LATE CENOZOIC GEOHYDROLOGY IN THE CENTRAL AND SOUTHERN PARTS OF NAVAJO AND APACHE COUNTIES, ARIZONA

By

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Navajo and Apache Counties, in the southern part of the Colorado Plateau, are drained by the Little Colorado River (Fig. 1) except for a narrow strip along the Mogollon Rim. In southern Apache County near St. Johns, large modern and ancient spring deposits are associated with former levels of erosion that record the development of the Little Colorado drainage system. Other ancient spring deposits in the Hopi Buttes volcanic field of Navajo County are part of the Bidahochi formation of Pliocene age. Relations of the spring deposits to the late Cenozoic erosional and depositional events give some insight into the ground-water paleohydrology of the area.

The parts of the two counties under discussion occupy much of a broad northwest-trending synclinal trough, which consists of the St. Johns sag and Black Mesa basin. The synclinal region is bordered to the northeast by the sharply-arched Defiance uplift. To the southwest the synclinal lowland is bordered by the gentle, northeast-dipping Mogollon slope. In the area, the Apache dome and the Holbrook and Antelope Valley anticlines and other structures locally interrupt the regional structural trends. One syncline, having a rather indefinite shape, is 3 to 5 miles southwest of the Cedar Mesa anticline. In the area where the syncline is crossed by the Little Colorado River, springs discharge a combined total of 4 to 10 cfs (cubic feet per second). In this reach the Little Colorado River is a perennial stream. The river also is perennial in a short reach along the northeastern limb of the Holbrook anticline a few miles southeast of Holbrook.

Most of the area of this report is underlain by thick, generally impermeable, shaly rocks of the Chinle and Moenkopi formations of Triassic age. The Kaibab limestone and Coconino sandstone of Permian age crop out only in the southwestern part of Navajo County. The Coconino is present in the subsurface throughout the area; however, the Kaibab is not present north of Winslow, Snowflake, and the Stinking Spring Mountains. Shales and sandstone of late Cretaceous and early Tertiary age crop out in isolated exposures in the White Mountains. The sedimentary rocks in much of the northern and eastern parts of the area are overlain by the Bidahochi formation of Pliocene age and, in the southern part of the area, by volcanic rocks of Tertiary and Quaternary age. The Bidahochi formation and volcanic rocks were not involved in the deformation of the older formations in the area.

The altitude ranges from about 5, 000 feet at Winslow to more than 6, 500 feet above sea level in the Hopi Buttes, and to more than 10, 000 feet on the summits of the White Mountains. The altitude of most of the land surface is between 5, 000 and 7, 000 feet.

GEOMORPHIC TERMINOLOGY

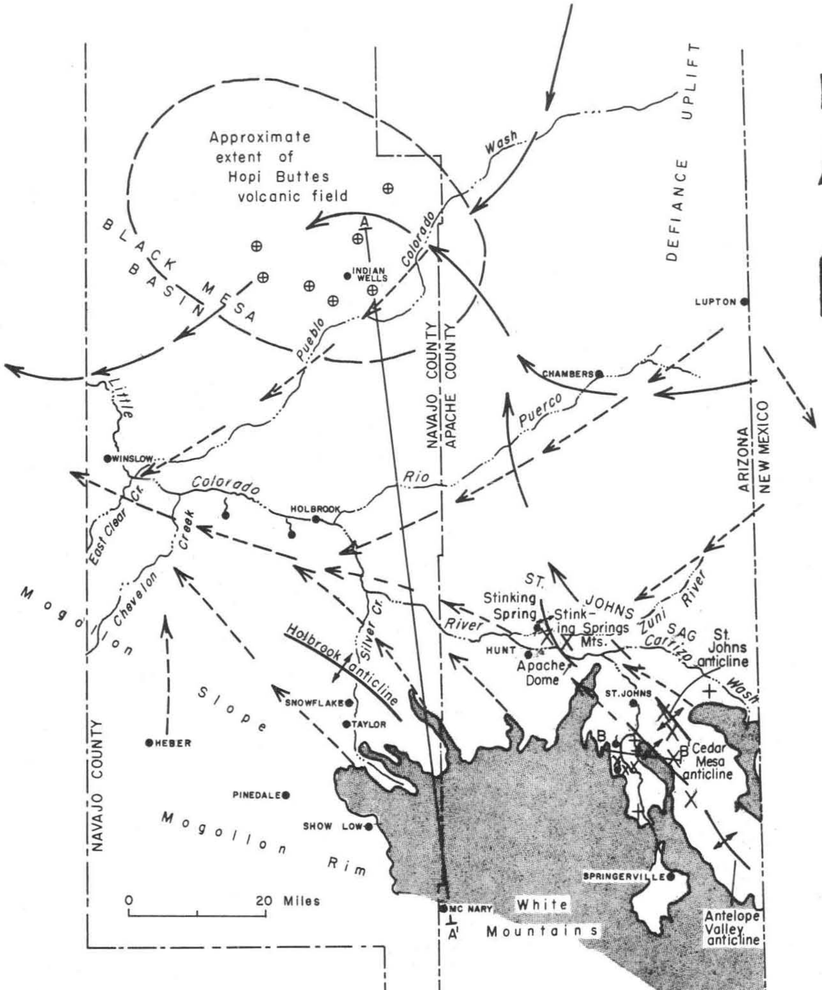
The developmental stages of the valley of the Little Colorado River are indicated by the large number of terrace deposits near the river, and by ancient erosion surfaces preserved beneath volcanic rocks in the highlands bordering the valley. The erosional levels representing stages in development of the valley have been traced throughout the drainage system from the Grand Canyon to the Arizona-New Mexico State line.

Late Cenozoic time (since the Miocene) is represented by three principal erosional cycles in the valley of the Little Colorado River (Fig. 2). These are the Hopi Buttes-Zuni cycle, named from the Hopi Buttes surface (Gregory, 1917) and Zuni surface (McCann, 1938); the Black Point cycle, named from the Black Point surfaces (Gregory, 1917); and the Wupatki cycle, named from the Wupatki surfaces (Childs, 1948). The Bidahochi formation was deposited by the ancestral Little Colorado River during the Hopi Buttes-Zuni cycle. The Hopi Buttes and Zuni surfaces underlie the lower member and the volcanic and upper members of the Bidahochi formation, respectively (Cooley, 1958, p. 147-148). These erosion surfaces record stages during the early development of the Little Colorado River system. The late stages of development of the Little Colorado system are represented by the Black Point surfaces and Wupatki surfaces. The Black Point surfaces in southern Navajo and Apache Counties are usually more than 200 feet above the Little Colorado River. The Wupatki surfaces are less than 200 feet above the river (Fig. 3A), and were cut in an inner valley below the lowest Black Point surface.

The surfaces in Navajo and Apache Counties are compound surfaces of erosion and deposition. The Black Point and Wupatki surfaces are overlain by 10 to 200 feet of gravelly sediments, and the Hopi Buttes and Zuni surfaces are overlain by the thick Bidahochi formation. These sediments were deposited in the valleys contemporaneous with erosion along the valley sides. Therefore, these compound surfaces consist of a lower surface of erosion and the uppermost surface of the associated deposit. In much of the area, the upper surface is more uniform and more easily recognized than the lower erosional surface. The lower erosional surface has a relief of more than 50 feet and is concealed in many places by slope wash and dunes.

The Bidahochi formation of Pliocene age, because it has datable fossils, is critical in establishing the age of the Hopi Buttes-Zuni and Black Point cycles. The Bidahochi formation was divided into an upper member, a middle volcanic member, and a lower member by Repenning and Irwin (1954, p. 1821-1826). The age of the Black Point cycle is late Pliocene to early Pleistocene. This designation is based on the fact that the Black Point surfaces bevel strata of the upper member of the Bidahochi and late Pliocene and early Pleistocene fossils were found near Taylor (Lance, 1960) in deposits that overlie a Black Point surface.

The Wupatki surfaces, forming two main levels in the area, are designated as probable middle to late Pleistocene in age on the basis of elephant remains and other mammalian fossils identified by J. F. Lance (oral communication, 1956) in sediments deposited on these surfaces near Holbrook and at several other localities near the Little Colorado River. Post-Wupatki time is represented by cutting and channeling and by alluvial deposits laid down during the Recent epoch. The valleys of the Little Colorado River drainage system that predate the present cycle probably were trenched partly during the



EXPLANATION

Tertiary and Quaternary volcanic rocks of the White Mountains

Spring deposits and diatremes associated with the Bidahochi formation

Travertine associated with the early Black Point surface

Travertine associated with the late Black Point surface

Travertine associated with the Wupatki surfaces

Anticline

Spring

Drainage on the early Black Point surface

Drainage of the early part of the Hopi Buttes-Zuni cycle

Figure 1.—Map showing locations, ancient drainages, and travertine deposits in the southern part of Navajo and Apache Counties, Ariz.

late Pleistocene and partly during Recent times.

REGIONAL GROUND-WATER HYDROLOGY

The Coconino sandstone of Permian age is the most important aquifer in both counties. In some places where the Kaibab limestone is present, the Kaibab and Coconino form a single aquifer. This aquifer is recharged principally in the area near the Mogollon Rim, by direct recharge from precipitation and by indirect recharge from percolation of ground water through the overlying volcanic and sedimentary rocks. The movement of ground water in the Coconino sandstone is generally northward. Southwest of the Little Colorado River, the water in the aquifer is partly unconfined and partly confined, but northeast of the river the Coconino sandstone nearly everywhere contains water only under artesian conditions (Fig. 3A). The gradient of the piezometric surface is between 25 and 100 feet per mile. Discharge from the Coconino sandstone occurs principally in the Holbrook-Winslow and St. Johns areas. Ground water also discharges to Silver Creek near Snowflake. In the Holbrook-Winslow area, springs discharge into the alluvial channel of the Little Colorado River or along some of its larger tributaries, namely East Clear and Chevelon Creeks. In the St. Johns area, ground water in the syncline to the southwest of Cedar Mesa anticline is under artesian pressure and issues from several large springs in the Chinle and Moenkopi formations. Most of this water runs into the Little Colorado River and is diverted for irrigation. The springs have built up circular mounds of travertine that are more than 25 feet high and as much as 200 feet in diameter. In some of the mounds a clear pool of water more than 20 feet across, representing the spring orifice, is present at the surface and some of the pools stand a few feet above the surrounding land surface.

The Bidahochi formation yields water to drilled wells in the northeastern part of the area. The ground water in the Bidahochi is unconfined, but in many places the Bidahochi is not water bearing because post-Bidahochi erosion has trenched many drainages below its base, thereby draining the formation. The alluvium underlying the flood plain of the Little Colorado and some of the tributary streams yields sufficient ground water for stock and domestic use. The other sedimentary rocks and the volcanic rocks of the area usually yield only small quantities of ground water.

PALEOGEOHYDROLOGY

The ancestral valley of the Little Colorado River was excavated during the early part of the Hopi Buttes-Zuni cycle and the cutting was virtually completed by the end of Miocene time. This ancient valley was cut principally on soft Triassic strata and later was partially filled by the Bidahochi formation. The ancient valley was generally to the north and east of the present valley and extended from the St. Johns area northward to the Hopi Buttes (Fig. 1). There it formed a broad arc through the volcanic field. In places in the Hopi Buttes volcanic field, spring deposits associated with the volcanism are interbedded with the volcanic and sedimentary rocks of the Bidahochi formation, suggesting there was discharge of ground water from the Coconino sandstone to the ancestral Little Colorado River in late Tertiary time. Later, principally during early Quaternary time after erosion had stripped off much of the Triassic shales and the newly deposited Bidahochi formation, the points of discharge of

<table>
<tr><th colspan="5">AGE</th><th>CYCLE</th><th>EROSIONAL UNIT</th><th>DEPOSITIONAL UNIT</th></tr>
<tr><td rowspan="10">CENOZOIC</td><td rowspan="5">QUATERNARY</td><td colspan="3" rowspan="2">Recent</td><td rowspan="2">Recent</td><td rowspan="2">Channeling and arroyo cutting</td><td>Deposition of alluvium</td></tr>
<tr><td>No alluvial deposits recognized</td></tr>
<tr><td rowspan="3">PLEISTOCENE</td><td colspan="2">Late</td><td rowspan="2">Wupatki</td><td rowspan="2">Wupatki surfaces</td><td rowspan="2">Terrace deposits (10 to 125 feet thick)</td></tr>
<tr><td colspan="2">Middle</td></tr>
<tr><td colspan="2">Early</td><td rowspan="2">Black Point</td><td>Late Black Point surface</td><td>Terrace deposits (10 to 200 feet thick)</td></tr>
<tr><td rowspan="5">TERTIARY</td><td rowspan="3">PLIOCENE</td><td colspan="2">Late</td><td>Early Black Point surface</td><td>Terrace deposits (10 to 100 feet thick)</td></tr>
<tr><td colspan="2">Middle</td><td rowspan="3">Hopi Buttes—Zuni</td><td>Zuni surface</td><td>Upper and volcanic members of the Bidahochi formation (as much as 1,000 feet thick)</td></tr>
<tr><td colspan="2">Early</td><td rowspan="2">Hopi Buttes surface</td><td rowspan="2">Lower member of the Bidahochi formation (less than 200 feet thick)</td></tr>
<tr><td colspan="3" rowspan="2">Miocene</td></tr>
<tr><td>Pre-Hopi Buttes—Zuni</td><td>Erosion</td><td></td></tr>
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Figure 2. --Chart showing late Cenozoic geomorphic terminology used in the Little Colorado River drainage system, Navajo and Apache Counties, Ariz.

the Coconino sandstone were in the St. Johns and the Holbrook-Winslow areas. Downcutting continued throughout the Quaternary with the formation of the Black Point and Wupatki surfaces. Travertine deposited by ancient springs discharging from the Coconino overlies these surfaces. The points of discharge, as indicated by the distribution of travertine, shifted laterally as the Black Point and Wupatki surfaces were formed (Fig. 1). The distribution of travertine is the basis for a reconstruction of the geohydrology of the Coconino sandstone-Kaibab limestone aquifer in southern Navajo and Apache Counties during late Cenozoic time.

The oldest spring deposits in Navajo and Apache Counties are associated with the volcanic member of the Bidahochi formation in the Hopi Buttes volcanic field. Most of the spring activity is related to the formation of the prominent diatremes (volcanic vents or pipes) for which the field is noted (Fig. 3B). The spring deposits are composed of travertine with some siltstone and sandstone. The deposits, some more than a quarter of a mile in diameter, generally are enclosed by tuffs and lavas. The travertine must have been deposited from ground water discharged from the Coconino sandstone as this unit is the only aquifer in the Hopi Buttes field capable of supplying large quantities of water. The diatremes formed conduits for ground water discharged under artesian pressure through about 2, 500 feet of nearly impermeable Triassic rocks which lay between the land surface and the Coconino sandstone.

Discharge of ground water under artesian conditions is further evidence that the strata of the region were folded before the Bidahochi was deposited, because the recharge area of the Coconino sandstone in the Mogollon Rim area and on the Defiance uplift had to be considerably higher in altitude than the points of discharge in order to provide the artesian head. This corroborates the generally accepted early Tertiary age for most of the folding on the Colorado Plateau.

Basin filling with sandy, generally permeable sediments of the upper member of the Bidahochi formation created a ground-water reservoir. The top of this newly formed reservoir probably coincided with the highest deposits of the upper member, which were about 1, 000 feet above the top of the lower member and the spring deposits in the volcanic member (Fig. 3B). Throughout the deposition of the upper member, the ground-water conduits of the Hopi Buttes area were probably open, and water moving upward from the Coconino sandstone mixed with that in the Bidahochi formation.

The deposition of the Bidahochi formation was terminated by downcutting during the Black Point cycle throughout the Little Colorado system. The cutting lowered the base level resulting in progressive dewatering of the upper member of the Bidahochi and part of the Coconino sandstone. The drainage on the early Black Point surface was integrated and formed the initial course of the present Little Colorado River system (Fig. 1). Reconstruction of the drainage patterns, based on the terraces along the Zuni River, Rio Puerco, Pueblo Colorado Wash, and other larger southwest-flowing tributaries of the Little Colorado River, indicates that these streams had courses which approximated their present positions. Downstream from Hunt, the ancient course of the Little Colorado River was only slightly different from its present position. However, upstream from Hunt the main course of the ancestral Little Colorado is difficult to locate; it may have followed a course a short distance east of the modern Little Colorado River or have been coincident with the present course of Carrizo Wash. In the area south of Hunt, several lava flows of the White Mountains volcanic field show remnants of old drainages. The streams flowed

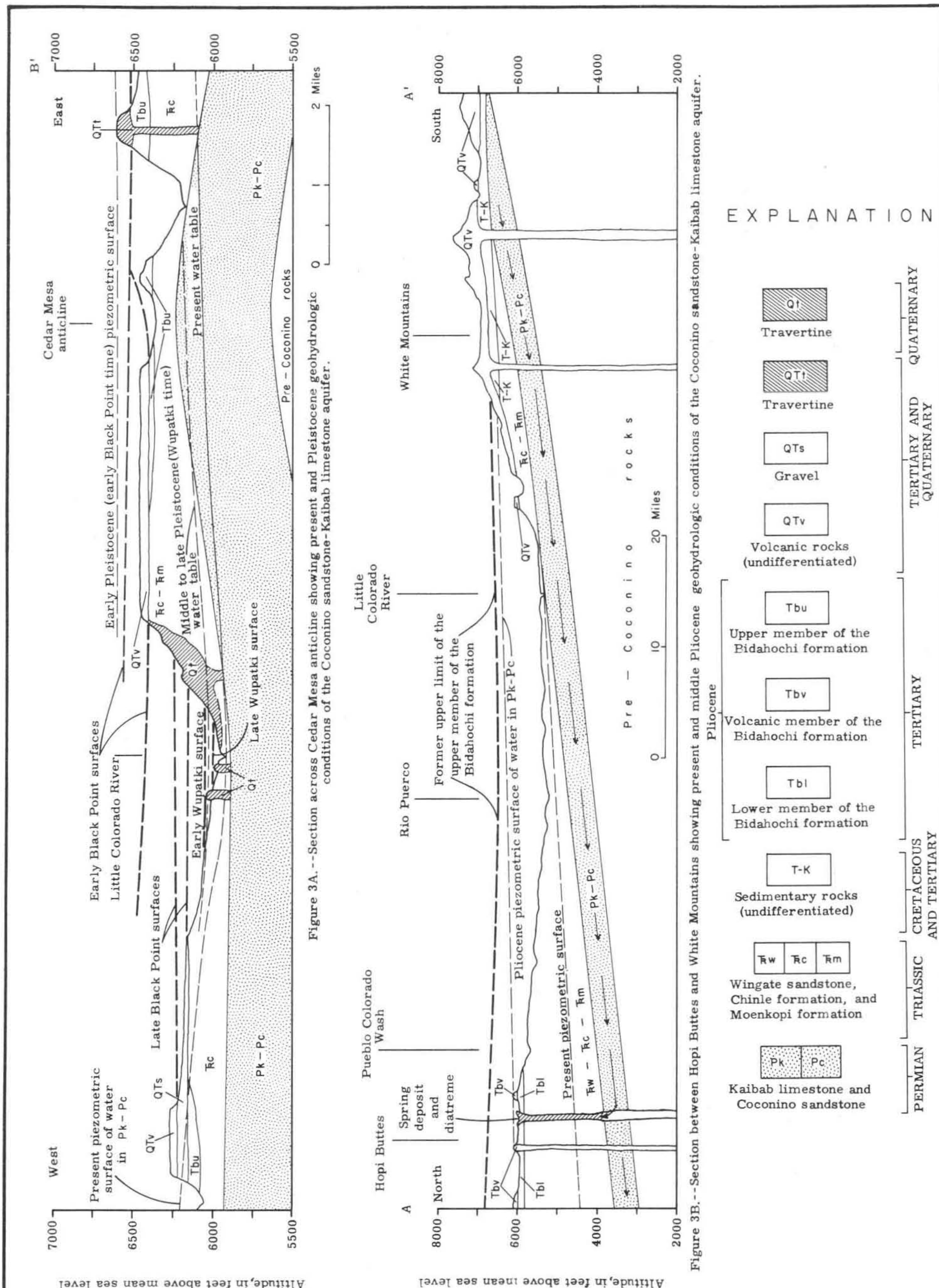

Figure 3A.--Section across Cedar Mesa anticline showing present and Pleistocene geohydrologic conditions of the Coconino sandstone-Kaibab limestone aquifer.

Figure 3B.--Section between Hopi Buttes and White Mountains showing present and middle Pliocene geohydrologic conditions of the Coconino sandstone-Kaibab limestone aquifer.

Figure 3.--Sections illustrating the paleogeohydrology of the Coconino sandstone and Bidahochi formation.

generally northward and northwestward to the ancient Little Colorado River.

The travertine deposited on the early Black Point surface, more than 400 feet above the present bed of the Little Colorado River, indicates that natural discharge from the Coconino sandstone-Kaibab limestone aquifer system in Navajo and Apache Counties was principally in two areas. One was along the crests of the St. Johns and Antelope Valley anticlines southeast of St. Johns, and the other was at Stinking Springs Mountains, on the Apache dome northeast of Hunt (Fig. 1). The travertine-depositing springs were probably in lowlands near the ancient stream courses, similar to the setting of springs presently discharging water from the Coconino sandstone-Kaibab limestone aquifer south of St. Johns. Near Antelope Valley anticline the travertine was deposited in an area of strong jointing and some faulting. Some of these deposits contain joints similar to those in the adjoining Upper Cretaceous strata. North of Apache dome, beds of the upper member of the Bidahochi formation have been tilted slightly, perhaps by recurrent folding movements associated with Apache dome.

As downcutting was accelerated slightly during the formation of the late Black Point surfaces, the streams flowing into the ancestral Little Colorado River from the White Mountains volcanic field cut valleys adjacent to the lavas which had flowed out on the early Black Point surfaces. These valleys were narrower and deeper than the early Black Point valleys. Possible recurrent movement on the St. Johns and Antelope Valley anticlines may have helped to shift the late Black Point drainage downdip along these structures. All the drainages of the late Black Point surfaces occupied positions nearly coincident with their present positions. The distribution of the travertine, at altitudes between 200 and 400 feet above the present stream beds on the late Black Point surfaces, suggests that the springs discharging ground water from the Coconino sandstone and Kaibab limestone (Fig. 1) also shifted laterally. These springs were in the area 5 miles south of St. Johns and along Carrizo Wash.

Erosion during the late part of the Black Point cycle continued, thus causing more of the Kaibab limestone and Coconino sandstone to be exposed. The uncovering of the Kaibab and Coconino allowed discharge from these formations directly to the land surface. Therefore, the piezometric surface was lowered, some dewatering of the formations occurred, and springs that had discharged onto the early Black Point surface dried up. Thus, by the end of early Pleistocene time, some dewatering of the aquifer had taken place on the crest of the Antelope Valley anticline and on the Holbrook anticline just north of Snowflake. The upper member of the Bidahochi formation in the area near the Little Colorado River was dewatered also, because erosion during late Black Point time had cut below the base of the formation, but in the upstream reaches of the tributaries it was only partially drained. During the formation of the Wupatki surfaces, the valleys of late Black Point time were widened and deepened nearly to their present size and depth.

The general entrenchment of the Little Colorado drainage system during late Cenozoic time caused a progressive lowering of the water table which decreased ground-water storage in all the water-bearing units, but this was most pronounced in the Bidahochi formation and in the Coconino sandstone-Kaibab limestone aquifer system. In the areas near the Little Colorado River where downcutting was greatest, the Bidahochi formation has been drained completely; but in the upstream regions of the tributary streams the cutting has not been as deep, and the Bidahochi in many places yields sufficient ground water for stock and domestic supplies. The piezometric surface of the Coconino sandstone-

Kaibab limestone aquifer near the Cedar Mesa anticline south of St. Johns, to cite an example, must have declined about 600 feet since the beginning of the Pleistocene and roughly 200 feet since the middle late Pleistocene (Fig. 3A). Since the end of deposition of the Bidahochi formation in Pliocene time, the piezometric surface has been lowered between 1, 200 and 1, 500 feet (Fig. 3B) in the Hopi Buttes area. The repeated cutting and partial filling by the Little Colorado River and its tributaries during the Black Point and Wupatki cycles affected the hydrology of the Coconino sandstone-Kaibab limestone aquifer. The cutting and filling, by lowering and raising the valley floors, also lowered or raised the ground-water discharge points, thus changing the areal extent of bodies of confined and unconfined water and altering the amount of ground water in storage in the aquifer. During the cutting of the modern valley of the Little Colorado River, possibly in late Pleistocene time and Recent time, many of the ground-water discharge points were 100 feet lower than at present, and the Coconino sandstone and Kaibab limestone contained less stored water than they do at present. Water-table conditions may have existed for a time in areas near the river where artesian conditions now exist. After the partial filling of the valley in Recent time, the present hydrologic conditions were established.

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