Late Cenozoic tectonic and geomorphic framework surrounding the evaporite dissolution area in west-central Colorado

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ABSTRACT

The west-central Colorado area of evaporite dissolution and related subsidence is within a wide region affected by late Cenozoic tectonic activity. The White River uplift to the north was uplifted and tilted northward in late Miocene time after Miocene alluvial deposits (Browns Park Formation) and interlayered basaltic lava flows had been deposited. Just to the east, the Gore Range—Park Range structural block was uplifted athwart similar deposits. The broad early Tertiary Sawatch anticlinorium (to the south and southeast) was split by the Rio Grande rift in latest Oligocene and Miocene times, and was filled by the alluvial Dry Union Formation. The block west of the rift was then uplifted and tilted west to form the present Sawatch Range. Rifting farther south in the San Luis Valley formed a half graben in which alluvial deposits (Santa Fe Formation) accumulated from latest Oligocene to the Pleistocene; in Pliocene time tilting expanded westward, and involved the whole San Juan Mountains area.

West of the subsided area, major uplift took place in late Miocene time after the 10 Ma basaltic lava flows capping Grand Mesa had been erupted. Resulting erosion stripped the area to the west down to and below the lower Mancos Shale. Complex geomorphic and structural events disrupted this stripped area, the most important of which was the rise of the Uncompahgre Plateau block with concurrent antecedent erosion of Unaweep Canyon. Subsequent general nonuniform uplift took place throughout the Southern Rocky Mountains, largely in the Pliocene, and caused rejuvenated erosion and cutting of sharp canyons along all of the main streams.

INTRODUCTION

Late Cenozoic evaporite dissolution and related subsidence in west-central Colorado (Kirkham et al., 1997; Scott et al., 1998; Scott et al., 1999; Kirkham and Scott, this volume) evolved concurrently with a complex sequence of regional tectonic and geomorphic events that probably triggered evaporite diapirism and dissolution, and certainly had significant control on their rates and extent. These tectonic and geomorphic events are commonly obscure and difficult to trace, and, to a great extent, have received scant attention in the geologic literature. Some localities, such as the Unaweep Canyon area, have been discussed repeatedly, but little consensus has been reached. This neglect and/or disagreement stems largely from the fact that erosion has been the dominant geologic process acting on the Southern Rocky Mountains during the late Cenozoic, and, by its nature, erosion progressively destroys the history of its own evolution.

This report is based on a study of erosional features over most of west-central Colorado where some features are clear-cut, others more enigmatic, and some downright daunting to interpret. Gaps in data are common and often inconvenient.
Figure 1. Map of western Colorado showing distribution of features discussed in text. AGR—ancestral Gunnison River; AUR—ancestral Uncompahgre River; ADR—ancestral Dolores River; ACR—ancestral Colorado River; CM—Cimarron fault; BCM—Book Cliffs monocline; UM—Uncompahgre faulted monocline; RM—Redlands faulted monocline; BC—Black Canyon of the Gunnison River; WMV—Wet Mountain Valley; GC—Gore Canyon; TC—Tomichi Creek; D—Delta; GJ—Grand Junction; SP—Steamboat Springs; G—Gunnison.
Subjective but consistent judgments are needed to bridge some of these gaps to achieve a coherent interpretive history. Timing of events is especially problematic, and for the most part can be established only within broad limits. Most emphasis will be given here to the areas downstream from the subsided area where tectonic and erosional events had major influence on the evolving area of evaporite-related subsidence in west-central Colorado.

**METHODS**

My lifelong emphasis on field-based investigations is no longer feasible, and my recent work has depended largely on careful study of published geologic maps and new, high-quality, topographic maps. The U.S. Geological Survey County Map Series (scale 1:500000), and 30 × 60 Minute Series (scale 1:100000) have been especially useful. Numerous field traverses have been made along accessible roads, and spot checks in the field have been made in important areas.

**REGIONAL CENOZOIC STRUCTURAL AND GEOMORPHIC FRAMEWORK**

Many widely divergent opinions are currently being discussed on the roles of climate change versus tectonism as the major driving force in developing the modern landscape of the Southern Rocky Mountains. In oversimplification, climate change proponents suggest that the general area was topographically high throughout most of the Cenozoic, only to be etched out in the late Cenozoic by accentuated erosion driven by a change in climate. In contrast, I am among those who believe that tectonism was the main cause of enhanced erosion during the late Cenozoic. According to this view, late Cenozoic tectonism began in the latest Oligocene and early Miocene along the Rio Grande rift, and extended episodically in time and space until all of the Southern Rocky Mountains, the Colorado Plateau, and much of the Great Plains were uplifted in late Cenozoic time. Rejuvenated erosion carved the present topography. This report is not the appropriate medium to discuss in detail such a broad and complex subject, and readers are referred to Steven et al. (1995, 1997) and McMillan et al. (2002) for evidence pointing toward tectonism and uplift as major driving forces, and for contrary opinions to Chapin and Cather (1994), Gregory and Chase (1992, 1994, Molnar and England (1990), and Wolfe (1992), and to references contained therein.

The Laramide orogeny and attendant erosion, extending from late Cretaceous (ca. 70 Ma) (Tweto, 1975), into and perhaps through the Eocene, left a mountainous upland where hard Precambrian rocks were exposed in the cores of uplifts; this upland extended laterally outward through foothills with progressively lower relief to widespread plains where flanking soft Phanerozoic sedimentary rocks were exposed (Steven et al., 1997). In Oligocene time, this "late Eocene surface" (Epis and Chapin, 1975; and discussed in Steven et al., 1997) was widely but irregularly covered by intermediate-composition and silicic volcanic rocks (Steven, 1975). The largest remnants of this volcanic cover still remaining are in the San Juan Mountains in southwestern Colorado, the Thirtynine Mile volcanic field in central Colorado, and the Rabbit Ears volcanic field and adjacent mountains in north-central Colorado (Fig. 1). Smaller remnants of volcanic rocks and numerous related plutons have been recognized elsewhere in the mountainous area.

Late in Oligocene time and extending into the Miocene, extensional tectonism developed a zone of rifting (the Rio Grande rift) along the trend of the earlier Laramide orogenic belt (Chapin and Cather, 1994). Local block faulting along the rift was accompanied by more widespread jostling and tilting of adjacent areas; effects of this marginal deformation can be recognized well out into the Great Plains of eastern Colorado (Steven et al., 1997). Concurrent erosion removed large areas of the volcanic cover, exhuming and variably modifying the prevolcanic surface so that little of the early Cenozoic paleotopography can be recognized (Steven et al., 1997; Steven, un-pub. data). Stream patterns were drastically modified, and the Rio Grande rift became a distinct feature of the topography. Details of the early Miocene geomorphic and tectonic evolution are sparse in west-central Colorado where the present volume is focused, and many interpretations made elsewhere in Colorado cannot be projected into it with confidence.

Beginning as early as the latest Oligocene, and in full progress by the middle of the Miocene, alluviation was taking place in lower areas, with concurrent erosion of adjacent higher ground, over much of present Colorado. As shown on the Colorado State geologic map (Tweto, 1979), Miocene sediments laid down at this time comprise the Browns Park Formation deposited widely in northwest Colorado, the North Park Formation in the North Park area, the Troublesome, Dry Union, and Santa Fe Formations along the Rio Grande rift, and the Ogallala Formation on the Great Plains of eastern Colorado. Significant block faulting took place along the Rio Grande rift during alluviation, with local blocks being strongly depressed or uplifted; adjacent areas were similarly affected but to a lesser degree. Few remnants of these Miocene sedimentary units have been found within the area of the evaporite dissolution discussed in this volume where stratigraphic and age control is provided largely by basaltic rocks.

The ongoing faulting, tilting, and uplift that accompanied late Miocene alluviation sharply increased in rate, magnitude, and area of involvement near the end of the Miocene (Steven et al., 1997), and related enhanced erosion continued through the Pliocene and into the Quaternary. Alluviation ceased as uplift caused rejuvenated erosion to cut deeply into underlying rocks, and regional excavation took place from near the eastern border of Colorado (Steven et al., 1997; McMillan et al., 2002), westward across the Southern Rocky Mountains, the Colorado Plateau, and into the Great Basin (Rowley et al., 1981). The term "canyon cycle of erosion" applied by Lee (1923) to the Front Range area can be applied regionally, with the under-
La Sal Mountains

Figure 2. Map of northern Uncompahgre Plateau-Grand Mesa area showing distribution of features discussed in text. ACR—ancestral Colorado River; AUR—ancestral Uncompahgre river; BCM—Book Cliffs monocline; RFM—Redlands faulted monocline. Dotted line outlines Cactus Park. Blank areas underlain by pre-Mancos Shale units (predominantly resistant sandstone) and post-Mancos Shale sedimentary rocks. Grand Mesa capped by 10 Ma basaltic lava flows.
standing that while always late in the history of geomorphic evolution, it was not necessarily simultaneous in all places.

Regional considerations tie all these late Miocene, Pliocene, and possibly early Pleistocene erosional events to tectonic causes:

1. Steven et al. (1995) described the San Juan Mountains (Fig. 1) as an east-dipping, slightly tilted block of volcanic rocks that extends >200 km from the present west margin of the mountains to the east side of the San Luis Valley segment of the Rio Grande rift; total structural discordance across this span is postulated to be on the order of 5–5.5 km, but this was incremental from ca. 26 Ma into the Quaternary (Steven et al., 1995; Brister and Gries, 1994). Based on rough calculations using Figure 2 of Brister and Gries, east downwarping of the San Luis Valley half graben was ~2900 m between 26 and 4.5–5 Ma (Rye et al., 2000), and was largely confined to the rift area. Younger (Pliocene–Pleistocene) intrafault tilting was ~1000 m, and was accompanied by irregular tilted uplift of the whole San Juan Mountain block to the west where Steven et al. (1995) demonstrated that the local depth of canyons then cut was proportional to the amount of uplift shown by structural-stratigraphic parameters, thus tying erosion closely to deformation. Rye et al. (2000) showed that canyon cutting in the central San Juans resulted from uplift younger than 4.5–5 Ma, and in progress at 3.5 Ma. Uplift and deep erosion in the San Juan Mountains block thus seem largely to have been Pliocene in age.

2. As outlined by Scott et al. (1998), the cap of 10 Ma basaltic lava flows on Grand Mesa (Larson et al., 1975; Marvin et al., 1989; Kunk et al., this volume) was at one time part of a widespread but discontinuous accumulation of 25–10 Ma basaltic flows whose remnants still extend over an area >200 km across (Fig. 1). The base of this sequence preserves part of a Miocene low-relief topography that was then the surface of the eastern part of the Colorado Plateau. Remnants of the basaltic lava flows have since subsided into the west-central Colorado area of evaporite dissolution where they form important markers (Kirkham et al., this volume; Lidke et al., this volume). North of the subsided area, on top of and on the north flank of the White River uplift that formed first in late Eocene time (Tweto, 1979), remnants of the basaltic flows are interlayered with sediments of the Miocene Browns Park Formation at altitudes of 3000–3600 m near the top, and extend down the north flank to altitudes of ~2100 m near the Yampa River. This difference (900 m or more) seems clearly to have resulted from late Miocene or younger (post–Browns Park Formation) uplift of the older highland area.

3. The major Sawatch Range along the southeast and south side of the subsided area (Fig. 1) consists of the western two thirds of a broad Laramide anticlinorium (Tweto, 1975, 1977) that was broken by repeated subsidence of the Rio Grande rift throughout the Miocene. The Dry Union Formation consists of alluvial fill that was deposited in the developing rift valley. Late faulting along the west side of the rift in the southern Sawatch Range involved Dry Union deposits, which occur in fault blocks at widely different altitudes along the east flank of the southern Sawatch Range (Tweto, 1977, 1979). These deposits indicate several kilometers of relative offset between the mountain block and the base of the Dry Union Formation in the rift valley. Consequent streams that formed on the west side of the southern Sawatch Range are deeply entrenched (as much as 1200 m) toward the crest of the range, and their canyons become progressively shallower westward toward the untilted West Elk Mountains. West-tilted uplift of a kilometer or more of the present southern Sawatch Range in late- or post-Miocene time seems inescapable.

4. The linear Gore (southern segment) and Park (northern segment)Ranges (Fig. 1) form a narrow 20–30 km wide block (partly horst, partly tilted fault block) that extends continuously from central Colorado north to beyond the Wyoming state line. Naeser et al. (this volume) demonstrate several successive ages of late Cenozoic deformation and uplift of the Gore Range based on apatite fission-track data and field relations. The overall block rose athwart a series of basins that contain Miocene alluvial deposits of the Troublesome Formation (in Middle Park east of the mountain block, Izett and Barclay, 1973) and Browns Park Formation (in Yampa River basin west of the block, Snyder, 1980). The Miocene deposits are in fault basins adjacent to the mountain block, and clearly existed before the block was uplifted. Snyder (1980) mapped remnants of Browns Park Formation or its equivalents along the bottom of a paleochannel that extends completely across the southern Park Range. Uplift of the mountain block varied from place to place, and at maximum exceeded a kilometer; all of this took place after the Miocene deposits were laid down, and thus in latest Miocene or Pliocene time.

5. This report documents complex geomorphic changes that took place concurrently with later Cenozoic deformation in the area west of the west-central Colorado area of evaporite-related subsidence where major uplift following emplacement of the 10 Ma basaltic lava flows capping Grand Mesa was followed by major erosion and complex local tectonism and related drainage changes (see detailed discussion below). Major deformation thus took place during latest Miocene and Pliocene time all around the periphery of the central Colorado area of evaporite dissolution, and by projection of the Miocene accumulation of basaltic lava flows from the White River uplift across the northern part of that area to Grand Mesa, inescapably took place within the evaporite dissolution area as well. Using the low-relief surface at the base of these flows as a datum, Kirkham and Scott (this volume), Kirkham et al. (this volume), and Lidke et al. (this volume) have documented subsidence of these basaltic flows within the area of salt dissolution, but this local deformation was superimposed on the earlier general uplift.
incised in hard Precambrian rocks at Gore Canyon, and flows into very rugged terrain eroded on sedimentary rocks in the subsided area. These contrasts suggest that evaporite-related subsidence and related headward erosion across a structural saddle in the Gore Range–Park Range block captured the Middle Park drainage at a very late stage in the geomorphic development.

2. Water from the present headwaters area of the Gunnison River did not contribute in any significant way to the evolving erosional patterns of the northern Uncompahgre Plateau until very late in the geomorphic history. A fragmentary but clear-cut paleostream course extends generally northeast for ~110 km out of the present headwaters area of the Rio Grande (Barton et al., 2000), alongs down across the north flank of the San Juan Mountains, and then out onto the plains flanking Tomichi Creek 15–20 km east of the town of Gunnison (Fig. 1). This paleostream existed in late Miocene time as part of a now high-level paleotopography (Steven et al., 1995), and was in existence at 4.5 Ma (Rye et al., 2000). Its headwaters were captured by the present Rio Grande ca. 3–4 Ma (Barton et al., 2000). Capture was a result of major faulting and enhanced erosion related to the Pliocene tilting and uplift of the San Juan Mountain block already described. Elsewhere in the upper Gunnison River drainage basin, upper Tomichi Creek (Fig. 1) flows southwest out of the west flank of the tilted Sawatch Range block to a point opposite the south end of that range, where it makes an abrupt (at least 110°) turn to the west where it becomes a major headwater contributor to the present Gunnison River. This upper course of Tomichi Creek, along with the paleostream course just described, probably are relict segments of an east-flowing dendritic drainage system that was disrupted by the Pliocene uplift of the Sawatch Range tilted block. Evidence that bears on the tectonic and geomorphic history of the Black Canyon of the Gunnison River, and its relation to the evolution of the landscape in the Uncompahgre Plateau–Grand Mesa area is beyond the scope of this report.

3. A stream approaching the magnitude of the present Dolores River did not flow northwest along the southwest side of the Uncompahgre Plateau in late Miocene time (Fig. 1). Hunt (1956a) first suggested that the headwaters of the Dolores River once fed the San Juan River system to the south, and Lohman (1981) later concurred. Headwaters of the modern Dolores River flow south-southwest from the westernmost part of the San Juan Mountains to the vicinity of Cortez. This segment of the Dolores is pointed directly toward a low saddle between Ute Mountain and Mesa Verde (20 km southwest of Cortez) (Fig. 1), and likely once flowed through it to join the San Juan River system just south of the southwest corner of Colorado. The projected course of the ancestral Dolores River is not incised, and I suggest that it may represent the general level of the topography at which the widespread, now incised, meanders on the Colorado Plateau were originally formed. About 15 km northeast of the town of Cortez, the modern Dolores River turns arcuately northwest at an angle of ~135° (Lohman, 1981), and flows in a complex, incised course across the structurally disturbed salt anticline area of the Paradox basin. Entrenched meanders occur at places along the course of the river through the disturbed area. Eventually the Dolores joins with the San Miguel River and the combined rivers flow north-northeast between the La Sal Mountains on the west and the northern Uncompahgre Plateau on the east to join the present Colorado River as a barbed tributary ~30 km into Utah. Entrenched meanders are clearly apparent in this lower, Utah segment of the modern Dolores. I agree with both Hunt and Lohman that the whole course of the Dolores River from near Cortez to its confluence with the Colorado is highly anomalous and bespeaks of capture and diversion; I suggest that the diversion took place before the widespread meanders on all the streams across the Colorado Plateau were superimposed and entrenched, and thus before late canyon excavation began.

A well-preserved, broad paleovalley extends west across the northern Uncompahgre Plateau at Glade Park (Fig. 2) where it is flooded by hard Jurassic and Triassic sandstone units near the present general altitude of ~2000 m. The fairly even crests of the Book Cliffs east of Grand Valley (tilted sandstone units in the Upper Cretaceous Mesa Verde Group) and possible low-relief relicts of a former paleotopography developed across soft, flat-lying early Tertiary strata of the Wasatch and Green River Formations in the Piceance basin (Fig. 1) to the east are at the same altitude level as Glade Park. The surfaces of flat-lying mesas on the eastern part of the Colorado Plateau west of the Uncompahgre Plateau also are near this same altitude.

The rocks east of Glade Park were deformed in early Tertiary time when a broad basin formed to the northeast and the Green River Formation was deposited in the resulting lake. The Redlands faulted monocline (Scott et al., 2001) along the east side of the northern Uncompahgre Plateau just east of Glade Park extends southeast from the area of the Colorado National Monument (Scott et al., 2001) to the vicinity of Cactus Park, where it passes into a southward-diminishing monocline shown by locally steep dips on a younger east-tilted block. Another early Tertiary monocline (Book Cliffs monocline) is marked by tilted strata along the Book Cliffs across the Grand Valley 20 km northeast of Glade Park (Cashion, 1973). The paleovalley at Glade Park and the accordant ridge crests at comparable altitudes in Piceance basin show no appearance of offset by the monoclines, even though the surfaces project across rocks of widely different inclinations, ages, and rock hardness; if these surfaces are indeed relicts of a single ancient topography, the erosion that formed them must have taken place much later than the deformation.

The stream that flowed southwest across Glade Park entered through a broad, low wind gap (Fig. 3) at the eastern margin of the park. I consider the morphology of this gap to reflect erosion by a stream of only moderate size, and certainly not one of the magnitude of the present Colorado River. This assertion is supported in a minor way by the lack of known stream gravels in the vicinity of Glade Park (Charles Betton,
GENERAL HISTORY OF THE UNCOMPAHGRE PLATEAU–GRAND MESA AREA

The general area downstream from the subsided area, embracing the northern part of the Uncompahgre Plateau, Grand Mesa, and adjacent river valleys, contains critical relationships bearing on the late Cenozoic geomorphic and tectonic evolution of a much larger surrounding area. Significant segments of both the Colorado and Gunnison Rivers traverse this area, and these rivers contain most of the surface water now draining west-central Colorado, including all the water now coming from the west-central Colorado evaporite dissolution area.

The dominant feature in the Uncompahgre Plateau–Grand Mesa area is the bold west front of Grand Mesa, which, at near 3000 m altitude, looms as much as 1600 m above the level of the Colorado River at Grand Junction (1400 m altitude). Inasmuch as Grand Mesa is capped by 10 Ma basaltic lava flows (Larson et al., 1975; Marvin et al., 1989), erosion that formed this escarpment inescapably took place in the late Cenozoic. Furthermore, most of this erosion must have preceded the complex geomorphic events recounted below, which are recorded by surficial erosional features that were cut into formations that were then exposed at elevations near the base of the great escarpment.

Regionally, the western front of Grand Mesa is part of a nearly continuous rim that forms the east and north margins of a core area of the Colorado Plateau from which the Upper Cretaceous Mancos Shale was largely stripped down to the harder underlying Mesozoic sandstone units. This rim includes the precipitous west front of Tertiary volcanic rocks in the San Juan Mountains of southwestern Colorado, north across the Gunnison River drainage to the bold west face of Grand Mesa, then to the westward-extending Book Cliffs of western Colorado and central Utah. This removal of Mancos Shale and underlying rocks seems to have been episodic, at least to the extent that two general periods can be recognized: (1) almost all of the main streams that cross the Colorado Plateau have meandering courses (Harden, 1990) that required low stream gradients when they were being formed. Low gradients over such a wide area imply that regional downcutting was at a very low ebb toward the end of the time during which the Mancos Shale was being removed, and (2) these meandering streams were later superimposed on hard underlying rock units (middle and lower Mesozoic sandstone formations and older units), and sharp canyons were cut. Such superposition and accompanying rejuvenated erosion is typical of the late canyon excavation (canyon cycle) that took place throughout the southern Rocky Mountains and Colorado Plateau.

The best evidence about the time of removal of Mancos Shale from the core area of the Colorado Plateau comes from the lower reaches of the Colorado River in the Salton Trough area of southern California and Arizona. Lucchitta (1972, 1990) reported that Cretaceous coccoliths that can only have come from the Mancos Shale have been found in the laterally equiv-

alent Bouse and Imperial Formations of late Miocene–Pliocene age. Fleming (1994) also reported that Pliocene sedimentary rocks in the Imperial and Palm Springs Formations (southern California) contain reworked pollen derived from the Mancos Shale on the Colorado Plateau. Specifically he suggested that erosion of the Mancos in the southern part of the plateau began ca. 4.5 Ma, and in the northern part of the plateau ca. 3.9 Ma (all within the Pliocene). Other evidence indicating that deformation in the western part of the Colorado Plateau may have begun in latest Miocene time and continued into the Pliocene is given by Lucchitta (1990), who summarized evidence that the western part of Grand Canyon was cut between 6 and 1 Ma, and that most likely this was accomplished largely between 5 and 4 Ma (early Pliocene).

Relations at Grand Mesa require that voluminous excavation of shale from the central part of the Colorado Plateau be later than the 10 Ma basaltic flows that cap the mesa. The cliffs of Tertiary volcanic rocks at the west margin of the San Juan Mountains are topographically analogous to the west face of Grand Mesa, and stratigraphically have Oligocene volcanic rocks overlying the Mancos Shale. It is here assumed that the two parts of the same regional topographic rim formed at about the same time and under the similar circumstances. Evidence given earlier in this report indicates that the San Juan Mountains were uplifted largely during Pliocene time.

EVOLUTION OF LATE MIOCENE–PLIOCENE TOPOGRAPHIES IN THE UNCOMPAHGRE PLATEAU–GRAND MESA AREA

Reconstructing the evolving topographies of the Uncompahgre Plateau–Grand Mesa area in the late Miocene and Pliocene from the many scraps of evidence available is difficult. To begin, I will list certain interpretations that have been made that are fundamental to many of the deductions that follow:

1. A major stream approximately commensurate in size with the modern Colorado River probably did not drain out of Middle Park, down through the area of evaporite-related subsidence, and across the Uncompahgre Plateau in Miocene and much of Pliocene time (Fig. 1). A preliminary scan of topographic maps of the structural saddle that joins the Gore and Park Ranges has led to the hypothesis that the Middle Park drainage for much of late Miocene and Pliocene time passed through the wind gap at Gore Pass (southern Park Range), through a sequence of fault-bounded basins containing Browns Park Formation on the west side of the southern Park Range, and into the Yampa River drainage near Steamboat Springs. The wind gap is sufficiently large to have been occupied by a stream of moderate size; the gap is localized on the downthrown side of a fault that appears to be part of a pattern that elsewhere cuts the Browns Park Formation (Tweto, 1979), and thus probably was active during late uplift of the Gore Range–Park Range block. In contrast, the present Colorado River leaves the mature, open topography of Middle Park through a deep, narrow gorge
Grand Junction Geological Society, 1999, 2000, personal commun.). These compounded assumptions suggest that the moderate-sized stream that flowed through Glade Park had a source in soft sedimentary rocks such as those in the Piceance basin, or in the west-central Colorado evaporate dissolution area. It is not clear whether this stream was an early phase of a developing ancestral Colorado River (as suggested by Sinnock, 1981), or was a relatively minor stream whose course was north of such an ancestral river.

South of Glade Park, erosion has obscured relations so that only the broader aspects of the late Miocene–early Pliocene topography can be discerned. If the effects of late uplift (discussed later) are removed, the area of Glade Park seems structurally to have been an extension of adjacent parts of the Colorado Plateau, and it may be a surviving relic of the surface of low relief on which widespread meanders developed along the main streams on the Colorado Plateau.

The enigma of the Glade Park area involves its position with respect to the structural history of northern Uncompahgre Plateau. Scott et al. (2001) interpret that the Redlands fault and associated monocline along the northeast side of Glade Park formed in early Tertiary (Laramide) time as a fault propagation fold above a west-dipping reverse fault exposed only in deep canyons in the underlying Precambrian basement. This is supported by the established early Tertiary age for a similar monocline along the east side of Grand Valley 20 km to the east (Cashion, 1973), and by the early Tertiary (pre-Oligocene volcanic rocks) Cimarron fault along the north flank of the San Juan Mountains 60–100 km southeast of Grand Junction (Fig. 1) (Steven and Hail, 1989). Scott et al. (2001) proposed a similar age for faults along the southwest flank of the Uncompahgre Plateau tilted block.

I question this last interpretation for several reasons: (1) Whereas the southwest-dipping Redlands fault had clear-cut reverse movement, as established by field relations (Scott et al., 2001), faults on the southwest side of Uncompahgre Plateau near Unaweep Canyon have only normal movement according to available geologic maps (Williams, 1964). (2) Whereas compressional stresses can be envisaged during movements on the Redlands fault, I would rationalize the several grabens Williams mapped in the western Unaweep Canyon area as more typically tensional features. (3) Erosional responses to deformation on opposing sides of the northern Uncompahgre Plateau contrast markedly. Mature, broad, shallow valleys flanking non- to only slightly incised, underfit southwestern-flowing streams characterize the Glade Park area (north of the hinge zone shown on Figures 2 and 3). The drainage pattern has only a few minor tributaries joining the main stream course. In contrast, the adjacent area south of the hinge zone is drained by a welter of young, generally north-flowing streams enclosed in sharp, youthful canyons. Many of these narrow, V-shaped canyons are as much as 300 m deep in their midcourses, and these depths diminish to very shallow northward as the mature topography of Glade Park is approached. Strata underlying the mature topography of Glade Park are virtually flat lying, whereas those beneath the young canyons are tilted a few degrees north. Narrow strips of Precambrian rocks are exposed in the bottoms of some of the sharp canyons, but none are exposed on the floor of Glade Park.

I interpret these relations to reflect a two-phased structural-geomorphic evolution of the northern part of the Uncompahgre Plateau. The Redlands faulted monocline formed during early Tertiary (Laramide) time, and separated a flat-floored plateau to the west from a gently sloping structural ramp to the northeast. This ramp in turn was bordered by another northeast-facing monocline (Book Cliffs monocline) in the vicinity of the Book Cliffs (these features are clearly shown by structure contours drawn by Cashion, 1973). A low-relief, mature topography now reflected by the Glade Park area was developed across this terrain, and reached its approximate present configuration some time subsequent to the eruption of the 10 Ma basaltic lava flows that cap Grand Mesa at an altitude that projects over the Glade Park area. The early Tertiary Redlands faulted monocline and associated flat plateau block to the west diminish to the southeast, and cannot be recognized beyond the Cactus Park area (see structure contours drawn by Williams 1964). Subsequently, probably in the late Miocene or early Pliocene, uplift was renewed in the Uncompahgre Plateau area, and a new faulted monocline formed along the southwest side of the major Uncompahgre Plateau tilted block that dips ~2° northeast and encompasses most of the present area of the Uncompahgre Plateau. Only the Glade Park area and the northwest-plunging nose of the plateau that adjoins it to the northwest escaped this late Cenozoic deformation. The approximate position of the subtle hinge zone at the transition between the older and the younger structural blocks is shown on Figures 2 and 3. The late tilting of the younger block triggered development of a multitude of downdip consequent streams that excavated sharp canyons throughout the lateral extent of the tilted block. Unaweep Canyon was formed by antecedent erosion by the only major stream that crossed the tilted block.

**UPLIFT OF THE UNCOMPAHGRE PLATEAU AND EVOLUTION OF UNAWEEP CANYON**

Unaweep Canyon has long been recognized as an abandoned stream channel that was etched deeply across the northern Uncompahgre Plateau, far above the levels of nearby modern rivers that conceivably might have cut it. The unique aspects of Unaweep Canyon have long been recognized, beginning with Peale (1877) a century and a quarter ago. Subsequent investigations are recounted by Hunt (1956a and b), Lohman (1961), and Cater (1966), and will not be summarized here, but inconsistencies in interpretations remain and studies continue. The depth of maximum incision (~1 km) is approximately comparable to the amount of uplift shown by structural contours drawn on the base of the Dakota Sandstone (~840 m) (Wil-
Figure 3. Map of Unaweep Canyon-Cactus Park area showing distribution of features discussed in text. Dotted line outlines Cactus Park. Blank areas underlain by pre-Mancos Shale (predominantly resistant sandstone units) and post-Mancos Shale sedimentary rocks. Grand Mesa capped by 10 Ma basaltic lava flows.
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Abandonment of East Creek is therefore factored out of this discussion of abandonment.

The surface when uplift began was part of the widespread late Miocene topography where streams of low gradient formed meanders along all major streams across the Colorado Plateau. This is shown by the incised meanders in De Beque Canyon upstream from Grand Valley, and by the widespread evidence that erosion west of the Grand Mesa escarpment had cut at least to the level of the lower Mancos, and in places such as Glade Park into underlying Mesozoic sandstone units. The regional surface of the Colorado Plateau after Unaweep Canyon had been cut across the rising Uncompahgre Plateau block appears to have been at the same general level as before, as shown by post-Unaweep meanders that formed along newly established stream courses around the north end of the Uncompahgre Plateau (Ruby Canyon), and along the Gunnison River gorge south of Grand Junction. These meanders formed in Mancos Shale not far below the level of the base of Unaweep Canyon, and above the underlying hard sandstone units in which they are now deeply incised. These new stream courses will be discussed at length in following sections. I thus date erosion of Unaweep Canyon as having taken place concurrent with the rise of a local structural block late during the period of widespread stripping of Mancos shale from the core of the Colorado Plateau when meanders were forming widely along low-gradient streams, and before regional uplift caused canyons to be cut and meanders to be incised throughout the Southern Rocky Mountains and Colorado Plateau.

Cater (1966) documented continued up arching of the Uncompahgre Plateau after the stream that cut Unaweep Canyon had been diverted. The existence of this late uplift is well established, but many details remain to be deciphered. These are still too poorly understood to be discussed further here.

Abandonment of Unaweep Canyon

The former course of ancestral Colorado River from the mouth of De Beque Canyon on the east side of Grand Valley to Cactus Park has been completely removed by erosion so no direct evidence of its position remains. However, the courses of the river above and below these points are about on line, and I presume that the eroded segment followed a similar course. The present course of East Creek north-northeast from Cactus Park follows the same trend, but its grade is steeper than that in Unaweep Canyon just to the west, and its appearance as an incised narrow slot is that of a much younger stream. This opinion is supported by the fact that this segment of East Creek connects the base of a stream course developed during antecedent erosion (Unaweep Canyon) and the base of Grand Valley, which was excavated during the late canyon development. East Creek is therefore factored out of this discussion of abandonment.

Antecedent streams continue to flow only as long as erosion keeps pace with uplift. When uplift exceeds erosion, or when some other factor intervenes, the stream is either diverted or ponded. Evidence and concepts are now available that permit postulating that both of these possible results took place at Unaweep Canyon. Lake sediments (thin-bedded yellow claystone and sandy claystone) are exposed beneath surface wash in gullies and on one 30-40 m high hill near the south end of Cactus Park. These were shown to a group of interested geologists (including me) by Charles Betton, Grand Junction Geological Society. These isolated deposits are near the bottom of the former channel of ancestral Uncompahgre River, and their original thickness and distribution are not known. Samples submitted to U.S. Geological Survey laboratories were examined by Rick Forester (1998, personal commun.) who found no microfossils; neither have any macrofossils been found to date. Thus, it has not yet been possible to determine the age of the deposits.

The chief value of the lakebeds so far has been to indicate that a lake of unknown dimensions did indeed form on the upstream side of the rising Uncompahgre Plateau structural block. These remnants are in the southern tributary of the Unaweep stream system, and all evidence of what happened in the main stream course has long been eroded. I propose that the southern tributary (ancestral Uncompahgre River) apparently flowed for most of its length from its headwaters south of the town of Ouray northward through a valley cut in Mancos Shale on the east side of the Uncompahgre Plateau block. A few miles south of Cactus Park, its course angled west across the lower eastern flank of the rising block, and downcutting superimposed this stretch of the river onto hard underlying sandstone units.

A terrain of unknown character that was underlain by Mancos Shale can be postulated to have formed the interfluve between lower ancestral Uncompahgre River and adjacent segments of the ancestral Colorado River; this terrain marked the lower slope of a great escarpment that then existed at the west end of Grand Mesa. By some unknown means, this divide was breached by the ponded Uncompahgre River water—either by overflow or by headward erosion of a stream from the north—and a new course of the ancestral Uncompahgre River developed along the general position of modern Gunnison gorge south of Grand Junction. This stream attained a low gradient, probably while it was still in the Mancos Shale, and pronounced meanders developed along it; these meanders have since been deeply incised into the underlying hard sandstone units. The level of this low-gradient, meandering stream course cannot be determined directly, but it probably was flowing through Mancos Shale at a level that can be bracketed between the lowest point of the paleostream at Cactus Park (1900 m), and the highest level at which the superimposing stream intersected the top of the Dakota Sandstone along the trend of Gunnison gorge (~1750 m).

A similar situation can be postulated around the north end of the Uncompahgre Plateau at Ruby Canyon. Some time near when Unaweep Canyon was abandoned, a northern tributary of...
an east-flowing dendritic stream system until relatively late in
determined. (2) The paleostream channel that occupied Cactus
River at the northwest end of Cactus Park seems to indicate that this area was originally drained by River in the headwaters of the modern Uncompahgre River south of the town of Ouray, and significant but minor clasts of Precambrian granitoid and gneissoid rocks whose nearest source would have been in the area adjacent to the western part of modern Black Canyon of the Gunnison River. A topographic divide of Tertiary volcanic rocks appears to have separated this last source area from a similar potential source in the headwaters of the Gunnison River that I believe was drained by the east-flowing dendritic stream system described previously. (4) The confluence at the north end of Cactus Park is a peculiar right-angle junction that appears to be abnormal for a stream system that shows evidence elsewhere (De Beque Canyon) for a mature, low-gradient course. Inasmuch as Cactus Park is about on trend with the south projection of the Redlands faulted monocline (see earlier discussion), its position may have been structurally controlled, and may represent merely the last of a series of shifting courses that may have migrated northeastward down dip on the rising Uncompahgre Plateau block (Sinnock, 1981). At present, it seems that the southern tributary here discussed is likely to have been an ancestral Uncompahgre River that had a subordinate tributary extending into the lower Black Canyon area.

Timing of the uplift that led to the antecedent erosion of Unaweep Canyon is fully as important from a regional point of view as the identity of the streams that cut it: It accords closely within the relative sequence of geologic events, but is considerably less well based on an absolute time scale. A very important bit of evidence that has guided much of my thinking is the maximum depth of Unaweep Canyon near the crest of the uplift is ~1000 m, which approximates the structural offset across the faulted monocline shown by structure contours drawn by Williams (1964) on the base of the Dakota Sandstone (~840 m). This measure of offset is taken from contours on strata in the eastern part of the Colorado Plateau near Gateway on the Dolores River to the crest of the uplift adjacent to Unaweep Canyon, and disregards the complex of fault blocks and progressively shallowing dips along the west flank of the monocline. Some of the discrepancy (160 m) between the figures quoted may have resulted from minor entrenchment of the ancestral Colorado River prior to the beginning of uplift of the Uncompahgre Plateau block, but this is unsupported speculation. The approximate concurrence of depth of erosion with structural offset requires that before uplift the area of Unaweep

River is relatively narrow and probably contained a stream smaller than the modern Gunnison River. A marked contrast in morphology exists between the apparently moderate-sized Cactus Park stream channel and the major Unaweep channel that I believed was cut mainly by an ancestral Colorado River.

A question that recurs through all previous investigations concerns what stream or combination of streams eroded Unaweep Canyon. My interpretation here is that an ancestral Colorado River significantly smaller than the present one probably was the main eroding agent in cutting the canyon. This supposition has support from the discovery of high-level gravels of Colorado River provenance ~12 km northwest of Cactus Park near the trend of the hypothesized river (Scott et al., 2001; Scott et al., 2002). This stream probably flowed out of the west-central Colorado area of evaporite dissolution along its approximate present course to modern Grand Valley because there was no other course available to it. Its course across the Grand Valley is problematic: At an early stage it may have flowed through Glade Park (Sinnock, 1981), but if so, it had to have been diverted somehow to the course now occupied by Unaweep Canyon. Erosion has completely removed all evidence for or against such hypothetical reconstructions. Wherever the course may have been, it probably had a low gradient, as indicated by the now-incised meanders in the sandstone beds of the Mesa Verde Group at De Beque Canyon northeast of Grand Valley (Cashion, 1973), which were formed at this time.

A tributary from the south joined this ancestral Colorado River at the northwest end of Cactus Park. Cater (1966) postulated that this stream was an earlier version of the Gunnison River. I challenge this interpretation for several reasons: (1) As explained earlier, my studies in the Gunnison River headwaters area seem to indicate that this area was originally drained by an east-flowing dendritic stream system until relatively late in the geomorphic history of the area. Just how late is still to be determined. (2) The paleostream channel that occupied Cactus Park just south of its confluence with the ancestral Colorado


liams, 1964), so that uplift and erosion seem penecontemporaneous and related, as typical for an antecedent stream.
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other investigators. I will consider only the succession of gravel-covered sloping surfaces (pediments) on the lower slopes of the west-facing Grand Mesa escarpment. The gravels consist dominantly of cobble-to-boulder-sized clasts of basaltic rock from the capping rim of Grand Mesa, with lesser quantities of sandstone and other lithologies. Cole and Sexton interpret these deposits as having been emplaced as mudflows or debris flows. I lack capability to comment on their assignments of these pediments to pre-Bull Lake, Bull Lake, and Pinedale glacial stages, and will deal only with the age relations of the pediments relative to each other, and to the sequence of geomorphic and structural events I have interpreted previously in this report. Except for the highest and oldest pediment, the successively younger pediments are inset one below another within stream valleys that are aimed directly at erosional gaps in the hard sandstone ridge that forms the east wall of the Gunnison gorge. The oldest (highest) pediment can be traced from its head at >2000 m altitude on the slopes of the Grand Mesa escarpment, down as continuous tongues, then into isolated remnants near the topographic low at the base of the escarpment (at 1700 m altitude). An isolated small remnant no more than a few tens of meters across is located 4.3 km farther west along the crest of the sandstone ridge that marks the east side of Gunnison gorge; this remnant is at about the same altitude as the remnants of the pediment just to the east, and the base of the remnant is inclined east at ~4°. Exposures are poor on the remnant, and no internal sedimentary features can be seen. I have made several visits to this site, alone and in company with other geologists. I have interpreted these described relations to indicate late eastward tilting along the eastern fringe of the Uncompahgre Plateau structural block; companions on these visits have had reactions that ranged from outright disbelief, to skepticism, to partial agreement. By my interpretation, the pediment developed after the Gunnison gorge diversion of ancestral Uncompahgre River had been accomplished and attendant erosion had removed all Mancos Shale above the level of the isolated remnant, but still within the time that the Uncompahgre block was tectonically active. Whether my interpretation is right or wrong, dating the age of the oldest pediment would provide a valuable marker point in the early history of late canyon excavation.

The nested younger pediments that point toward the erosional gaps in the east wall of the Gunnison gorge are easily explained as reflecting successive stages in downcutting of the river that was flowing through the gorge. The youngest pediment appears to project a few tens of meters above the present level of the Gunnison River. Age determinations on any of these pediments would be valuable and in determining the time and rate of incision, which are so needed by those interested in the history of dissolution in the west-central Colorado subsided area. (Note added in proof: Recent work by several members of the Grand Junction Geological Society, faculty members of Mesa State College, and others has found occurrences of Lava Creek B ash from the Yellowstone Park area that can be related to these pediments and to other young geomorphic features. I eagerly await publication of their results.)

Cole and Young (1983) have suggested that Unaweep Canyon was occupied by glaciers during middle and perhaps late Pleistocene time, citing the presence of U-shaped valleys, truncated spurs, cirques, hanging valleys, and scattered patches of till as their evidence. This proposal has elicited much discussion, and the status of their hypothesis is still in limbo. Based on several brief personal visits, I am greatly impressed by the glacial morphology described by Cole and Young, and a careful study of topographic maps has convinced me that the glacial hypothesis has merit. A solution to this problem is important here because of the relationship between the proposed glaciation and the last vestiges of tectonic uplift of the Uncompahgre Plateau, as well as its bearing on the origin of the canyon of East Creek downstream from Cactus Park, which cannot be established without the validity of the glaciation hypothesis being proven or discounted. No satisfactory solution to this controversy can be achieved by theoretical speculation; additional fieldwork is the only reasonable alternative.

SUMMARY

The late Cenozoic was a time of tectonic unrest in the area of the Southern Rocky Mountains surrounding that part of west-central Colorado where evaporite dissolution caused widespread subsidence. This tectonism began in the latest Oligocene and earliest Miocene with inception of block faulting along the trend of the Rio Grande rift, and extended, now here, now there, throughout the Miocene, and reached a maximum in the Pliocene and early Pleistocene. Two structural patterns developed: (1) high, narrow horsts with adjacent deep grabens or half-graben troughs (the Sangre de Cristo Range horst bordered by the Wet Mountain Valley graben on the east and the San Luis Valley half graben on the west, and the Gore Range–Park Range block bordered on its southern half by a graben on the east are the best examples) (Fig. 1), and (2) large tilted blocks ranging from a few tens of kilometers to a few hundreds of kilometers across that extend from the Great Plains of eastern Colorado westward to the Basin and Range province in western Utah.

Tilted blocks predominate north, south, and west of the west-central Colorado evaporite dissolution area, where they are recognized in the White River uplift, Sawatch Range, San Juan Mountains, and Uncompahgre Plateau. Tilting generally produced dips of only a few degrees, but across the width of the large blocks these dips resulted in structural discordances of several kilometers. Tilt directions are diverse: The White River uplift block is inclined to the north, the southern part of the Sawatch Range inclined to the west, the San Juan Mountain block inclined to the east, and the Uncompahgre Plateau block inclined to the northeast.

Just east of the evaporite dissolution area, the narrow Gore Range–Park Range block changes character markedly from one part to another. The southern part of the Gore Range is narrow
the Colorado River west of the Uncompahgre Plateau eroded headward through soft Mancos Shale, around the plunging north nose of the plateau, and then south to capture the ancestral Colorado somewhere northeast of Unaweep Canyon. The level of this capture was above the point where later incision superimposed the stream through the Mancos Shale onto the underly­ing Dakota Sandstone at Ruby Canyon. At the time of cap­ture, this stream also had achieved a low gradient, as shown by the well-formed meanders that were later deeply incised at Ruby Canyon during late regional excavation of canyons.

The precise timing of the capture of the Colorado River northeast of Unaweep Canyon described above relative to the abandonment of that canyon and subsequent diversion of ancestral Uncompahgre River down its new course is difficult to establish. I prefer the hypothesis that capture preceded deposition of the lake sediments along lower ancestral Uncompahgre River, and that such capture caused instantaneous abandonment of Unaweep Canyon. Erosion by ancestral Uncompahgre River waters alone would not have been sufficient to maintain flow across the rising structural block, and they became ponded in a progressively deepening lake that eventually was drained down a new course along the trend of the modern Gunnison gorge.

LATE CANYON EXCAVATION

Young, steep-walled canyons occur throughout the Southern Rocky Mountains and Colorado Plateau, and broad valleys excavated in soft sedimentary rocks of the adjacent Great Plains of eastern Colorado are graded to the base of these canyons where they emerge from the mountains. These canyons and valleys represent what Lee (1923) called his “canyon cycle of erosion,” and are clearly apparent in the Uncompahgre Plateau–Grand Mesa area discussed here. In the Front Range–Great Plains area where erosion can be tied to deformation, Steven et al. (1997) proposed a two-phase evolution of the present landscape, with deformation in middle Miocene and again in latest Miocene to Pleistocene, and the canyons were formed during the latter period. I no longer ascribe to all aspects of this proposal (Steven, unpub. mapping), but believe that the deformation that began in the Front Range in middle Miocene continued episodically at an irregularly increasing rate and expanding area of involvement until well into the Quaternary. The canyons were probably eroded largely during the Pliocene after the Ogallala Formation ceased to be deposited on the Great Plains (latest Miocene or earliest Pliocene–middle Hemphillian time).

No such extended transition was noted in the San Juan Mountains (Steven et al. 1995), where canyons were eroded directly into an earlier paleotopography as the whole mountain block was being tilted up to the west. Tilting and rejuvenated erosion began sometime between 4.5 and 3.5 Ma (Rye et al., 2000), and the canyons appear to have been eroded largely during the Pliocene and early Pleistocene. This timing is close to that of the less precisely dated events interpreted for the Front Range–Great Plains area, and to that proposed by Lucchitta (1990) for Grand Canyon far to the west.

Canyon excavation in the Uncompahgre Plateau–Grand Mesa area seems analogous to that within the San Juans, as no transitional erosional stages have been recognized. I am reluctant to extrapolate specific San Juan age relations to this area without supporting data, but suggest that the approximate conformity of ages from the Front Range, San Juan, and Grand Canyon area makes an early Pliocene age for the beginning of canyon erosion in the Uncompahgre Plateau–Grand Mesa area a likely possibility. Although deformation and accentuated erosion (canyon excavation) are closely linked in both the Front Range and San Juan Mountains, no such tie has yet been established in the area being considered here. Such a link has not been eliminated, just not yet proven.

How deep were the canyons eroded? In the Grand Valley, the present level of the Colorado River at Grand Junction is at 1400 m altitude, 600 m below the level of Glade Park at 2000 m. De Beque Canyon northeast of Grand Junction is now 400 m deep, but this is only a minimum measure of the original depth of the canyon. Another minimum measure is the depth of Gunnison gorge south of Grand Junction where the canyon walls are now as much as 250 m high; the true depth of incision cannot now be determined, but it had to have been <400 m to be below the level of the prior stream course at Cactus Park. The Dolores River on the southwest side of the Uncompahgre Plateau below the San Miguel River junction is ~400 m below nearby rims on adjacent mesas; this difference is close to that between the Dolores and the base of the original Unaweep Canyon to the east. The terrain along the incised drainages varies widely, depending largely on the resistance of the wall rocks to erosion. Soft Mancos Shale forms the flanks of broad valleys such as Grand Valley, whereas steep walls formed where hard sandstone units are exposed. Incised meanders are clearly recognizable where the walls are of hard rocks, but generally have not been preserved where the wall rocks are soft.

The time span of canyon cutting has not been determined yet. The deep canyons along the Colorado River downstream from the subsided area provided the outlet for the dissolved salts from the west-central area of salt dissolution (Chafin and Butler, this volume) and the progressively lowering base level during canyon erosion was a major control on the quantity of solute removed and rate of resulting subsidence. Scott et al. (2002) summarized data from several sources indicating that volcanic ash either positively or possibly identified as the Lava Creek B unit (age 639 ka, Lanphere et al., 2002), derived from Yellowstone National Park area, occurs at levels 80–91 m above modern streams. They thus calculated valuable incision rates bearing on this problem. Additional age control in the history of canyon excavation would be very desirable, and suggestions are given below on where such data might be obtained.

Cole and Sexton (1981) summarized the age and stratigraphic relations of surficial deposits in and around the Grand Mesa area, and tabulated the age assignments made by several
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and high, and is a true horst being bounded on both sides by steep linear faults. The northern part of the Gore range and the southern part of the Park Range are lower and form a structural saddle in the overall uplifted area; this saddle in part is transitional into an east-titled block, and the Rio Grande rift to the east ceases to be a recognizable feature in the landscape. The northern part of the Park Range is again a high horst block, but this in turn becomes a broader and lower north-titled block as it approaches the Wyoming state line.

Uplift versus downfaulting (or warping) can be measured in a rough way by relations of the alluvial formations that were deposited widely during the Miocene. These deposits are in fault blocks adjacent to many of the uplifted structural blocks, and they are inclined along with interlayered volcanic rocks on the backs of some of the tilted blocks. These alluvial deposits not only help in estimating the amount of local structural uplift and depression, but they give evidence on the times when local deformation took place. Some faulting took place during alluviation, but most deformation seems clearly to postdate alluviation. Pliocene seems to be the time when tectonic uplift and rejuvenated erosion were most active.

The differential jostling of local blocks during the Pliocene was an aspect of a regional uplift of the whole Southern Rocky Mountains–Colorado Plateau area, and the resulting erosion reflects the local sums of regional and local tectonic events. In most areas, uplift exceeded local downwarping or faulting, and young canyons of varied depths are widespread (thus the “canyon cycle” of Lee, 1923). In a few places (most notably San Luis Valley), east-tilted downfaulting depressed the surface below local base level, and alluviation resulted. Not surprisingly, the highest parts of all the structural blocks active during this late period of tectonic activity are the areas most extensively and deeply eroded. Miocene alluvial deposits in the structurally deformed troughs commonly extend well below local stream levels. This widespread correspondence between structural level and depth of erosion demands a genetic link.

The evidence for widespread young tectonism and related erosion throughout the Southern Rocky Mountains indicates that the present mountainous topography was formed largely by erosional etching of jostled late Cenozoic structural blocks. Inherited aspects can be recognized where late structural blocks are superimposed on older Laramide uplifts (Kellogg et al., 2000) but in most places the diverse internal geologic relations displayed within each block are reflected in modern topography more by rock hardness than by geologic history. Climate changes are real, and are amply demonstrated by human experience and by scientific evidence from the more remote past. However, they affect the rate and type of erosion more than they do the extent (depth) of erosion, which is limited ultimately by tectonically controlled base levels. We lack time controls sensitive enough to differentiate many of the varied effects of these competing influences.

ACKNOWLEDGMENTS

The late Fred W. Cater first introduced me to the fascination of Unaweep Canyon during several long discussions we had while he was preparing his 1966 contribution on its origin (Cater, 1966), and I served as technical reviewer on the completed manuscript. Although the conclusions given here differ in many ways from Fred’s, they depend greatly on data and interpretations presented by him.

My late colleague Ogden Tweto and I shared personal geologic avocations on the geomorphic evolution of the Southern Rocky Mountains for > 40 yr, and I have benefited greatly from our association. I have also benefited from many discussions on the geomorphology of the Southern Rocky Mountains with Glen Scott and Richard Taylor. James Ratté and Peter Lipman were at different times close associates of mine in studying the bedrock geology of the San Juan Mountains. Robert Scott and I have beneficially belabored the geology and geomorphology of west-central Colorado many times. I have participated in field conferences in the Unaweep Canyon area with Emmett Evanoff (University of Colorado), and Glenn Miller, Charles Betton, and William Hood (Grand Junction Geological Society). All these people, and many others too, have shared their knowledge and ideas with me, and I thank them deeply.

The conclusions and interpretations given are mine alone, and I am fully aware that many do not represent consensus opinions.

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