath the Oligocene deposits of the San Juan, Thirtynine Mile, and West Elk volcanic fields, Colorado. Elsewhere, covering deposits remain only in Oligocene or Miocene channels cut below the general level of the surface. These deposits are best preserved in channels that parallel grabens, that were dammed by volcanic rocks, or that were blocked by faults. In the mountains, most of the deposits probably were removed from the late Eocene surface during Miocene or more recent erosion, whereas on the plains of southeastern Colorado, the erosion probably took place in both Chadron (early Oligocene) and part of Ogalalla (late Miocene) time.

Other small, unburied parts of the original surface were protected from erosion by their positions behind rising mountain blocks; streams behind these blocks generally managed to maintain their courses and to drain the protected areas but were unable to cut deeply into them. One of the best examples of such a protected area is the De Weese Plateau, west of the Wet Mountains. Less than one-fifth of the streams that originally crossed the future site of the Wet Mountains were able to hold their courses as the mountains rose, and then only because they gained extra water from other streams that were blocked. Another example of a tectonically protected area can be identified along the east flank of South Park where a large area of the late Eocene surface was well preserved by downfaulting and by being thinly buried.

In many places, the late Eocene surface is clearly recognizable in the modern topography even though unprotected parts have been eroded to a greater or lesser degree. With experience, an observer can recognize probable remnants of the surface even where they have been severely modified by erosion or disrupted by faulting. Generally, the surface has been dissected by a drainage network that cut sharp stream canyons but did not appreciably lower the intervening ridge crests. Over large areas, such as the Rampart Range (Fig. 7), the ridge crests are nearly accordant and represent an upland surface that is possibly less than a few tens of meters below its original level, as indicated by remnants of the early Oligocene Wall Mountain Tuff that filled shallow swales cut below the main flats of the surface. The highest parts of the late Eocene surface generally were eroded the most, especially in regions that were glaciated during the Pleistocene. Remnants of surfaces generally are seen only on the broader ranges; narrow ranges, such as the northern half of the Sangre de Cristo, have lost all recognizable remnants of the surfaces that once existed there.
Figure 6. Inferred late Eocene paleovalleys through which detritus of the Echo Park Alluvium and the Huerfano Formation was carried. The Echo Park and Wet Mountain Valley grabens subsided at about the same rate as they were filled. The grabens probably began to form late in Eocene time. Undoubtedly, many more streams engaged in lateralplanation than are shown here.
In the Front Range north of the South Platte River, most outflowing drainage was not blocked as it was behind the Wet Mountains and Rampart Range. Apparently, few of the late Cenozoic faults in that part of the range had sufficient downward movement on the west to block drainages as did faults in the Wet Mountains. The late Eocene surface to the north, therefore, generally has been more eroded than the same surface to the south. Only two places are known where drainage was blocked: one west of the Kennedy Gulch fault at Kennedy Gulch, and another at Bergen Park. Tertiary gravel deposits show that the Kennedy Gulch fault moved up on the east nearly 300 m (980 ft) since late Eocene time (Fig. 8).

The late Eocene surface at Bergen Park is now 600 m (1,970 ft) below the same surface on a block to the west across the major Floyd Hill fault (Sheridan and others, 1972), but is only about 100 m (330 ft) below the late Eocene-surface on a block to the east across a small fault.

The most definitive evidence regarding the age and geomorphic character of the late Eocene erosion surface is in the area of the Thirtynine Mile volcanic field (Epis and Chapin, 1975) where Oligocene volcanic rocks and younger rocks, briefly summarized below, have buried and preserved extensive segments of the surface.

**OLIGOCENE VOLCANIC AND ASSOCIATED ROCKS**

Within the area of the Thirtynine Mile volcanic field, in early Oligocene time (35–36 million years), ash flows of the Wall Mountain Tuff were extruded from a caldera probably near Mount Aetna (Figs. 9 and 10) in the present Sawatch Range. The ash flows generally followed valleys, but the present outcrop pattern of tuff indicates that they also overflowed interfluves and spread widely over the late Eocene surface, covering much of the area from South Park southward to the Wet Mountain Valley and eastward across the present Rampart Range onto the Great Plains near Castle Rock. Andesitic and rhodacitic volcanism from various centers followed, with deposition of laharc breccias, lavas and ash-flow tuffs up until at least 28 million years ago.

Streams eroded and channeled the Wall Mountain Tuff immediately following its deposition. They deposited gravel of the Tallahassee Creek and Castle Rock Conglomerates across the tuff and many parts of the late Eocene surface (Fig. 11). These conglomerates contain volcanic rocks from early activity in the Thirtynine Mile volcanic field. Later, minor channels were cut, and they also were filled by Tallahassee Creek Conglomerate (Fig. 11). Alluvial and Illuvial deposits of the Echo Park Alluvium (late Eocene) and Tallahassee Creek Conglomerate were important host rocks for uranium deposits in the southern part of the Thirtynine Mile volcanic field in the Tallahassee Creek district.

Beginning about 34 million years ago, the Thirtynine Mile Andesite was erupted from numerous local vents and spread across much of the area north of the Arkansas River. Lake basins formed along the north and west sides of the volcanic pile where drainages were diverted and blocked. The Florissant Lake Beds and the Antero Formation accumulated in these basins to the level of spillover (Fig. 12). The Badger Creek Tuff (which may also have been erupted from the Mt. Aetna caul-
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Figure 8. View to west across north end of Rampart Range west of Sedalia. The late Eocene surface at or near skyline lies just east of the Kennedy Gulch fault. Alluvium lies on this surface west of the Kennedy Gulch fault but was stripped from the segment of surface shown here.

dron) makes up a large part of the ashy material in the Antero Formation. Some pre-volcanic channels remained open and active through all of Tertiary time, but most were occupied for only part of that time.

The Gribbles Park, Thorn Ranch and East Gulch Tuffs were erupted about 29 million years ago and transported in part along paleovalleys as shown in Figure 13. Growth of the large, composite Guffey volcano (comprised mainly of the upper member of the Thirtynine Mile Andesite) in the central portion of the volcanic field further contributed to disruption of drainages. The volcano must have formed a barrier to northward and northeastward spreading of these ash-flow tuffs and confined them to areas west, southwest, south and southeast of the site of the volcano. The source of these younger ash flows is unknown, but it must have been west or southwest of the main portion of the present volcanic field.

After deposition of these ash-flow tuffs, the paleovalleys remained open into early Miocene time and streams deposited volcanioclastic debris from fairly distant sources. The Goat Creek-Hillside channel (Fig. 13), in early Miocene time, carried well rounded clasts of syenite, Dakota Sandstone, jasper from an equivalent of the Ralston Creek Formation, and Leadville Limestone, all from sources apparently existing at that time along the trend of the present Sangre de Cristo Range. East of McClure Mountain (Fig. 13) this channel carried clasts of Cambrian syenite from the McClure Mountain Complex. The Oak Creek and Howard paleovalleys carried rounded andesite clasts; andesite and other volcanic rocks, probably derived from the Bonanza volcanic field and from the Rito Alto center, apparently veneered the ancestral Sangre de Cristo Range. The Trout Creek paleovalley (Fig. 14) carried clasts of rhyolite from the Nathrop Volcanics (28–29 million years, Van Alstine, 1969). The Florissant-Divide-Woodland Park paleovalley (Fig. 14) carried clasts of Wall Mountain Tuff, Thirtynine Mile Andesite and phonolite (dated at 28 million years) from Cripple Creek.

Steven (1975) and Steven and Epis (1968) described Cenozoic volcanic piles elsewhere in Colorado and suggested that together with rocks of the Thirtynine Mile pile, they coalesced into a single, large, composite volcanic field constructed largely in Oligocene time. What are known today as individual volcanic fields, are merely remnants of the larger composite fields that were isolated by later Cenozoic block faulting and erosion. Volcanic rocks similar in age, composition and style of emplacement to those of the Thirtynine Mile volcanic field occur in the San Juan Mountains, Spanish Peaks, Wet Mountains and Wet Mountain Valley, Elk and West Elk Mountains, Rabbit Ears Range, and Never-Summer Mountains. Generally, the oldest volcanic rocks in these fields are intermediate in composition and of earliest Oligocene age. They rest on the late Eocene surface described above, but detailed studies of the nature of the pre-volcanic surface have not been undertaken. Epis and Chapin (1975) have suggested that the surface beneath these volcanic fields is very likely similar to that beneath the Thirtynine Mile volcanic field. Volcanism extended into Miocene time in most areas, and together with Oligocene volcanism, created local geomorphic elements formed by constructional volcanic and volcanotectonic processes.

The Oligocene rocks covered the late Eocene surface, filling and overlapping extensive shallow channels that had been cut below the general surface level. The floors of some of the channels were covered by meager deposits of Eocene pre-volcanic alluvium probably equivalent to the Huerfano Formation or the
Figure 9. Location of the Thirtynine Mile volcanic field in relation to other middle to late Cenozoic volcanic rocks. Important localities mentioned in the text are included. Modified from Burbank and others (1935), Chapin and Epis (1964), and Epis and Chapin (1968).
Figure 10. Paleovalleys existing at the time of emplacement of ash flows of the Wall Mountain Tuff. Drainage pattern is based on scattered outcrops of the tuff and on the evolution of drainages during Echo Park and Tallahassee Creek times. Ash flows filled valleys, overrode many interfluves, and crossed the ancestral Rampart Range. The dashed line shows the inferred extent of the Wall Mountain Tuff based on outcrops; the maximum extent may have been much greater. The extent west of the inferred source at Mt. Aetna and east of this figure near Castle Rock is not shown.
Figure 11. Inferred paleovalleys used during deposition of the Tallahassee Creek Conglomerate. Locally the alluvium was spread across the late Eocene surface, as in High Park, but elsewhere it was confined to channels cut during Tallahassee Creek time. The northwest-trending paleovalley through Rosita is lined by an ash-flow sheet that was deposited both north and south from the Rosita volcanic center.
Figure 12. Present extent of the Thirtynine Mile Andesite showing how the Florissant Lake Beds (horizontal lines) and the Antero Formation (stippled) were deposited in water impounded by andesitic laharc breccias. The Florissant Lake Beds were deposited behind a dam formed by the lower member of the Thirtynine Mile Andesite and, later, the lake beds were covered by the upper member of the Thirtynine Mile Andesite. Arrows show trends of paleovalleys.
Figure 13. Late Oligocene paleovalleys existing at time of deposition of the East Gulch, Thorn Ranch, and Gribbles Park Tuffs (29 m.y.). These tuffs were nearly the last deposits to occupy these channels before the beginning of block-fault movement in early Miocene time. We believe that many of the paleovalleys of early Oligocene time, especially across the Wet Mountains, also remained open until early Miocene time.
Figure 14. Principal Neogene faults that blocked paleovalleys and disrupted the late Eocene surface. Blockages are shown by bars upstream from faults. Nearly all paleovalleys were blocked when these faults became active in early Miocene time. Most of the faults had earlier histories of movement, many as early as Precambrian. Faults compiled from Scott and others (1978), Bryant and Wobus (1975), and Tweto (1979).
Volcanism began in early Oligocene time and some remained open through Neogene time. In the southern Front Range area, the channels were partly filled and locally overtopped by early Oligocene ash flows, gravel, and tuffaceous sedimentary beds that are, in part, equivalent to the White River Group. These were overlapped by volcanic rocks that erupted later in Oligocene and part of Miocene time. Channel cutting continued in Oligocene time, forming such features as the channel in the Wall Mountain Tuff at Castle Rock (subsequently filled with Castle rock conglomerate). Some Oligocene channels can still be traced or inferred for more than 160 km (100 miles) (Fig. 15).

Oligocene deposits changed the topography and modified the drainage systems. In the large volcanic fields, all features of the pre-existing landscape were buried. On the peripheries of the large fields, and in smaller fields, large parts of the late Eocene surface were buried, but peaks and ridges projected through the Oligocene deposits. Many streams were dammed by volcanic flows or lahars and forced into new courses, in part cutting across the volcanic piles and, in part following around the margins of the volcanic accumulations. Lakes locally formed behind the volcanic dams, and the lake beds deposited in them, contain abundant fossils which tell much about the Oligocene climate. The most important lake deposits are at Creede (Miocene) in the San Juan Mountains and at Florissant (Oligocene) in the southern Front Range.

**EARLY MIocene Through PlIOCENE UPLIFT, EROSION AND DEPOSITION**

A major episode of Tertiary uplift, erosion and deposition that started in early Miocene and continued through Pliocene time profoundly disrupted the Eocene surface and the overlying Oligocene deposits. Vertically uplifted mountain blocks were deeply eroded, and the resulting debris filled adjacent grabens and basins. Offset may have exceeded 6,000 m (19,700 ft) along the west flank of the Sangre de Cristo Range (Davis and Keller, 1978), and lesser amounts are suggested elsewhere. Eocene and Oligocene tectonic stability ended in early Miocene time when most ranges of the Southern Rocky Mountains began to rise. Basal sediments deposited in related grabens have been dated as early Miocene by vertebrate fossils (Edward Lewis, 1970, 1972, written communication) indicating that the deformation began before Harrison or Marsland (early Miocene) time and continued through the Miocene.

Important evidence on the Neogene uplift comes from offset of Oligocene and Miocene volcanic deposits and of drainage elements. Deposits once continuous are now separated by as much as 1,500 m (4,900 ft) of vertical movement. The paleovalleys that formerly crossed the Sangre de Cristo Range and the upper Arkansas Valley (Fig. 14 and 15) were extensively disrupted during this period of deformation, and the deposits on the upthrown blocks were largely removed. For example, an excellent section of Oligocene rocks exists in the Arkansas Valley near Howard, but the channel extensions across the mountains on both sides have been removed by erosion.

An especially informative exposure of faulted Oligocene deposits lies on the plains south of Canon City where Grabbles Park Tuff (dated at 29 million years) and associated volcanic conglomerates and lahars lie at the same elevation (105 m, 344 ft) above the Arkansas River (30 m, 98 ft on projected profile) as the Slocum Alluvium of Illinoian or Sangamonian age. Equivalent rocks in the neighboring mountains are as much as 1,080 m (3,540 ft) higher as a result of Neogene tectonism. Evidently the Oligocene rocks south of Canon City were displaced by this amount, buried by later Tertiary deposits, and then exhumed during the Quaternary.

Miocene alluvium was deposited in valleys formed by grabens, in basins or bajadas bordering the mountains, and in channels (Fig. 16). Graben-fill deposits are largely confined to the San Luis Valley and upper Arkansas Valley segments of the Rio Grande trench and to the Wet Mountain Valley. The basin fills or bajadas are in the south end of South Park, in Middle and North Parks, on the Great Plains and at Browns Park. Channel-filling deposits of inferred Miocene age are known on the plateau west of the Wet Mountains; at Howard (which in part are also graben-filling); at Divide (Fig. 17), west of South Platte (Petersen, 1964); near Wilds Peak (Bryant and others, 1973), at Pine Junction, west of Sedalia; at many places along Clear Creek, west of Golden (J. C. Reed, Jr., R. B. Taylor, and D. M. Sheridan, 1972, oral communication); north of the Big Thompson River (W. A. Braddock, 1972, written communication); north of the Cache la Poudre River (W. A. Braddock, 1972, written communication); (Fig. 18); at Prairie Divide (M. E. McCaullum, 1972, oral communication); and in the Northgate district where
Figure 17. Miocene (?) alluvium (grassy area) in paleochannel on upthrown east side of Manitou Park graben east of Woodland Park. Paleochannel was incised only several to a few tens of meters below the bordering tree-covered late Eocene surface to left and right. Woodland Park is in foreground.

Figure 18. Miocene (?) alluvium in paleochannel north of Cache la Poudre River. This channel can be traced for about 40 km (24 mi). Axis of channel shown by straight tree line.
the North Park Formation lies in channels cut into the White River Group (Steven, 1956). Other gravel deposits of possible Miocene age have been listed by Ives (1953) and by Wahlstrom (1947).

The Miocene deposits range widely in thickness and in elevation above nearby major modern streams. The graben fills are several thousand meters thick, but very little fill lies above modern stream level; the bajada deposits are as much as 120 m (390 ft) thick and commonly lie 150 m (490 ft) or more above major streams; most of the channel deposits are 100 or 200 m (330 or 660 ft) thick or less and generally lie more than 150 m (490 ft) above adjacent major streams. The deposits range from boulder alluvium to silt and sand; the coarsest deposits are nearest the mountains and the finest deposits are near the centers of the graben fills. Volcanic-ash layers have been found in the fine-grained deposits, but not in the coarse-grained deposits. Fossils generally are preserved only in the fine-grained deposits. No ash beds or fossils have been found in the channel deposits; their Miocene ages are, therefore, inferred.

We believe that, during Miocene time, the elevation of the lower mountains probably was similar to what it is now; the higher mountains probably were not so high as today. The Miocene pollen is similar to an impoverished Cordilleran flora of modern aspect (Leopold and MacGinitie, 1972, p. 163).

Preservation of the Miocene deposits depended largely on position relative to modern drainage. Deposits on elevated blocks were largely removed by erosion. The graben fills are almost completely preserved because of their protected positions relative to the bordering uplifs. In the San Luis Valley the Miocene-Pliocene deposits are almost completely buried by Quaternary alluvium and outwash and are scarcely dissected. The basin-fill or bajada deposits are locally well preserved. Few of the original channel deposits have been preserved; most occur now in channels abandoned because of stream captures, in channels along or across grabens, and in areas where channels were segmented and lowered by faults.

Erosion of the uplifted blocks and deposition in the basins were contemporaneous with Miocene deformation. Faults active in the Miocene mark the margins of nearly all the graben fills and can be well documented along both flanks of the Sangre de Cristo Range and along the borders of the upper Arkansas Valley. Channels were disrupted by faults or fault systems. Many streams were tectonically dammed or were disrupted and rerouted; valleys were abandoned, and stream captures were commonplace. An example is a channel that was disrupted by a north-trending fault at Divide and, to the east, broken again by the Ute Pass fault at Woodland Park.

**Pliocene Canyon Cutting**

Uplift apparently was greatly accelerated in Pliocene (through Blanco Formation) time, and the resulting accelerated erosion cut the deep canyons that characterize the mountain flanks (Figs. 19, 20). At the Rocky Mountain front these canyons were cut only to a level 135 m (440 ft) above modern stream levels by the time the Nussbaum Alluvium was deposited in early Pleistocene or Pliocene time.

Most of the deeper parts of the modern canyons are cut near the mountain front close to the Great Plains, but major drainages extend as deep canyons many miles back into the mountains where they commonly grade to the base levels occupied by Pleistocene glaciers. These narrow, steep-walled canyons were incised either in the Eocene surface or in the floors of Miocene channels. Along Clear Creek canyon west of Golden the Pliocene canyon was cut 405 to 435 m (1,330 to 1,430 ft) below the Eocene surface and about 135 m (440 ft) below the base of Miocene (?) alluvium (Scott, 1972).

Figure 19. Major Pliocene canyons along the eastern flank of the Front Range and Wet Mountains. All canyons are the same as the modern stream valleys.

Figure 20. Typical Front Range canyon showing the form resulting from Cenozoic geomorphic processes. The four marks in the lower part of the canyon represent the levels of the four pre-Bull Lake pediments.

The initial positions of many major canyons seem to have been largely controlled by superposition as the streams cut through the sedimentary cover into the underlying Precambrian rocks. These positions were locally modified as erosion was later influenced by faults, rock structure, and rock hardness. Superposition of some canyons, such as Clear Creek canyon, West Monument Creek canyon, and the Royal Gorge, apparently started in Late Cretaceous time when streams cut through the sedimentary rock cover into Precambrian rocks, establishing courses across the rising mountains and carrying coarse volcanic and nonvolcanic detritus out onto the plains. These courses later became main drainage elements on the late Eocene surface. The late Eocene surface flanking Clear Creek is about 16 km (9.6 mi) wide at the mountain front between Mount Tom and Mount Morrison, but decreases in width to the west. In Miocene time ancestral Clear Creek cut a channel 1.5 km (0.9 mi) or more wide and about 240 m (790 ft) deep. In Pliocene time the canyon was deepened by 135 m (440 ft) and in Quaternary time by another 105 to 135 m (340 to 440 ft) to its present depth. Some stretches of the creek obviously were localized for short distances by shattered zones along faults, but in general, rock structure seems to have had little influence on the course of this drainage.

Although locally modified, the Pliocene canyons are still preserved throughout the mountains. Most of the detritus that resulted from canyon cutting apparently was transported across
the plains and out of Colorado, but some was deposited as a thin, widespread sheet of alluvium, the older part of which possibly now comprises the Kimball Member (of Lugn, 1938) of the Ogallala Formation on the eastern Great Plains, and the younger part of which possibly now comprises the lower beds of the Nussbaum Alluvium near the mountains (Scott, 1963a).

In the mountains, the upper part of the Santa Fe Formation in the San Luis Valley, the Santa Fe (?) Formation in the Wet Mountain Valley, and the upper part of the Dry Union Formation in the upper Arkansas Valley south of Salida probably include some of the Pliocene material resulting from canyon cutting. South of Salida, the upper part of the Dry Union Formation of Miocene and Pliocene age consists of slightly rounded and poorly sorted Precambrian boulders, cobbles, and pebbles; it dips southward from the basin into a major fault that truncates the north end of the Sangre de Cristo Range. This Pliocene upper part overlies beds, rich in volcanic detritus, which are of late Miocene age and correlative with the Ash Hollow Member (of Moore and others, 1951) of the Ogallala Formation. These gravelly deposits apparently formed after great local Pliocene uplift of the north end of the Sangre de Cristo Range accelerated the erosion of the Precambrian rocks in the core of this range.

Pliocene uplift of the northern Sangre de Cristo Range appears to have been more than 1,200 m (3,936 ft). This uplift, and concurrent downfaulting of comparable scale in the San Luis Valley, had a major influence in shaping the modern landscape, perhaps equaling the effects of Quaternary events.

SUMMARY OF CENOZOIC GEOMORPHIC, VOLCANIC AND TECTONIC FEATURES

ROCKY FLATS, VERDOS, AND SLOCUM ALLUVIUMS

The Rocky Flats, Verdos, and Slocum Alluviums are all alluvial covers on pediments. These units have been correlated from their type localities near Denver, by use of geomorphic position, paleosols, and lithology, with deposits to the south across the South Platte River basin and into the Arkansas River basin. Each major pediment has locally been found to contain more than one level. These probably result from a stream that created and did not destroy an intermediate level in the process of cutting down from one major geomorphic level to the next lower major level. These intermediate levels generally are found along only a few kilometers of stream length in the areas of greatest base-level and tectonic instability only a few miles from the mountain front. The intermediate-level pediment deposits are best mapped as genetic parts of the next younger, formally named, pediment alluvium.

Typically, in the plains areas, the Rocky Flats Alluvium (Nebraska or Aftonian in age) is about 105 m (340 ft) above modern stream levels, the Verdos Alluvium (Kansan or Yarmouth) about 75 m (250 ft) and the Slocum Alluvium (Illinian or Sangamonian) 30 m (98 ft) above stream level. Along major drainages in the mountains, the elevations above streams are tens of meters less than on the plains because of the greater hardness of the Precambrian rocks. Local geomorphic and structural conditions in the mountains cause great variations in the positions of these alluviums above streams; for instance, the Verdos Alluvium at Westcliffe lies only 6 m (20 ft) above Grape Creek.

LOUVIERS AND BROADWAY ALLUVIUMS AND HOLOCENE ALLUVIUM

These formations are all valley fills lying respectively about 21 m (70 ft), 12 m (39 ft), and <12 (<39 ft) above the major streams. Along some streams in the plains just east of the mountains, the episodic progression of downward cutting took place from the beginning of Quaternary time only through Louviers time; thereafter, these streams merely reworked the upper part of the thick Louviers Alluvium. Along other streams, however, the downward cutting progressed through Holocene time to the present.

GLACIATION

A general cooling of climate in Quaternary time caused cyclic glaciation. Most Quaternary glaciers in the Southern Rockies...
were confined to valleys and the pre-Bull Lake glaciers never extended far beyond the limits of Bull Lake Glaciation. The time of earliest glaciation in the Southern Rockies is unknown, for glacial deposits of early Pleistocene age are poorly known. The earliest recognized pre-Bull Lake till is possibly Nebraskan in age. The obvious Bull Lake and younger moraines are, from oldest to youngest: lower Bull Lake and upper Bull Lake (equivalent to Louviers Alluvium), lower Pinedale, middle Pinedale, and upper Pinedale (equivalent to Broadway Alluvium), and very minor younger moraines. Outwash terraces can be traced away from each of the two Bull Lake moraines, but they merge into one terrace within a few kilometers. Similarly, Pinedale deposits merge into one terrace, and the Holocene outwash equivalent to neoglacial apparently either underlies the floodplains of modern streams or forms very low flanking terraces.

Glacial erosion was the chief cause of the destruction of the Eocene surface in the higher parts of the mountains. No remnant of the surface remains in narrow ranges such as the northern half of the Sangre de Cristo. In the glaciated parts of the broader ranges, such as the Front Range, small remnants of a postulated old surface are found, as in Flattop Mountain in Rocky Mountain National Park (Lee, 1917, p. 28). No glaciation took place in lower mountain ranges such as the Wet Mountains, and consequently the Tertiary surfaces and deposits were more widely preserved.

Throughout the glaciated mountains, in addition to destruction of the surfaces, erosion related to glaciation also removed most of the Tertiary alluvial deposits (even in the lower parts of middle Tertiary channels) that had not already been removed in Pliocene time. In addition, along the Arkansas River, melt water removed most of the older Quaternary alluvium deposits; they remain only where the canyon parallels a major fault far enough to have a wide valley where terraces could be preserve. Many of the preserved older Quaternary alluvium deposits were cemented by travertine and thus were not easily eroded. Most of the alluvium remaining in the mountain valleys is Bull Lake and Pinedale outwash. These remnants help to extend and correlate the outwash sequence with the nonglacial terrace sequence on the Great Plains.

RECOGNITION OF TERTIARY SURFACES AND DEPOSITS

Surfaces in the mountains may be very difficult to recognize and differentiate. Proving that a local flat or semi-flat area is a geomorphic surface is difficult, but determining whether it is an exhumed pre-Paleozoic or pre-Mesozoic surface or a primary Eocene, Oligocene, Miocene, or Quaternary erosion surface is virtually impossible in many places. The only certain way of identifying a surface is by means of overlying datable deposits, and these are all too scarce. Many factors combine to make the surfaces difficult to recognize and differentiate:

1. Stream or glacial erosion has removed most or all of the overlying deposits, severely modified the surfaces, and reduced the extent of both surfaces and deposits;
2. Faulting has segmented the surfaces and changed the vertical positions of both the surfaces and deposits;
3. Deposits do not contain datable materials;
4. The sources of the rocks in the deposits cannot be identified;
5. Surfaces and deposits are buried under basin fills and cannot be seen.

Generally, it is easier to distinguish Quaternary from Tertiary surfaces and deposits than it is to differentiate the Tertiary surfaces and deposits. The following criteria are helpful in differentiating the Tertiary and Quaternary:

1. Tertiary surfaces are commonly extensively developed on Precambrian crystalline rocks, whereas only extremely small areas of Quaternary surfaces were cut on crystalline rocks. The only widespread surface of low relief was cut in Eocene time. No widespread, montane Quaternary stream-cut surface exists at any level.
2. Normally, no montane Quaternary alluvium lies higher than 108 m (354 ft) above major streams. However, Tertiary alluvium can be 108 m (354 ft) or less above stream levels in downfaulted areas or where later entrenchment has been minor.
3. No high-elevation gravel deposit far from areas of Bull Lake Till is glacial in origin. All known pre-Bull Lake till is adjacent to Bull Lake Till and was deposited by valley glaciers. Furthermore, no icecap glaciers that could have deposited the high-elevation gravels are known in Colorado or New Mexico.
4. Precambrian rock beneath the late Eocene surface is weathered to depths of about 10 m (33 ft) to more than 40 m (131 ft), whereas under Quaternary surfaces in the lower parts of the canyons weathering is less than 3 m (10 ft) deep.

Although it generally is possible to determine whether a surface or a deposit is Tertiary or Quaternary in age, it is more difficult to distinguish which Tertiary surface is present unless a datable overlying deposit is found. Following are some suggestions for differentiating the Eocene, Oligocene, and Miocene surfaces.

EOCENE SURFACE

1. The Eocene surface was very widespread, and much of it was nearly flat, although some high ridges and peaks persisted locally.
2. Underlying rocks were weathered to depths of about 10 m (33 ft) to more than 40 m (131 ft).
3. The Eocene surface was widely covered by alluvial or volcanic deposits.
4. The Eocene surface may lie at any height in relation to modern streams, depending on local structure.
5. Amount of offset by faults is greater than it is for younger surfaces.

OLIGOCENE CHANNELS

1. Minor Oligocene channels have been recognized in central Colorado, but major channels existed in Wyoming.
2. Underlying rocks are weathered like those under the Eocene surface.
3. The Oligocene-channeled surface was widely covered by volcanic deposits.
4. Oligocene canals may be incised into the more gentle Eocene surface, where both can be recognized.

MIOCENE CHANNELS AND GRABEN FILLS

1. Minor Miocene channels are cut into the Eocene surface: they tend to be narrower than Oligocene channels.
2. The bedrock is weathered about 10 m (33 ft) deep beneath the channels.
3. The associated alluvial gravels contain mainly fragments of Precambrian rocks, but locally contain some volcanic rocks. The gravels are generally not covered by volcanic deposits.
4. Local structure determines height above modern major streams.
5. There is a characteristic reddish-brown (Santa Fe Formation) color for deposits in graben fills.
6. Pliocene canyons are entrenched into these channels and deposits.
As a result of the recent work done on Cenozoic surfaces and deposits, we believe that the following previously stated or implied ideas in the geologic literature should be discarded:

1. That there are many levels of high surfaces, each level representing a separate major episode of cutting.
2. That remnants of surfaces can be correlated on the basis of their altitudes. The old surfaces were offset in many places by Cenozoic faulting.
3. That fault movement since Laramide time is minor. Local offset of as much as 6,000 m (19,700 ft) is probable since Laramide time.
4. That high-elevation gravels in the mountains are the result of icecap glaciation.

We believe, instead, that there was a single major surface of low relief, the late Eocene surface described here, and that the altitude of remnants of this surface depends on faults that had displacements that ranged up to thousands of meters in Neogene time. Clearly, the impressive, modern geomorphic elements of Colorado are not the result of the Laramide orogeny. Rather, they are the result of middle to late Cenozoic volcanism, uplift, basin-range-style block faulting, and attendant erosion (Figs. 21, 22).

REFERENCES CITED


