Pleistocene drainage changes in Uncompahgre Plateau-Grand Valley region of western Colorado, including formation and abandonment of Unaweep Canyon: a hypothesis

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PLEISTOCENE DRAINAGE CHANGES IN UNCOMPAHGRE PLATEAU-GRAND VALLEY REGION OF WESTERN COLORADO, INCLUDING FORMATION AND ABANDONMENT OF UNAWEEP CANYON: A HYPOTHESIS*

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INTRODUCTION

This paper presents a model for geomorphic changes that culminate in the present landforms of the Uncompahgre Plateau and Grand Valley region of western Colorado (fig. 1). This model is but one of an infinite number of possible solutions to the problem of geomorphogenesis in the study area; it can be no more.

Figures 2, 5 and 7 through 11 present the landform development as a series of schematic cross sections and maps representing a seven-stage evolutionary sequence. The following narrative outlines the evolutionary hypothesis as a continuum of changes and stresses the conditions represented on the figures. More detailed discussion is available in Sinnock (1978). See Figure 1 of companion paper (Sinnock, this guidebook) for a location map of geographic names referred to in the following discussion.

*Field activities were performed during the summers of 1976 and 1977 while the author was attending Purdue University. Preparation of this manuscript was supported by the U.S. Department of Energy

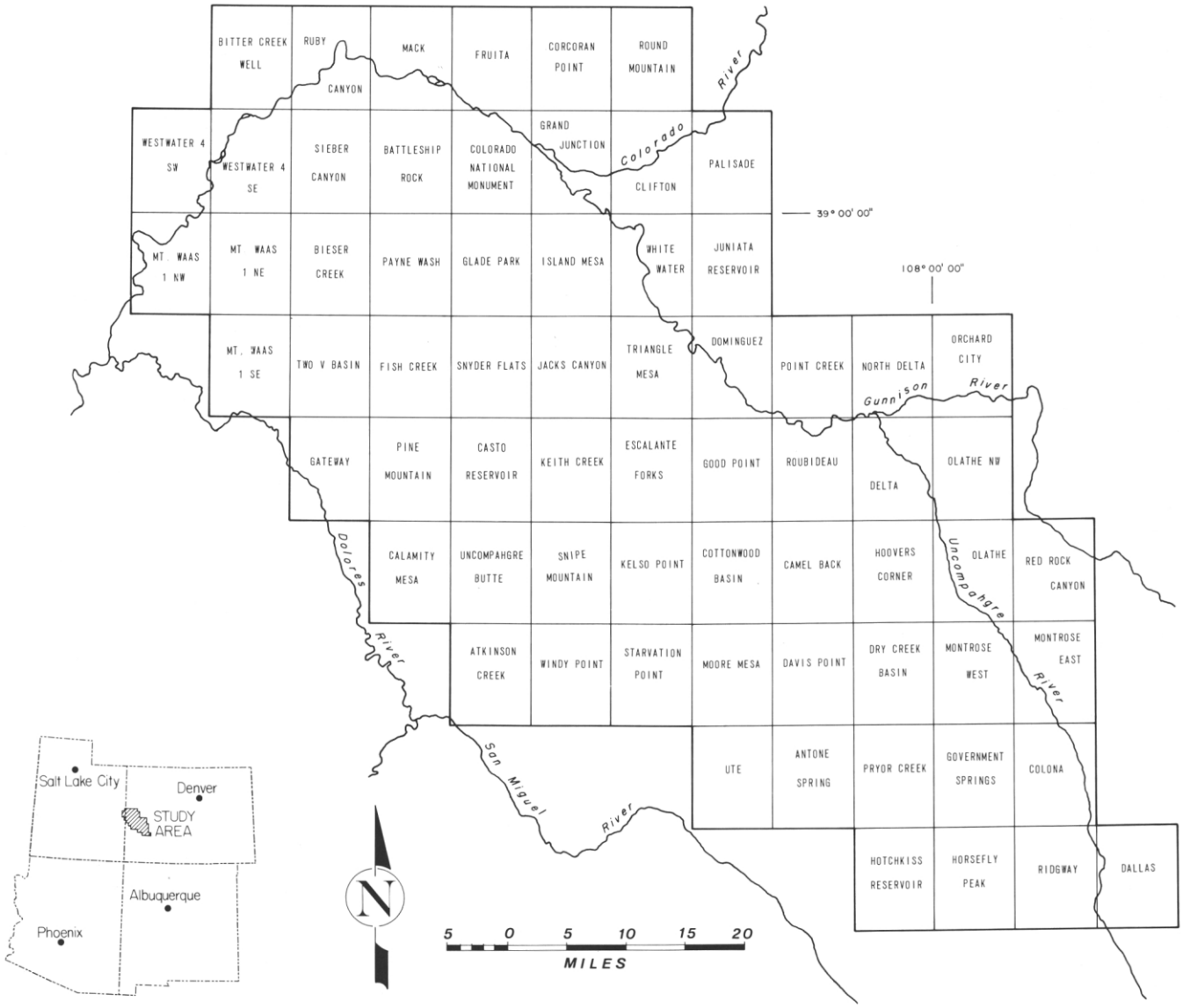
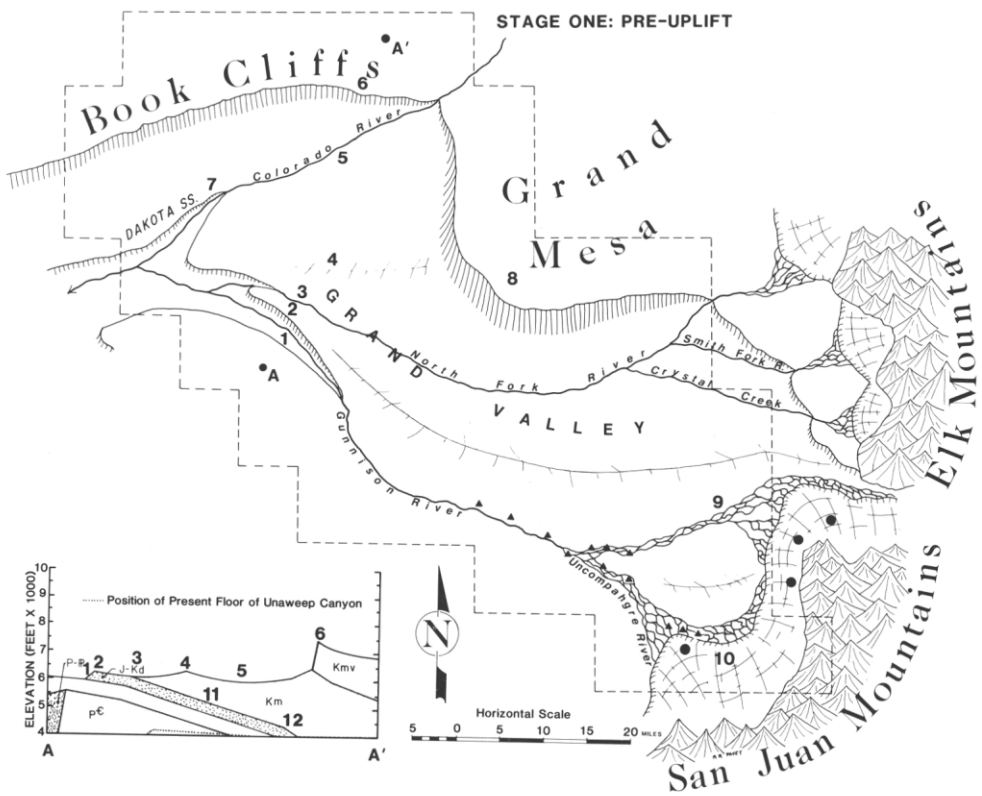


Figure 1. Study area, including an index of 7½ minute topographic quadrangles. The dashed outlines on Figures 2, 5, and 7–11 correspond to the boundary of the index map.



Key to map and cross section:

1. Gunnison River flows on Triassic sandstone surface northeast of present Uncompahgre fault scarp. Surface corresponds to present-day Massey Bench, Leonards Ridge and Bug Point.
2. Embayment into Dakota cuesta extends along Gunnison River.
3. North Fork River occupies strike valley nestled at Dakota–Mancos contact upstream from small embayment into Dakota cuesta.
4. North Fork and Colorado basins are separated by low pediment divide on Mancos Shale.
5. Colorado River flows on Mancos Shale at about 6,000 ft elevation in vicinity of present-day Glade Park.
6. Book Cliffs are about 1,000 ft high and 10 to 15 mi south of their present location.

Key to map only:

7. Colorado River cuts embayment into Dakota cuesta in vicinity of modern Glade Park.
8. Grand Mesa extends to about present Gunnison Canyon between Delta and Whitewater.
9. Gunnison River flows from Cerro Summit area and joins Uncompahgre River near present bifurcation of Dry Creek.
10. Horsefly Peak glaciers extend 8 to 10 mi northwest of San Juan Mountains.
    Solid triangles represent deposits of volcanic-provenance outwash gravels preserved as low hills rising above Dakota uplands of present Uncompahgre Plateau.
    Solid circles represent till deposits preserved at Horsefly Peak, Cerro Summit, and along flank of Cimmaron Ridge.

Key to cross section only:

11. Structural gradient slopes northeastward about 65 ft/mi toward Piceance Basin.
12. Book Cliff Monocline is slightly southwest of Book Cliff topographic scarp.

Figure 2. Physiographic diagram and cross section of conditions at the time of Stage One: pre-uplift.

GEOMORPHOGENESIS

The analysis begins before the Uncompahgre Plateau existed as a structural or topographic feature. At this time, the Grand Valley, San Juan and West Elk mountains, Colorado, Uncompahgre, Gunnison, and North Fork rivers, Grand Mesa and the Book Cliffs were present, though not in their current forms nor locations (fig. 2). Piedmont glaciers flowed from the San Juan Mountains onto a gentle slope of Mancos Shale at the head of ancestral Grand Valley. One glacial lobe terminated near present-day Horsefly Peak on the Uncompahgre Plateau and deposited the till preserved there today (figs. 2, 3). Another lobe deposited correlative till in the Cerro Summit area and perhaps near Paonia. Glacial meltwater poured from the ice front along anastomosing outwash channels of the ancestral Gunnison, Uncompahgre and North Fork Rivers. The ancient Gunnison flowed from the Sawatch Mountains, past the Cerro Summit ice front and joined the ancestral Uncompahgre River near the present bifurcation of the two forks of Dry Creek on the flank of the Uncompahgre Plateau. The Uncompahgre River flowed to its Gunnison confluence from the ice front located in the Horsefly Peak region. At this time, the ancestral Colorado River emerged from the Book Cliffs near the present townsite of Grand Junction. The Colorado flowed up-dip through about 600 m of Mancos Shale, breached a cuesta capped by Dakota Sandstone, and flowed out of the study area on a surface of Triassic sandstone.

Outwash terrace gravels of the ancestral Gunnison and Uncompahgre rivers are partly preserved on low hills, some cored with Mancos Shale, rising above the present Dakota Sandstone surfaces of the Uncompahgre Plateau (figs. 2, 4). The Uncompahgre outwash occurs near Johnson Reservoir and east of Dry Creek; the Gunnison gravels are found between the two forks of Dry Creek and at the upper end of Roubideau Creek. Presumably outwash was deposited along the entire courses of the ancient anastomosing Gunnison and Uncompahgre meltwater channels. However, in the region between the ancient Cerro Summit and Horsefly Peak glaciers, the gravels were deposited on thick Mancos Shale and were subsequently cannibalized as the rivers cut into the underlying shales.

Figure 3. Till deposits on Horsefly Peak. View is to the north from SE ¼, Sec. 35, T.46N., R.10W.

Figure 4. Outwash gravel-capped hill on uplands of Uncompahgre Plateau. View is to the northeast from Colorado State Road 90, NE ¼, Sec. 10, T. 47N., R.11W.

Downstream from the confluence, the ancestral Gunnison River flowed northwest, along the Dakota-Mancos contact while descending from an elevation of about 8,000 ft near the ice front to about 6,500 ft 30 mi downstream*. Upstream from the confluence the ancestral Gunnison transected about 450 m of Mancos Shale. A Triassic sandstone bench occurred along the ancestral Gunnison River below its embayment into the Dakota-capped cuesta. Remnants of this bench are preserved southwest of the present Uncompahgre fault scarp at Massey Bench, Leonards Ridge and similar areas and northeast of the fault between outliers of Dakota Sandstone such as Uncompahgre Butte and Monument Hill. This bench is preserved also at the southern end of Palisade Butte, 1,500 ft above the present Dolores River near Gateway. The confluence of the Gunnison and Colorado rivers was near the present confluence of Granite Creek and the Colorado River north of Moab. Hence, the ancestral Gunnison River crossed the inactive Uncompahgre fault zone near the present location of Columbine Pass.

North Fork River flowed around Grand Mesa, whose cliffs were approximately where the present Gunnison River is entrenched into the flank of the Uncompahgre Plateau. Upstream from its embayment through the Dakota Sandstone cuesta, North Fork stripped the lower part of the Mancos Shale from the Dakota surface. Downstream from the embayment the North Fork joined the Gunnison on the Triassic sandstone bench near Gateway. Just above the confluence, the North Fork flowed across the inactive Uncompahgre fault zone near the present mouth of Unaweep Canyon.

At the time of these conditions no Precambrian rocks were exposed in the study area and uplift of the Uncompahgre Plateau had not yet begun. An isostatic monocline similar to the one today occurred southwest of the Book Cliffs and Grand Mesa. Stresses from isostatic compensation migrated northeastward with the retreating cliffs. After the cliffs migrated past the southwestern edge of the late Paleozoic Uncompahgre Highland, compensating stresses were focused along the ancient Uncompahgre fault zone contributing to its renewed movement.

When uplift began (fig. 5), the part of the ancestral Gunnison River above Columbine Pass was trapped on the raised side of the fault. The reentrant into the Dakota Sandstone cuesta was abandoned as tilting associated with the uplift forced the river to pond and spill northeastward to a new position along the Dakota-

*All elevations are expressed in terms of present day sea level. True elevations of past times are unknown, but relative heights defined by elevation differences are unaffected by the chosen reference horizon. English units are used because the source data from topographic maps are so expressed.

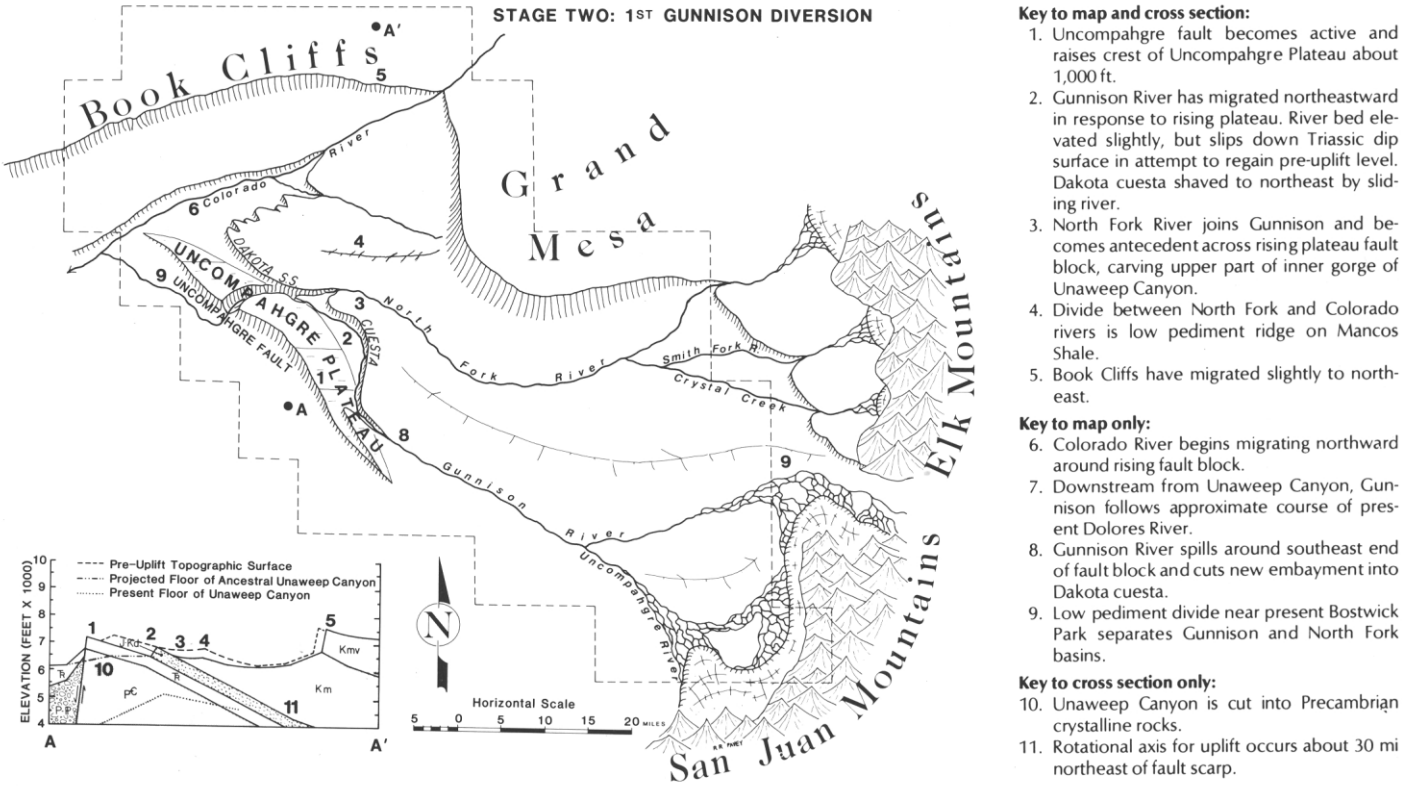


Figure 5. Physiographic diagram and cross section of conditions at the time of Stage Two: 1st Gunnison Diversion.

Figure 6. Perched ancestral Gunnison River Valley near Smith Point on the Uncompahgre Plateau uplands. View is to the north from NW ¼, Sec. 13, T.15N., R.16W.

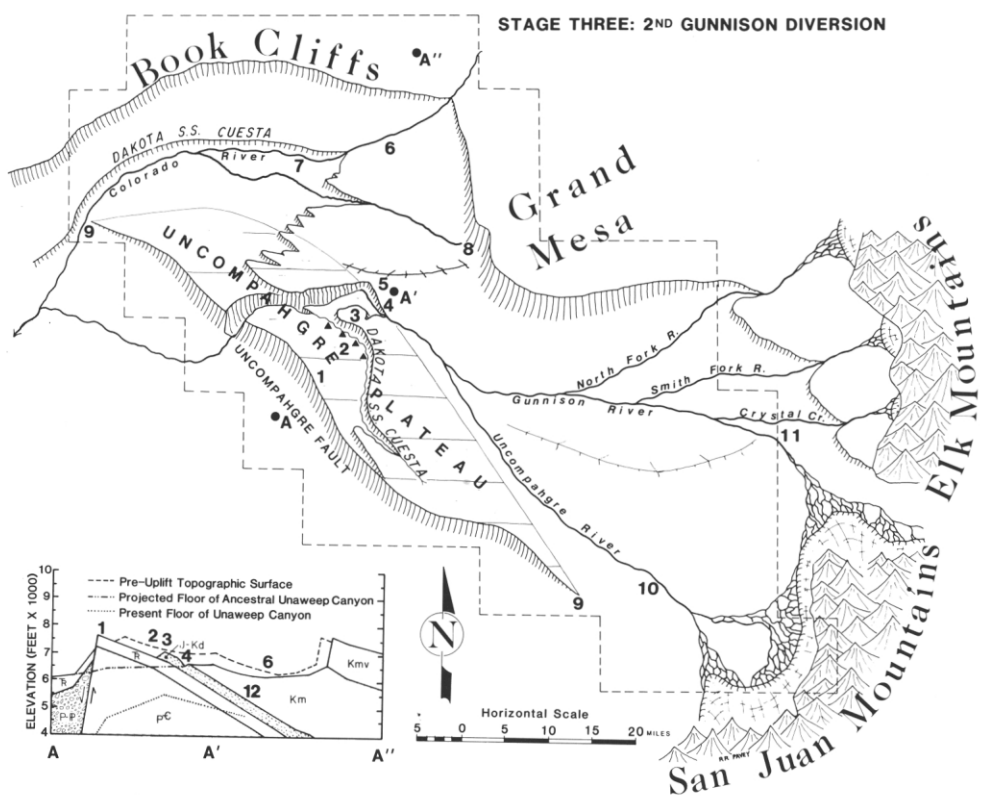
Mancos contact. A new reentrant through the cuesta formed near the present location of a perched valley between Snipe Mountain and Uncompahgre Butte. Below the cuesta the river migrated to the northeast on the Triassic sandstone, shaving Morrison shales and Dakota Sandstone from its northeastern valley wall (fig. 6). The North Fork joined the Gunnison on the Triassic sandstone bench where they began cutting the upper parts of Unaweep Canyon. As uplift continued, antecedence deepened and extended the Unaweep gorge headward. After 600 to 700 ft of uplift, the Precambrian surface was encountered and entrenched (fig. 5). Upstream from the gorge the Gunnison migrated down-dip on the Triassic bench to the vicinity of Gill Creek. After headward extension of the gorge passed the ancestral Gunnison-North Fork confluence, entrenchment into the Triassic rocks occurred along the present stretch of Gill Creek between Casto Reservoir and Unaweep Canyon. The current anomalous up-dip flow of this small, ephemeral stream is inherited from the course of the Gunnison at this time.

The Colorado River was relatively unaffected during the initial phases of uplift. Its embayment into the Dakota Sandstone cuesta expanded by normal headward migration. Below the cuesta the Colorado shaved the cuesta scarp, enlarging the Triassic Sandstone bench in Glade Park.

An axis of structural rotation during uplift was located at the approximate site of the present Dakota Sandstone-Mancos Shale contact in Grand Valley. Thus 1000 ft of uplift at the plateau crest corresponded to only a few hundred feet near the head of the cuesta embayment along the ancestral Gunnison River. Similar reductions in the amount of uplift occurred along all transects from the crest of the rising plateau to the Dakota-Mancos contact in Grand Valley. The ancestral Colorado River and other master streams in the area approximately maintained a constant elevation during uplift. The Colorado flowed quasi-normal to strike, and eroded vertically a few hundred feet into the rising shales of Grand Valley. The Gunnison and North Fork rivers flowed quasi-parallel to strike and shifted laterally along the contact between the Dakota Sandstone and Mancos Shale in order to remain graded to the Colorado. Downstream from Gateway, the ancestral Gunnison River retained its former course along the present position of the Dolores River, but flowed about 1500 ft above the present river level.

Glaciated headwaters of the master streams were relatively unaffected by the Uncompahgre fault. Figure 5 indicates a slight retreat of the Cerro Summit-Horsefly Peak glaciers only because glaciation in general is characterized by alternating advance and retreat of the ice, and it is inferred that a glacial event as significant as the Horsefly Peak glaciation was characterized by more than one advance-retreat episode.

When the plateau crest had risen about 1,000 ft, the ancestral



Key to map and cross section:

1. Crest of plateau has risen about 1,500 ft.
2. Gunnison River abandons course along plateau crest. Ancestral Gill Creek occupies abandoned valley.
3. Salient develops along Dakota cuesta north of abandoned Gunnison Valley, as
4. Embayment into cuesta migrates headward along new Gunnison's course.
5. Distance decreases between Gunnison River and pediment divide separating Gunnison and Colorado basins.
6. Colorado River incises into Mancos Shale while remaining at about same elevation above sea level.

Key to map only:

7. Colorado River migrates northward around rising plateau and planes Triassic sandstone bench in Glade Park.
8. Ancestral Kannah Creek begins notching embayment into Grand Mesa.
9. Uncompahgre fault laterally expands to northwest and southeast.
10. Uncompahgre River headwaters are isolated from Gunnison River because
11. Gunnison River spills across low pediment divide into upper North Fork basin.

Triangles represent deposits of agatized gravels eroded from Dakota cuesta deposited in valley of underfit Gill Creek near modern Casto Reservoir.

Key to cross section only:

12. Thickness of Mancos Shale is decreasing in area of present Uncompahgre Plateau.

Figure 7. Physiographic diagram and cross section of conditions at the time of Stage Three: 2nd Gunnison Diversion.

Gunnison and North Fork basins were separated only by a low divide perched upon a thin layer of Mancos Shale upstream from their respective reentrants through the Dakota Sandstone cuesta. Below the cuesta the Gunnison was impeded from rapid homoclinal migration by the cuesta scarp and was ponded because it was unable to maintain grade by lateral migration down the dip slope of the Triassic surface as the plateau rose. In response, the Gunnison abandoned its course along present Gill Creek by spilling into the North Fork basin upstream from the cuesta (fig. 7). A new confluence with the North Fork formed near the lower end of present Dominguez Canyon. The resulting embayment into the Dakota Sandstone cuesta extended headward at a position up-dip from present Horse Mesa, isolating a ridge of Dakota Sandstone between two regions of Triassic sandstone benches. The remnants of this ridge are now low hills rising above the Triassic sandstone bench northeast of Casto Reservoir. Downstream from the cuesta the river turned southwest and eased into the deepening and lengthening inner gorge of Unaweep Canyon.

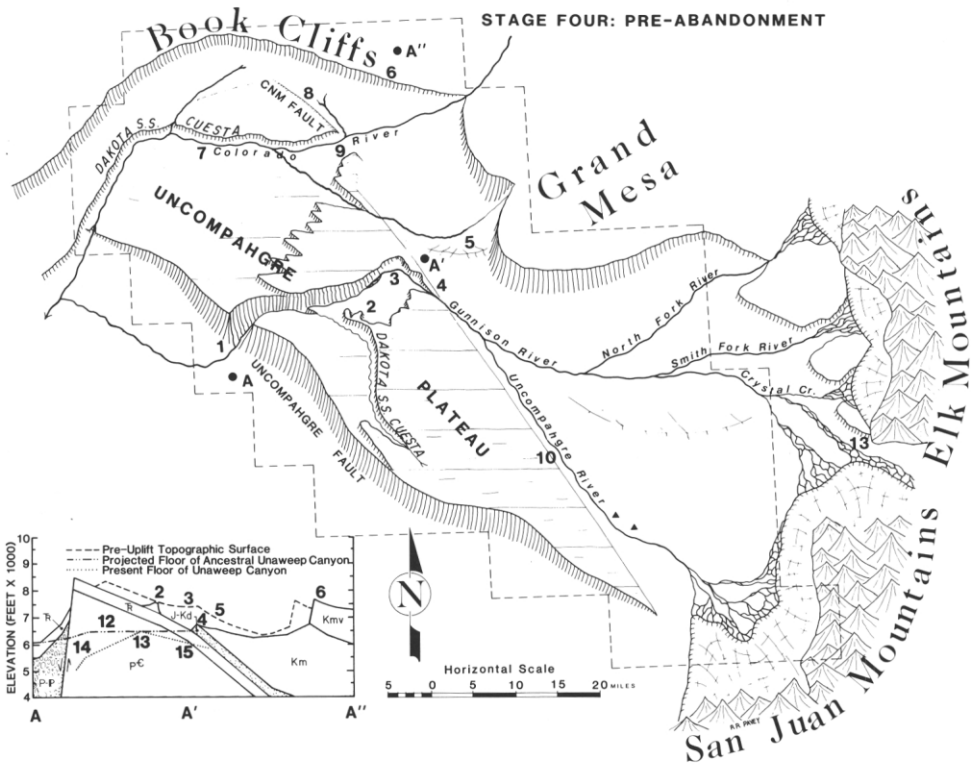
The abandoned Gunnison Valley near the plateau crest was occupied by ancestral Gil l Creek. Where it crossed the cuesta scarp, Gill Creek eroded agatized c lasts from Dakota conglomerates and deposited them along its underfit course below the cuesta. These deposits are preserved near Casto Reservoir and shown by triangles on Figure 7.

As the plateau rose it also impeded the flow along the upper courses of the Gunnison River. As a result the partially dammed Gunnison spilled across a low divide on Mancos Shale upstream from its confluence with the Uncompahgre River and occupied the lower parts of the North Fork basin, where it captured the lower courses of ancestral Crystal Creek and Smith Fork River (fig. 7).

As uplift proceeded, the Gunnison and Uncompahgre rivers continued to homoclinally migrate northeastward, stripping the Dakota Sandstone surface of the Uncompahgre plateau. Retreat of the Book Cliffs and Grand Mesa accompanied the river migrations, but at a lesser rate, resulting in steepened slopes.

At some time after the ancestral Colorado River had planed a considerable part of the Glade Park surface, uplift commenced along the fault at the Colorado National Monument. During early stages of this uplift, the Colorado was able to maintain its course across the newly uplifted terrain and planed the Dakota and underlying Jurassic rocks from the Triassic sandstones in the vicinity of present Little Park (fig. 8). This brief period of antecedance separated the Dakota-capped uplands northwest of Unaweep Canyon from those northeast of Glade Park, while preserving the continuity of Dakota Sandstone down-dip from the fault. A tributary, ancestral Kannah Creek, flowed to the Colorado from Grand Mesa and through a notch into the Dakota cuesta at the location of present headwaters of Northeast Creek.

The embayment into the Dakota cuesta along the Gunnison River likewise migrated northeastward. Below the cuesta, the river stripped Jurassic and Cretaceous rocks from the present outer valley of Unaweep Canyon. The inner Unaweep gorge concurrently lengthened headward. The ridge of Dakota Sandstone down-dip from Gill Creek was reduced in area by headward abstraction



Key to map and cross section:

1. River in Unaweep Canyon is graded to Triassic sandstone surface on present Palisade Butte.
2. Salient along Dakota cuesta between old courses of Gunnison River is eroded at heads of dip-slope tributaries to Gunnison.
3. Head of inner Unaweep gorge has migrated about 4 mi northeastward.
4. Embayment into Dakota cuesta has likewise migrated northeastward to southwest edge of modern Horse Mesa.
5. Only low pediment divide on Mancos Shale separates Colorado and Gunnison basins.
6. Book Cliffs continue to retreat to northeast.

Key to map only:

7. Colorado River continues to migrate northward in Glade Park area, but
8. Monument fault begins to lift northern corner of plateau.
9. Colorado River becomes antecedent across Monument uplift zone, stripping Jurassic and Dakota rocks from Little Park.
10. Uncompahgre River migrates northeastward across Dakota surface, stripping remaining Mancos Shale.
11. Gunnison is blocked by readvance of Horsefly Peak–Cerro Summit glaciers and diverted to its approximate present course.

Triangles represent volcanic provenance fluvial deposits presently resting on Uncompahgre Plateau uplands along Dry Creek.

Key to cross section only:

12. Just prior to abandonment, Gunnison River in Unaweep Canyon possessed essentially flat gradient.
13. Present divide between East and West creeks is only point of pre-abandonment floor of Unaweep Canyon not significantly lowered by erosion along the two creeks.
14. West Creek has cut maximum of about 1,700 ft, and
15. East Creek has cut maximum of about 500 ft below abandoned valley floor.

Figure 8. Physiographic diagram and cross section of conditions at the time of Stage Four: Pre-abandonment.

along developing dip-slope tributaries to the Gunnison. Similar tributaries developed on the newly stripped Dakota surface of the rising plateau and formed precursors of Dominguez, Escalante, Roubideau and Dry Creek canyonlands.

River gravels presently about 1,000 ft below those discussed earlier (fig. 2) were deposited on the stripped plateau surface at about this time by the ancestral Uncompahgre River (fig. 8). These gravels are possibly outwash from a readvance of the Horsefly Peak glaciers or perhaps from an intermediate age glaciation not evidenced by preserved till deposits.

The glacial readvance in the Cerro Summit area dammed the ancestral Gunnison River and forced it to escape along a new course near the present location of Black Canyon. The abandoned course of the Gunnison below the ice dam was occupied by an outwash channel that flowed quasi-parallel to the Gunnison in the vicinity of Bostwick Park and Red Rock Canyon.

Conditions represented on Figure 8 occurred just prior to the abandonment of Unaweep Canyon and Glade Park by the ancestral Gunnison and Colorado rivers, respectively. Figure 9 illustrates conditions just after both abandonments occurred. The timing of these major river diversions relative to each other is uncertain.

A few assumptions regarding the inferred geomorphogenesis of the Uncompahgre Plateau should be made explicit:

1) the river that abandoned Unaweep Canyon possessed an essentially flat gradient at the time of abandonment;

2) as a result, the Gunnison River was ponded and spilled across a low divide on Mancos Shale and into the adjacent basin of the Colorado River*;

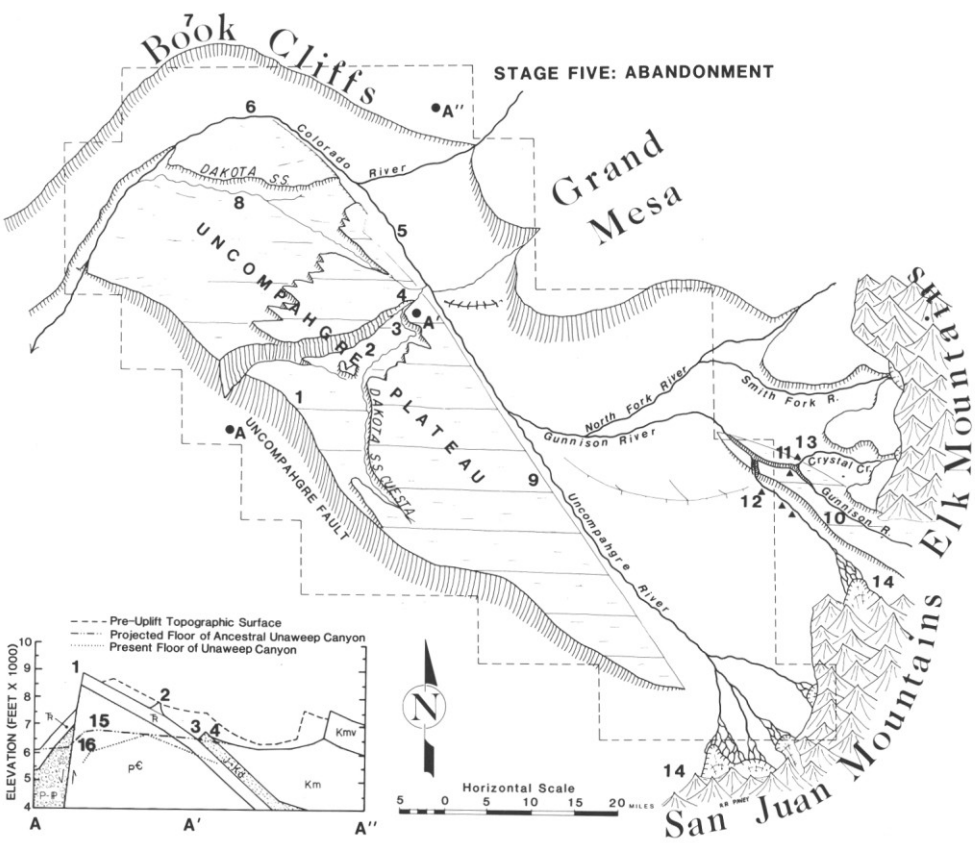
3) the gradient of the river in Unaweep Canyon at the time of abandonment steepened near the Uncompahgre fault zone and merged with the bench on Kayenta Sandstone near Palisade Butte;

4) canyon deepening has occurred along East and West Creeks since abandonment;

5) the present divide between these creeks occurs in the only vicinity of Unaweep Canyon that has not been significantly lowered by post-abandonment erosion;

6) 1,000 ft of uplift has occurred along the plateau crest since abandonment of Unaweep Canyon;

"These first two assumptions apply to all antecedant river diversions. However, diversion occurs only if ponding raises the river bed or a resultant lake surface to the height of a basin-defining divide upstream from the rising structure. Hunt (1956) considers a combination of antecedence and superposition from ponded deposits immediately upstream from the uplift zone meritorious of a special name, "anteposition." Actually, "anteposition" is normal during antecedance.



Key to map and cross section:

1. Crest of plateau has risen about 500 ft since abandonment of Unaweep Canyon.
2. Old salient along Dakota cuesta is breached as Gibbler Gulch captures headwaters of Gill Creek, isolating Dakota-capped outlier northeast of modern Casto Reservoir.
3. Gibbler Gulch impinges down-dip against Dakota cuesta and scours its southwest facing edge.
4. Northeast Creek and East Creek begin flowing to Gunnison.

Key to map only:

5. Ponded Gunnison spills across low, pre-abandonment pediment divide into Colorado basin.
6. Ponded Colorado River spills around north end of rising Monument Uplift zone, causing
7. Book Cliffs to rapidly retreat, accentuating their arcuate trend around north end of plateau.
8. Little Dolores River occupies abandoned Colorado Valley in Glade Park.
9. Uncompahgre River continues to migrate across Dakota surface, stripping Mancos Shale from Uncompahgre Plateau.
10. Black Canyon Uplift commences, creating Fruitland Mesa which is still largely covered with Mancos Shale, except where
11. Antecedent Gunnison River breaches Dakota Sandstone and begins cutting Black Canyon.
12. Antecedent tributary cuts Red Rock Canyon; another,
13. Crystal Creek, flows up-dip through Grizzly Gulch.
14. Last remnants of early Pleistocene glaciers are rapidly disappearing.

Triangles represent volcanic provenance fluvial deposits presently resting on upland surfaces along rim of Black Canyon, in Grizzly Gulch, and below pediment deposits in Bostwick Park and Shinn Park.

Key to cross section only:

15. Divide between East and West creeks forms on abandoned floor of Unaweep Canyon.
16. West Creek plunges across post-abandonment-produced fault scarp, causing divide between East and West Creeks to migrate to northeast.

Figure 9. Physiographic diagram and cross section of conditions at the time of Stage Five: Abandonment.

7) because uplift was rotational, post-abandonment uplift has raised the present East-West creek divide about 500 ft;

8) just before abandonment the Gunnison River flowed in ancestral Cactus Park near the southwest edge of present Horse Mesa; and

9) the Bangs Canyon monocline had not formed at the time of abandonment.

Uplift following the conditions shown in Figure 8 caused the Gunnison River to pond and overtop the low divide that separated it from the Colorado River basin. The spillover occurred downdip from the former river course and at about the same elevation as the head of the Gunnison's reentrant into the Dakota Sandstone cuesta. After diversion, the Gunnison joined the Colorado in Grand Valley near the east entrance to the Colorado National Monument (fig. 9).

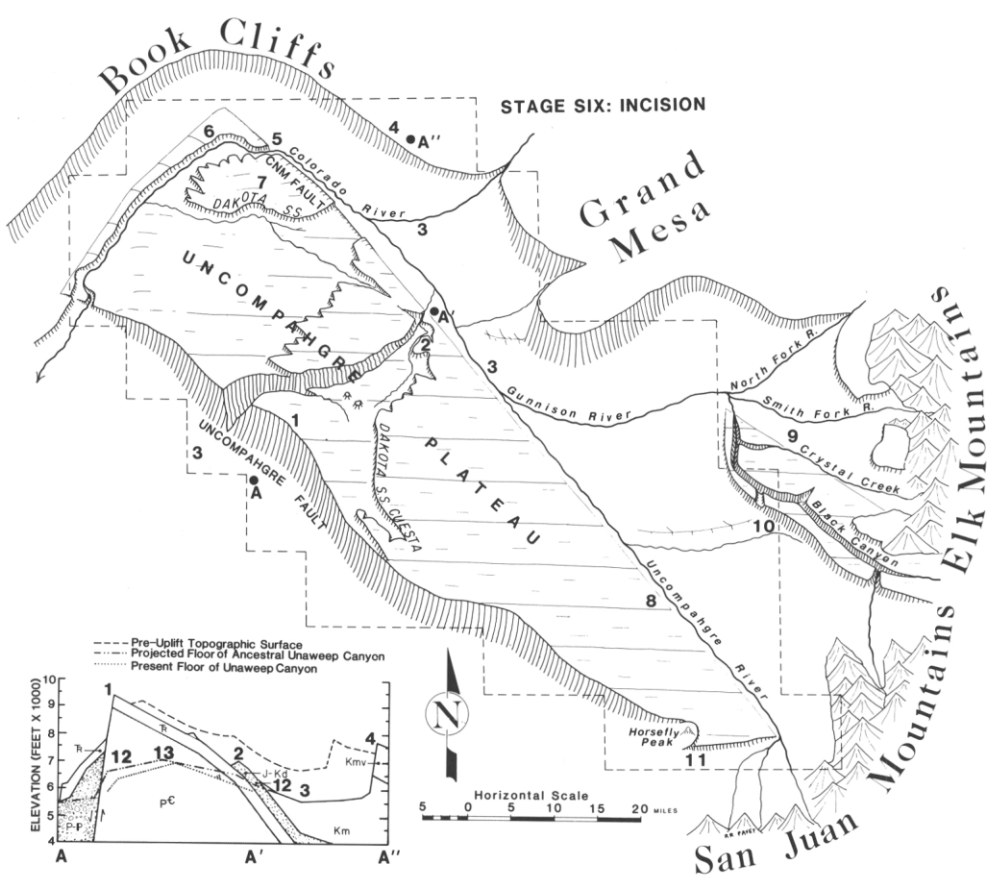
Post-abandonment uplift soon rotated the plateau block and reversed the previous southwesterly slope of the canyon floor. A divide between East and West Creeks formed near the crest of the fault scarp and then rapidly migrated northeastward due to headward capture caused by steeper gradients along West Creek in the vicinity of the fault scarp. East Creek was unable to significantly erode into the abandoned canyon floor because its low gradient was determined by post abandonment tectonic rotation.

The upper reaches of ancestral Gill Creek were captured by headward erosion along ancestral Gibbler Gulch which eventually cut through the Dakota Sandstone ridge formed by the earlier diversion of the Gunnison River to the North Fork basin. Later erosion of the Dakota caprock outliers formed the present small, Jurassic-sandstone-capped hills rising above the stripped Triassic surface north of Gill Creek. Gibbler Gulch occupied the abandoned course of the Gunnison through ancestral Cactus Park where it scoured the southwest side of the cuesta scarp, eventually causing Cactus Park to migrate to its present location.

Diversion of the ancestral Colorado River from Glade Park occurred because the river was ponded upstream from the Colorado National Monument fault and overflowed to the northwest (fig. 9). The river escaped around the northwestern end of the expanding uplift along a new route generally corresponding to its present course downstream from Fruita. In response, the Book Cliffs rapidly migrated northward, accentuating their arcuate form around the northern corner of the plateau.

Uplift in the Black Canyon area also commenced about this time, forcing the ancestral Gunnison River to entrench the Dakota Sandstone and begin carving Black Canyon (fig. 9). Ancestral Crystal Creek cut through the Mancos Shale and into the Dakota Sandstone along Grizzly Gulch. The pre-ice-dammed course of the Gunnison became antecedent across the rising monoclinal scarp and carved the upper slopes of Red Rock Canyon. Upstream from the uplift this stream deposited the gravels which are found today at Bostwick Park beneath locally derived pediment deposits. Penecontemporaneous fluvial gravels are preserved along the rim of Black Canyon and in Grizzly Gulch (fig. 9). During uplift of the Black Canyon area Smith Fork River homoclinally shifted northward across the rising slopes of Fruitland Mesa.

The early glaciers in the San Juan and West Elk Mountains disappeared about this time. Uplift along the Uncompahgre Fault ended after raising the crest of the plateau more than 3,000 ft (fig. 10). However, movement along the Colorado National Monument



Key to map and cross section:

1. Uplift is complete, plateau crest has risen to more than 9,000 ft.
2. Dakota cuesta is eroded by Gibbler Gulch and tributary of East Creek.
3. Gunnison, Dolores, and Colorado rivers vertically incise about 700 ft.
4. Book Cliffs increase in height.

Key to map only:

5. Colorado River antecedently incises across Monument Uplift for second time, forming Horsethief–Ruby–Westwater Canyon and separating Dakota capped uplands of
6. Westwater Cuesta and
7. Black Ridge.
8. Uncompahgre River continues sliding down plateau dip slope and stripping Mancos Shale from Dakota surface.
9. Crystal Creek abandons Grizzly Gulch for easier strike-trending course.
10. Red Rock Canyon is abandoned because antecedence is unable to keep pace with continuing uplift of Fruitland Mesa.
11. Uncompahgre Uplift extends to Ridgway Basin; thrust faulting near Horsefly Peak accompanies last stage of uplift.

Key to cross section only:

12. East and West creeks steepen as they incise to maintain grade to master streams.
13. Divide between two creeks becomes sharper and migrates northeast.

Figure 10. Physiographic diagram and cross section of conditions at the time of Stage Six: Post-Abandonment Incision.

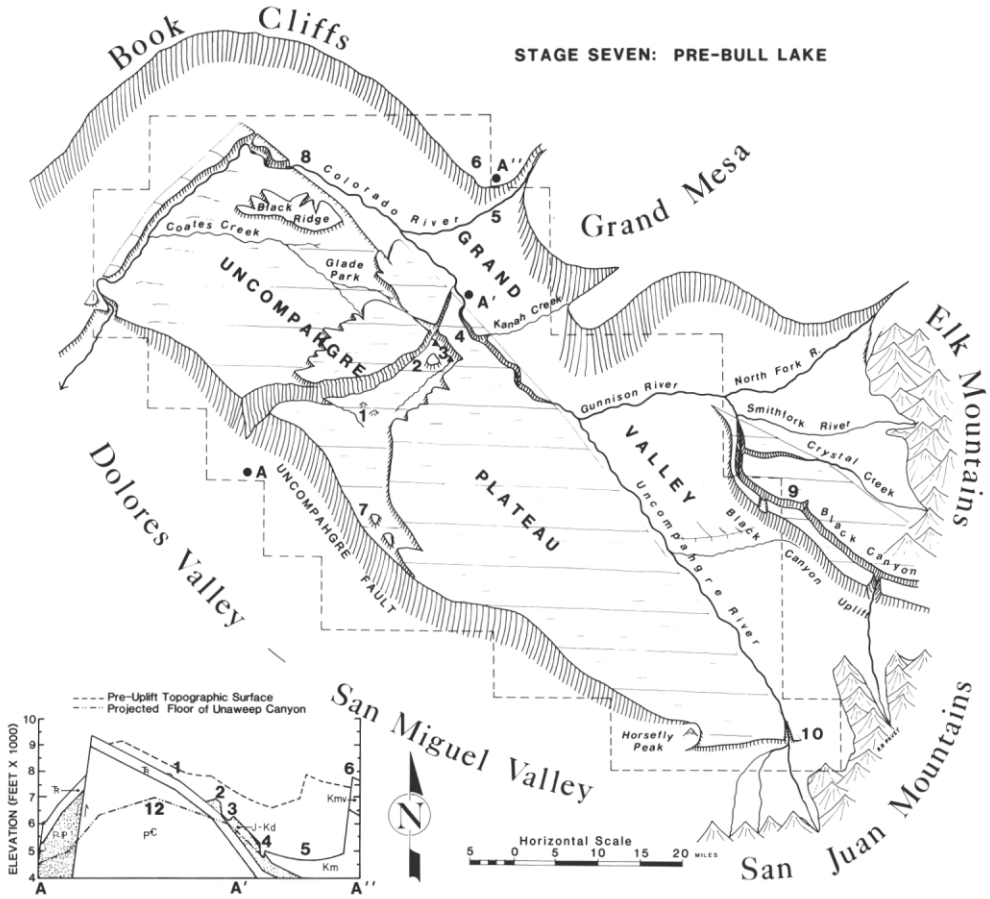
fault zone continued, and the Colorado River again became antecedent, carving the upper slopes of the present canyon downstream from Fruita. This canyon may have formed by superposition from the Mancos Shale during regional incision of the drainage net after uplift ceased.

Stream profiles before and after abandonment of Unaweep Canyon support the fact that regional drainage incision followed the abandonment. A projection of the Unaweep Canyon floor profile to Grand Valley at the time of abandonment (fig. 9) indicates that about 1,500 ft of vertical incision has occurred since abandonment (fig. 11). Stream bed lowering relative to an arbitrary horizon is assumed to have been minimal or nonexistent during antecedent sculpting of Unaweep Canyon. Erosional and sediment transport energy of the drainage system was consumed by rapid homoclinal shifting across the rising plateau slopes and antecedant incision of Unaweep Canyon. After uplift, the tectonic impetus for continued rapid homoclinal migration was removed, and available erosional energy was redirected to regional incision. The increased flow of the Colorado River owing to the addition of the Gunnison's flow volume also may have assisted incision. In either event, the master rivers began to lower their beds through the shales of Grand Valley (fig. 10).

The lower course of East Creek steepened toward the deepening Gunnison. Streams in the Colorado National Monument began flowing across the fault scarp to the Colorado river, carving the canyons of the Monument. West Creek continued cutting into Precambrian rocks below the abandoned floor of Unaweep Canyon as the creek's base level, the Dolores River, deepened at the same rate as the Colorado. The Triassic sandstone bench preserved on Palisade Butte became perched at this time. Gibbler Gulch continued to notch the Dakota cuesta near the present upper edge of present Horse Mesa. Eventually, this notch intersected the course of a small northwest flowing tributary to East Creek and Horse Mesa was separated from the Dakota-capped uplands of the Dominguez Creek canyonlands (fig. 11). Gibbler Gulch then flowed in present Cactus Park where it deposited reworked ancestral Gunnison River gravels derived from near the plateau crest. Similar volcanic provenance gravels are presently found near Smith Point and also are interpreted as deposits from ancestral Gunnison River gravels reworked by this dip-slope flowing stream (fig. 10).

As incision occurred along the lower course of the Gunnison River, compensation was accomplished upstream as the Uncompahgre River continued to homoclinally migrate across the Dakota Sandstone surface in the vicinity of Dry Creek, stripping the remaining Mancos Shale from the Uncompahgre Plateau. The Gunnison likewise migrated across lower parts of the present Dominguez, Roubideau and Escalante creeks. At a certain point, the Gunnison crowded the oversteepened slopes along Grande Mesa and was unable to shift farther. To maintain its vertical component of erosion, the Gunnison was forced to lower its course through the Dakota Sandstone, carving the upper part of the present canyon along the flank of the Uncompahgre Plateau between Delta and Whitewater. Simultaneously, the Colorado River deepened its gorge along the north end of the plateau, etching Horsethief, Ruby and Westwater canyons.

Development of deeply incised canyonlands along Dominguez,



Key to map and cross section:

1. Jurassic-capped hills northeast of Gill Creek remain as small cuesta outliers.
2. Horse Mesa is detached from Dakota uplands of Escalante Canyonlands.
3. Cactus Park is excavated by Gibbler Gulch.
4. Gunnison River incises along lower flank of Uncompahgre Plateau.
5. Colorado River deepens De Beque Canyon and flows across Grand Valley on reduced thickness of Mancos Shale.
6. Book Cliffs continue to retreat and increase in height.

Key to map only:

7. Uncompahgre Butte and Monument Hill are isolated as outliers from Dakota cuesta by dip-slope drainage (not shown) of Escalante Canyonlands.
8. Horsethief–Ruby–Westwater Canyon is deepened along Colorado River.
9. Gunnison River continues deepening Black Canyon.
10. Uncompahgre River begins to entrench southeast corner of Uncompahgre Plateau near Colona.

Triangles represent volcanic-provenance Gunnison River gravels reworked by Gibbler Gulch and deposited in Cactus Park.

Key to cross section only:

11. Divide between East and West creeks approaches present position. Both streams have eroded Precambrian rocks to attain their approximate present position and gradients.

Figure 11. Physiographic diagram and cross section of conditions at the time of Stage Seven: Pre-Bull Lake.

Escalante, and Roubideau drainage nets accompanied entrenchment of the Gunnison. These streams eroded deeply into the plateau in order to join the Gunnison at stratigraphic levels below the Dakota. Concommitant retreat of the Dakota-capped valley sides caused widening of the canyons and resulted in the distribution throughout the study area of volumetrically comparable erosional rates. As entrenchment of West and Middle forks of Escalante Creek extended to the crest of the plateau, it captured the upper drainage of ancestral Gibbler Gulch (formerly Gill Creek and still earlier the Gunnison River). Headward abstraction through the old salient on the Dakota Sandstone cuesta resulting from the first diversion of the Gunnison River, created Uncompahgre Butte, Monument Hill, and other Dakota-capped outliers on the present plateau crest. Big Dominguez Creek worked headward to the outer valley of Unaweep Canyon and captured the middle section of ancestral Gibbler Gulch. The process of capture is continuing. Present Gill Creek is about to be pirated by the LaFair branch of Little Dominguez Creek. Meanwhile, the Little Dolores River and Coates Creek drainage nets deepened the canyons of Glade Park. Their headwaters reduced the surface area of Dakota Sandstone northwest of Unaweep Canyon and at Black Ridge while their main channels incised to the Precambrian surface in Glade Park. In the Black Canyon area, the Gunnison cut more deeply into the rising Black Canyon Uplift. Incision along the stream flowing to the Gunnison through Bostwick Park and Red Rock Canyon eventually was unable to keep pace with uplift, and escaped around the eastern edge of the uplift zone (fig. 10). Continued uplift caused antecedence along this new course, forming Pool Gulch north of present Cerro Summit (fig. 11). A similar diversion occurred later, Pool Gulch was abandoned, and the present course of Squaw Creek to Cimarron was established. Crystal Creek was blocked in Grizzly Gulch by the rising slope of Fruitland Mesa and escaped along its present course.

The conditions shown on Figure 11 occurred immediately prior to the Bull Lake glacial episode. At this time, all drainage lines were approximately in their present positions. Regional incision had progressed to within a few hundred feet of the present valley floors. A companion paper (Sinnock, this guidebook) details succeeding events with emphasis on terrace and pediment development in Grand Valley. This paper concludes with a few general comments about the outlined early to mid-Pleistocene adjustments.

DISCUSSION

It is proposed that significant changes occurred during the Pleistocene in the geographical position, arrangement, and elevation of the major drainage channels throughout the western Colorado region.

If 500,000 years were required for the events outlined in this paper, then the maximum deepening of 3000 ft along Unaweep Canyon required only about 0.1 in. of abrasion per year from the floor of Unaweep Canyon. This task would be quite easy for the ancestral Gunnison River considering the hard milling agents of large volcanic, granitic, and metamorphic clasts and abundant grit (quartz, zircon, garnet, etc.) that comprised its bedload. Similarly, if concurent uplift along the Uncompahgre fault occurred from about 500,000 to 300,000 years ago, only the same general rate of uplift (— 0.1 in./year) is required. In general terms, this rate of tectonism is compatible with occurrence of an earthquake on the scale of that at Hegben Lake, Montana (Morisawa, 1975) or Wonder, Nevada (Slemmons and others, 1959) once every few hundred to a thousand years; this is a reasonable assumption for an active uplift zone.

Cliff migrations inferred herein as the dominant erosional events must have occurred on an annual basis of about one inch per year to produce ten miles of cliff retreat in 500,000 years. These rates of scarp retreat are the same general order of magnitude as those estimated by Gustaysen and others (1980a, b) for the Caprock Escarpment along the Little Red River Basin in Texas. Gustaysen and his colleagues measured sediment yields and changing erosion pin positions along the Caprock and estimated a scarp retreat rate of 110 mm (about 4 in.) per year for the past 380,000 years. Many features produced by these changes have been discussed by others, and most previous studies concluded that the events producing the current landform features are older, perhaps much older, then Pleistocene. Hunt (1956, 1969) summarized earlier works on the erosional history of the Colorado River Basin and concluded that gravels at Horsefly Peak and on the Uncompahgre Plateau uplands were deposited during the Miocene by the ancestral Uncompahgre River. He believed, as do I, that the Uncompahgre River homoclinally migrated to its present position from the vicinity of the gravel deposits on the plateau uplands, but thought this migration was essentially accomplished by the beginning of the Pleistocene. Hunt agrees with Cater (1966) that Unaweep Canyon was abandoned in late Pliocene or earliest Pleistocene and that uplift accordingly commenced in early to mid-Pliocene. Lohman (1961, 1965) suggests, and Hunt (1956) and Yeend (1969) agree, that Unaweep Canyon was formed by superposition of the Colorado River from Grand Mesa basalts and early Tertiary sediments. Cater (1966) concludes that only 100 to 200 ft of deepening along the Dolores River occurred during the entire Pleistocene. Hunt (1969) concurs, and extends the same order of magnitude of deepening to the Black Canyon, where he allows 400 ft of incision during the Pleistocene. He draws on Hansen (1965), who places the beginning of Black Canyon incision in mid- to late Pliocene. Hansen suggests that the Black Canyon formed by superposition upon a pre-existing uplift from a synclinal axis developed in San Juan and West Elk volcanic deposits.

These previous studies, in effect, have assumed that tectonic activity essentially stopped before or shortly after the Pleistocene began. Additionally, these studies require that most or all Plio-Pleistocene erosion along the master streams was essentially vertical, with the exception of Hunt's mention of homoclinal migration by the Uncompahgre River.

Another group of workers agrees somewhat more with the assumptions presented in this paper by concluding that tectonic activity continued well into the ice ages and perhaps continues unabated even today. Shawe (1968) describes tectonic warping of Pleistocene outwash terraces in Disappointment Valley south of the study area. Similar synclinal warping can be observed on the highest terrace along the Roaring Fork River between Glenwood Springs and Carbondale northeast of the study area. Atwood and Mather (1932) concluded that Black Canyon represents an ice-dammed diversion of the Gunnison River by Horsefly Peak-Cerro Summit glaciers. However, they correlate the highest terrace in Montrose Valley, rather than the gravels on the plateau uplands, with this early glaciation.

If, as proposed by Cater (1966), only 200 ft of vertical incision has occurred in the region during the entire Pleistocene (I will assume about two million years), then only about 0.001 in. of drainage net lowering occurred per year. This corresponds to about 6,000 ft in 60 million years, an amount compatible with removal of the entire Mesozoic section since regression of the Mesaverde seas. However, the 200 ft of vertical erosion cited by Cater was based on an "in-canyon" environment. Volumetrically, this reduces the inferred

erosion rate several orders of magnitude, because canyons are merely linear gashes cut below broad regional surfaces which once supported thick overlying Cretaceous and early Tertiary deposits. Also, throughout much of the early and perhaps middle Cenozoic, deposition rather than erosion characterized the region. Thus, 30 million years is a more likely time period for post-Cretaceous erosional activity in the study area (Hunt, 1956; Dutton, 1882).

Migration rates for the Book Cliffs of about 0.25-1 in. per year would yield about 120-480 mi of stripping in the 30 million years since erosion of the region began in earnest. Assuming stripping of the Book Cliffs occurred in two directions from a central area, this reduces to only 60-240 mi in the same time period. The equivalent of the Book Cliffs at Mesa Verde National Park near Cortez is about 130 mi from those in the study area.

Erosional rates postulated by previous workers for the Pleistocene would remove only about one-half of the Mesozoic and none of the Tertiary section presumed to have been deposited in western Colorado. Additionally, it is reasonable to presume that denudation rates have accelerated throughout the middle and late Tertiary and into the Quaternary due to increasing river gradients associated with epeirogenic uplift. Thus, Pleistocene erosion rates probably represent a maximum during the Cenozoic. Considering these facts, the erosion rates postulated in this paper are consistent with the erosional work that has been accomplished during the past 30 million years or so.

It is evident that most denudation in the study region (and most probably elsewhere in the Colorado Plateau) occurred along fine-textured, low-order drainage nets of steep, retreating scarps. The processes by which cliffs retreat and the morphologic forms developed upon and below them are well described by Smith (1958) and Bryan (1932, 1940). Cliff retreat occurred along small tributaries to consequent streams of the Uncompahgre Plateau and along obsequent streams of the Book Cliffs and Grand Mesa. Similar retreat of the Uncompahgre fault scarp was precluded by the relation between available erosional energy and the erosional resistance of the uplifted wedge of Precambrian crystalline rocks. This helps explain the absence of large pediment or fan deposits along the base of the fault scarp, because the existing entrenched tributaries to the San Miguel River were capable of transporting the material eroded from the southwest side of the plateau. Material eroded from Book Cliffs and Grand Mesa was transported to the appropriate master stream along concave pediments cut on Mancos Shale. Pediment erosion lowered the valley floor between the cliffs and the river. The pediment surfaces merged with Dakota Sandstone at the rivers, so the master streams were required to remove only a thin layer of Mancos Shale while migrating northeastward. Volumetrically, the master streams eroded very little, but transported much. They provided only the final polishing touches to the stripping of the great structural plains so abundant throughout the study area. The process of cliff-pediment-river migration exemplified in the study area was probably common throughout the Colorado Plateaus, but the foregoing discussion of erosion in the Uncompahgre Plateau-Grand Valley region suggests that it is unwise to call upon "regional" processes to describe the formation of local landforms.

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