COLORADO DRAINAGE BASIN.

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ABSTRACT. The diverse views of the physiographic history of the vast area drained by the Colorado River seem to be the result of scant knowledge of sedimentation, tectonic movements and cyclic erosion in post-Cretaceous time. The record of events is blurred especially by inadequate faunal evidence and the local scope of field studies. However, published and unpublished material relating to the High Plateaus of Utah, the Green River basin, the San Juan Mountains, the Navajo Country and to the Colorado and its tributary canyons serve to outline a pattern that involves the recognition of a regional uplift in late Miocene or early post-Miocene times and a high-level surface of erosion on which the Colorado River began its life as an integrated, generally superposed stream system.

INTRODUCTION.

THE pioneer contributions to the history of the Colorado drainage system date from the decade 1850-1860, when American geology was in its swaddling clothes. Much of the present day knowledge was formulated in 1871-75 by the Wheeler and Powell surveys, which undertook the amazing task of interpreting the stratigraphic, structural, and volcanic features of a large, entirely new region—most of it the work of three field seasons. Beginning with the decade 1900-1910 studies have progressed with increasing tempo until reconnaissance or detailed areal surveys and economic surveys have covered substantially the entire Colorado Plateau province. In the more recent reports the earlier work has been revised and much new material added, but despite nearly a century of intermittent studies the written geologic history, especially for the Tertiary and Quaternary epochs, remains far from complete and presents many troublesome inconsistencies; field work still "yields more questions than answers." Regional investigations have been handicapped by the lack of suitable base maps, the exasperating scarcity of diagnostic fossils, and perhaps most of all by the fact that papers on stratigraphy, structure, and physiography deal with scattered, relatively small areas whose relations to other parts of a vast province were unknown to their authors. Therefore it occasions little surprise to find divergent views regarding the history of the Colorado River drainage system in the pioneer reports of Newberry, Powell, Dutton, Gilbert, Howell, Holmes, and Hayden, and in later reports by Davis, Robinson, Johnson, Huntington and Goldthwait, Darton, Gregory, and McKee. Students of the Grand Canyon and its immediate borders have set tentative dates for the inception of integrated drainage as early Eocene, late Eocene, early Miocene, Miocene, Pliocene, and Pleistocene; have described the Colorado River as wholly or in part antecedent, consequent, subsequent, and superposed; and have considered some of the major tributaries as unrelated to their master stream in origin and history. On the other hand, students of the "back country," where Tertiary rocks are exposed, seem to have favored the view that the Colorado River originated in post-Eocene—pre-Pliocene time; that the present stream pattern is largely the result of superposition; and that in their broader relations the different parts of the drainage system have had a common history. That conflicting views of plateau physiography persist is shown by recent publications, in which Hunt (1946) assigns the birth of the through flowing Colorado to early Tertiary (Eocene ?), Longwell (1936) to the Pliocene (?), and also (1946) "after late Miocene," and Blackwelder (1943) to the beginning of the Pleistocene. Added confusion arises from the fact that the diverse views of these authors are largely diverse interpretations of substantially the same formations in a small part of the Colorado Valley. At Longwell's suggestion, the applications of the evidence recorded in the Boulder Dam region to the Colorado basin as a whole, and especially to the High Plateau of southern Utah, are considered in this paper. Inasmuch as the material presented is based on reports awaiting publication by the U. S. Geological Survey and the National Parks Service, it has seemed appropriate to cite only the specifically pertinent literature, withhold discussion, and for most statements to omit the qualifications otherwise desirable. Attention is restricted to the essential factors involved in the physiographic history of the Colorado drainage basin; the physical characteristics and age of the Tertiary deposits; the age and effect of the major faults; the ancient surfaces of erosion; and the work of streams as recorded in the present day landscape.

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TERTIARY FORMATIONS.

Though the once widely spread rocks of Tertiary age have been stripped from large parts of the Colorado drainage basin, particularly along the Cataract, Glen, and Grand Canyons, they occupy the Green River and Uinta basins, form the almost continuous cap of the Utah High Plateaus, and are represented by distinctive material in the upper San Juan Valley, the Navajo Country, Muddy Mountains, along the lower Colorado, and on both sides of the Nevada-Utah boundary line. Very few of these scattered outcrops hold firmly established positions in the time scale. However, the meager faunal evidence in combination with physical features and stratigraphic sequence seem to set approximate limiting dates for the major orogenic movements, volcanic activities, and cycles of erosion.

In the western part of the Colorado Plateaus the stratigraphic units of most direct use in determining the age of the major erosion surfaces, of the prominent faults, and of drainage channels are the Muddy Creek formation in the Lake Mead region, and the Brian Head formation on the Markagunt Plateau. In topographic expression, color, and overall physical makeup these two formations have much in common, and they may prove to be equivalent. In general views both appear to be regularly stratified, but few fine-grained layers retain their individuality for as much as 300 feet, and the coarser ones are markedly lenticular; sections measured a mile apart are but roughly comparable. Both formations consist dominantly of buff, yellow, and white clays and silts and gray sands and gravels, with a wide range in composition and texture. A distinctive common feature is an abundance of pyroclastics and lavas. The salt and gypsum locally prominent in the Muddy Creek formation is inconspicuous in the Brian Head, and the white, hard, thin-bedded lacustrine limestone in the Brian Head seems not to be duplicated in the Muddy Creek. The sediments of both formations are believed to have come to rest in a series of depressions in an arid or semiarid "hill and basin country"; there is no evidence of exterior drainage. Because the Muddy Creek formation antedates the origin of any perennial stream in the lower valley of the Colorado River, and the Brian Head formation antedates the production of the High Plateaus of southern Utah—probably the site of the first abundant precipitation and run-off in Tertiary times—the age of these formations is a decisive factor in the life history of the Colorado River.

The age of the Muddy Creek has been rather fully discussed in the literature, and needs little comment here. Pertinent evidence is the report of Stock that the mammalian fauna is suggestive of Miocene date; that the formation contains no detritus that could have been carried by streams from the plateau lands farther east; and that above it lie the oldest sediments deposited by the Colorado River, including those whose fossil fauna is classed by Simpson as Pliocene or Pleistocene. Longwell concludes that his tentative assignment of the Muddy Creek formation to the Pliocene is invalid; that the evidence favors an assignment to the Upper Miocene rather than older; and that "presumably the [Colorado] river acquired its present course west of the Plateau after late Miocene time."

Like the Muddy Creek, the Brian Head formation occupies no closely definable place in the time scale. The snails, reptilian bones, and diatoms (?), few of which have been specifically determined, represent genera that range throughout the Tertiary. *Helex spatrosa* and *Celliforma spirifer* are reported "from the later Eocene chiefly," and some silicified plant fragments are thought to be "younger than the Wasatch." On faunal evidence more precise classification seems unjustifiable for the pyroclastics and also for the limestones below them—the two radically different groups that together constitute rock commonly mapped as Wasatch on the southern Utah highlands. However, no existing knowledge of the Tertiary faunas of Utah seems to make invalid the classification of the "pink Wasatch" ("Pink Cliffs series") as Eocene, and the "white Wasatch" (Brian Head) above it as Miocene, and this age distinction is strongly suggested by the regional relations and stratigraphic sequence. The tuff, ash, and lavas of the Brian Head, the oldest known Tertiary volcanics of southern Utah, are characteristic likewise of Miocene formations in adjacent areas and are consistent with the regional evidence that the Miocene was an epoch of major volcanic activity. In several places unconformable above the stratigraphic position of the Brian Head lie strata of unquestioned Pliocene or very early Pleistocene age, and below it lie undoubted Eocene sediments. However, in the southern High Plateaus the lower part of the Eocene as represented elsewhere is lacking: the basal Tertiary rests on an erosion surface believed to have been developed in early post-Cretaceous time. Along this unconformable contact beds classed as Wasatch directly overlie beveled Cretaceous formations, and in places the Jurassic beds, down to the Navajo sandstone; the hiatus in sedimentation measures 1,000 to 5,000 feet. It seems clear that the Tertiary deposited after this long period of erosion is unlikely to be Paleocene or the oldest Eocene. An assignment of this expanse of limestone to the upper Eocene, possibly Oligocene, and the distinctive formation above it to the Miocene permits a reasonable interpretation for the Tertiary of the Markagunt and adjacent plateaus, and may be applicable to other parts of the Colorado drainage basin.

FAULTS.

Disregarding age relations there has been no dissent from the conclusion of Powell, Dutton, Gilbert, and Davis that the present well-watered surfaces of the Markagunt, Paunsaugunt, and Aquarius plateaus represent a former low-altitude, imperfectly drained land area; that the radical change in regional topography is due chiefly to large scale orogenic disturbances. Faults accompanying and in part causing regional uplift have broken all the sedimentary formations below the Pliocene and also the extensive sheets of andesite and basalt; the strata on the downthrown and upthrown sides of the faults are counterparts. In the Hurricane zone of faulting, less clearly in the Sevier and Paunsaugunt zones, three periods of major disturbance are recognized; all of them post-dating the Kanarra fold, the Kaibab upwarp, and similar structures farther east. Field observations of various students formulated by Gardner (1941) serve to date and give measurements to these movements as follows: 1. post-Eocene (post-Wasatch), less than 300 feet, restricted to Ash Creek valley; 2. post-Miocene-Quaternary, 7,000 (possibly 8,000) feet—75 percent of the total uplift, regional in scope; 3. two closely spaced movements totaling about 800 feet, recorded in the conspicuous Hurricane, Sunset, Elkhart, and Table Cliffs. The lapse of time between the first and second movements is uncertain, probably not great; that between the second and third was long enough to permit the development of drainage systems; it seems to have been an interval of structural quiescence, substantially the "era of great denudation" of Dutton, the "interfault cycle of erosion" of Huntington and Goldthwait, the "pre-canyon" cycle of some other writers. The third uplift—probably still in progress—introduced the present period of intensified canyon cutting. Though in places one, maybe two of these movements seem not to have occurred it is believed that throughout its course the Hurricane fault represents one general zone of fracture. Within and outside the zones of major disturbance small scale orogenic movements are plainly recorded in broken sheets of basalt of post-Miocene age.

In the process of faulting the individual interfault blocks were tilted eastward, and in places broadly uparched. In combination they formed a regional surface that sloped southward and northward from the east-west belt of greatest uplift that crosses the present Kolob, Moccasin, and Skutumpah terraces. As measured along the Hurricane fault, the uplift decreased southward from more than 7,000 feet near Kanarra to approximately 5,000 at Rock Creek and 1,500 feet where it crossed the Colorado River. The Sevier and Paunsaugunt faults that show displacements of 1,200 to 3,000 feet in the High Plateaus decrease in magnitude southward, and die out before reaching The Grand Canyon. Obviously this faulted highland was characterized by long slopes, by vertical cliffs, angular ridges, and structural valleys of huge dimensions, all trending approximately north and south, and it must have presented a variety of less prominent topographic features. Even today much of the original pattern remains.

MIOCENE EROSION SURFACE.

Most writers on the Colorado plateaus have postulated an expanse of land not far above sea level that during some part of the Tertiary era had no persistent outlet to the sea; an extensive surface whose low altitude and arid climate were unfavorable for the development of long permanent streams. In Dutton's view such a surface—developed near the close of the Cretaceous—was originally the site of brackish water ponds and indefinitely defined outlet streams; then, after various changes in altitude and climate, the surface became largely covered by Eocene lakes whose waters were kept in bounds by surrounding highlands produced by localized, pre-Eocene, crustal warping. Later studies suggest that the region retained its low altitude until middle Tertiary times; that its surface included fluviatile and lacustrine sediments of Eocene and Miocene age; and that it had considerable relief as the result of erosion and the presence of such masses as Tushar and San Juan Mountains. Possibly also the Uintas and the laccolithic Navajo, Abajo, and the Henry Mountains, rose above the generally subdued surface. It is thought that low altitude, semi-arid climate, and local barriers prevented the development of through-flowing drainage; that some short perennial, many intermittent, and innumerable ephemeral streams carried water to separate and overlapping basins, where much of it was lost by evaporation.

The known events in the history of the Colorado drainage basin seem best interpreted on the assumptions that the former low altitude, arid surface was uplifted in late Miocene or very early Pliocene time and carried with it much of the original topography; that in the process of uplift the surface was fractured and moderately warped; and that in its newly attained lofty position a humid climate made possible the development of fully organized river systems. Under these favorable conditions stream erosion guided by topographic relief, geographic position, and the type of rock encountered has largely remodeled these original highlands, and over large areas completely destroyed them. In places the wastage has been slight; in other places prodigious. The most clearly recognizable parts of the original surface are on the High Plateaus, where massive lavas have retarded erosion; on the downthrown blocks of faults where protected by alluvial fans; and in such areas as the Green River basin, where dissection by streams has been the longest delayed.

The old age topography of the plateau tops in southern Utah and of the downthrown blocks of the Hurricane fault zone is thought to be represented by the "Miocene erosion surface" of the San Juan Mountains, and it has seemed appropriate to extend the application of that term to areas of similar character and substantially equivalent age throughout the Colorado drainage basin. These include the scoured rock surfaces of very low relief in the Navajo Country, the Zuni Mountains, the San Francisco Mountains, and the Green and

Yampa river basins. In the absence of adequate faunal evidence these surfaces are but approximately dated. By field workers they have been classed tentatively as Miocene (?), late Miocene, post-Miocene, and early Pliocene and Pliocene (?). It is significant that wherever examined the rocks on which the surface has been developed are Miocene or older, and those above are Pliocene, Pliocene (?), or Pleistocene.

THE PRESENT LANDSCAPE.

The outstanding characteristics of the Colorado plateau landscape are angularity in vertical and horizontal topographic profiles, and the seemingly haphazard intermingling of land forms diverse in origin and history. As fully exhibited in northern Arizona and southern Utah, the "terrace province" of Fenneman—the dominant features are platforms, terraces, and benches crossed by canyons, and whether the scoured rock surface measures square yards or square miles in area, and the cliffs and canyon walls feet or hundreds of feet, the rugged topographic pattern persists; in detail the results of selective erosion are bewildering. In physiographic terms the landscape comprises such heterogeneous elements as graded platforms trenched by vigorous meandering streams, erosion surfaces terminating in high walls, downthrown fault blocks higher than the upthrown blocks, terraces of rock, alluvium, and locally made gravel at various altitudes, and superposed drainage channels. Old age valleys and youthful valleys are common; intermediate forms are conspicuously absent. Though it seems clear that the present landscape has been shaped by streams during Pliocene and more recent times, obviously these discordant features are not records of uninterrupted reduction of rugged highlands to slopes and on to plains of low relief; they point to intermittent uplifts, still stands, climatic cycles and particularly to the attitude and relative durability of the rocks.

For convenience of description the term "canyon cycle" has been applied to the era of entrenchment of the Colorado Canyons, and "pre-canyon cycle" to an era during which the bordering lands were reduced to "base level." To Powell and his associates such surfaces as the interstream areas of the Uinkaret, Kanab, and Coconino plateaus, were developed during a period of crustal stability, and the great gorge in response to uplift. Accepting Dutton's view that these worn rock floors mark the end of a cycle of erosion, various writers have outlined sections of a once continuous peneplain that covered large parts of the plateau province. Fuller knowledge of the plateau physiography discredits these interpretations, which even if valid could fully apply mainly to that small part of the Colorado basin between the Vermilion Cliffs and the Grand Canyon. Attempts to correlate the disconnected "peneplanes" in southern Utah and northern Arizona have been futile. These post-mature surfaces stand at altitudes of 1,000 (?) to 7,000 feet in positions not consequent on orogenic movements. Of those developed on friable rocks, some are so flat as barely to carry runoff; others include considerable elevations within their borders; and many terminate abruptly against high cliffs. Some are local features closely related in origin to the nearby drainage channels; others are correctly classed as pediments, which obviously have no time significance. Such stripped rock surfaces as the Esplanade, the Paria plateau, the Glen Canyon platform, the Little Creek and Moccasin terraces, the Gooseberry Mountain, and Pioneer and Smith Mesas bear no evidence of cyclic denudation; they are believed to illustrate stream erosion controlled by the attitude and relative resistance of the rock strata and from time to time intensified or abated by tectonic movements and climatic fluctuations. Davis pertinently remarks, "It is difficult to point out representations of the very flat expanse [postulated by Dutton] that was produced when the plateau cycle was interrupted by the uplift that introduced the canyon cycle"; "a single down cutting and a single uplift is recorded in the [Grand] Canyon." Certainly for the Kanab and Uinkaret Plateaus and the eroded surfaces farther north in Utah, clear evidence of peneplanation is lacking.

Under the conditions prevailing, lofty escarpments, mesas, deep canyons, rock terraces, and old age erosion surfaces must have characterized the plateau landscape since the beginning of Pliocene time, and the retreat of cliffs with little change in form seems to have been a normal process. Doubtless at several times the progressive reduction of the plateau borders was marked by events reproduced in recent geological history: deep, narrow, rock-floored canyons filled or partly filled with gravel, swept clean, then refilled with the alluvium which is now vigorously in process of removal. In view of these considerations it has seemed appropriate to divide the physiographic history of the Grand Canyon district into a plateau cycle—the period of preparation for the later stupendous erosion—and a canyon cycle during which the uplifted plateau blocks have been carved into the present scenic terrane.

DRAINAGE.

In consequence of post-Miocene uplift the High Plateaus (present elevation 9,000 to 12,000 feet) were brought within the range of heavy precipitation. Guided by the topography, rains and melting snows doubtless spread a net of short consequent, subsequent, and obsequent streams over the plateau tops, and supplied water for longer consequent streams that made their ways down the available regional slopes inclined roughly north and south. It may be conjectured that the south-flowing waters from the uplifted, warped, and fractured highland found a resting place on the structural lowlands in the approximate position of the present Grand Canyon and the synclinal Little Colorado Valley; that their most easily developed outlet to the sea was westward; and that along this course the new-born stream, locally expanded into lakes, descended from one to another plateau block over high cliffs, and thus developed energy rarely acquired by running water. It is believed that these favorable conditions for runoff were restricted to the region of fault topography, where the post-Miocene surface had the highest altitude, the steepest overall slopes, and received the heaviest precipitation. It seems probable that the original Colorado was a relatively short stream of moderate volume fed from the north by the ancestral Virgin, Kanab, and Paria Rivers, and from the south by the Little Colorado, which gathered water from the large region between Navajo Mountain and the Mogollons. The evidence available indicates that north of the latitude of the Kaiparowits Plateau the ancient erosion surface was largely unbroken; it presented long slopes and broad basins trending in various directions within the intermountain geosyncline. Westward the Sevier, the Spanish Fork, and other streams must have carried water to the Great Basin from areas far east of the present plateau rims: northward the ancient Green River and its tributaries which drain a large area in Wyoming and Colorado "apparently must have flowed eastward or northeastward" perhaps to the ancestral Platte River and on to the Missouri; and southeastward no known topographic obstacles would have prevented some drainage to the Rio Grande.

In the contest for the enlargement of these four drainage basins, the young Colorado and its vigorous tributaries possessed advantages not shared by streams on flatter lands farther east. Steep gradients and a shorter course to sea level permitted progressive upstream encroachment on extraneous drainage areas until a dominant runway was established. In this process the streams flowing to the Great Basin were beheaded, and the ancient Green River system seems to have been redirected southward to the Colorado. Though southeastward in Colorado and New Mexico the evidence for stream capture is less conclusive, ancient valleys on erosion surfaces suggest streams not connected with the Colorado. It seems probable that in the same general region, eastward and south flowing streams of moderate gradient were undercut by steeply inclined west flowing streams and it may be that some of the run-off, once tributary to the Rio Grande, now passes to the Colorado through the canyons of the San Juan.

With the increased volume of water incident to the enlargement of its drainage basin, the Colorado was equipped for quarrying a runway through surface rocks of various resistance and through tectonic structures encountered in downcutting. In its efforts to establish grade the river has readjusted its alinement at various times and places: a striking example is the abandonment of its canyoned course across the Uncompahgre Plateau.

Admittedly the conclusions in the present paper are tentative and in some degree speculative. They rest on a few well established facts and many unverified beliefs and hunches gained during years of field work. It is thought that some gaps in the physiographic history of the plateau country may be filled by the recognition of a regional Miocene surface of erosion on which after uplift the Colorado River began its life as the master stream in an integrated, through-flowing, generally superposed, drainage system.

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