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PROGRESS REPORT ON THE LATE CENOZOIC GEOLOGIC EVOLUTION OF THE LOWER RIO PUERCO

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INTRODUCTION

The geologic evolution of the lower Rio Puerco has been studied during the past two years as part of a long-term New Mexico Bureau of Mines and Mineral Resources project in the Albuquerque Basin, and as part of two specific projects on the Rio Puerco related to archeology (Love and others, 1982) and possible mine-generated radionuclides in sediments (Popp and others, 1983). These two studies concentrated on deposits of the modern Rio Puerco and the valley fill, but we studied the adjacent valley borders as well to determine sediment sources and to provide a longer time framework. Observations of deposits exposed along the valley borders (Young, 1982) suggested that evolution of the tributary drainages was more complicated than previously described (Denny, 1941, 1967; Wright, 1946; Kelley, 1977). Subsequent reconnaissance of deposits along the tributaries draining the Ladron and Lucero Mountains south of Mesas Mohinas (fig. 1) revealed some details of the development of this corner of the Albuquerque Basin. These investigations, coupled with studies in nearby areas by Machette (1978a, 1978b, 1982; Machette and McGimsey, 1983) document considerable variations in the tectonic and depositional development of the Albuquerque Basin in late Cenozoic time.

The physiography and hydrology of the Rio Puerco drainage basin are described by Love and others (1982) and by Heath (this guidebook). This paper concentrates on the area between Mesas Mohinas, the Ladron Mountains, the foothills of southern Sierra Lucero, and the Llano de Albuquerque (fig. 1). The relatively low-relief valley border west of the Rio Puerco in this area is known as Sabinas Solas (Wright, 1946) or Llanos del Rio Puerco (Titus, 1963). A topographically lower part of Llanos del Rio Puerco, known as Montano Flats, occurs approximately 40 m above the present valley floor west of the Rio Puerco and slopes gently to the east. Valleys of major tributaries of the Rio Puerco, such as Comanche Arroyo and Coyote Draw, are incised from the foothills of the Lucero uplift to the Rio Puerco valley. Valleys of Arroyo Monte Belen, Alamito Arroyo, and Mariano Draw become incised midway across the Llanos del Rio Puerco.

Methods of study included detailed measurements of stratigraphic sections with standardized pebble counts (Young, 1982) and reconnaissance of surficial deposits and exposed sections with qualitative estimates of clast size, rounding, and composition. Complications are related to poor exposures, downslope movement of loose clasts, differential cementation, and possible tectonic juxtaposition. We sketched exposures of valley fill in greater detail to help interpret valley-fill stratigraphy for archeological purposes. Valley fill beneath present exposures was augered to a depth of 41 m (see Heath, this guidebook). We located fault scarps using aerial photographs and traced some scarps during reconnaissance field studies (fig. 2).

DESCRIPTIONS AND SEDIMENTOLOGIC IMPLICATIONS OF DEPOSITS EXPOSED ALONG THE LOWER RIO PUERCO

Although some exposures of lower basin fill (Popotosa Formation) occur adjacent to the Ladron Mountains, only the past several million years of basin evolution are considered below. Geochronologic events pertinent to the development of the area are listed in Table 1. The

Table 1. Geochronologic ages relevant to development of the lower Rio Puerco.

Age (m.y.)	Location	Method	Reference
0.14 (±0.038)	youngest Cat Hills flow	K-Ar on basalt	Kudo and others (1977)
0.32 (±0.2)	Cerro Verde-Suwanee flow	K-Ar on basalt	Bachman and Mehnert (1978)
0.62	ash in fluvial beds of Apache graben	correlation to Lava Creek B ash from Yellowstone	Izett and Wilcox (1982)
1.1	overlying Cerro de Los Lunas	correlation to Tsankawi ash of Jemez Mountains	Bachman and Mehnert (1978); Izett and others (1981)
1.01 (±0.10) 1.12 (±0.04) 1.31 (±0.05)	Cerro de Los Lunas	K-Ar on basalts	Bachman and Mehnert (1978)
1.1-1.3	Rio Grande valley	Cerro Toledo pumice and ash from Jemez	Izett and others (1981)
1.4	beneath Los Lunas volcano; correlative beneath basalt of Cat Mesa (?)	Guaje pumice and ash from Jemez	Izett and others (1981)
1.4-4.0	exposed fill in central Albuquerque Basin	Blancan-age fossil fauna	Tedford (1981)
3.34 (±0.16)	East Grants Ridge	K-Ar on obsidian	Lipman and Mehnert (1980)
2.92 (±0.86)	East Grants Ridge	K-Ar on basalt underlying the obsidian	Lipman and Mehnert (1980)
3.7 (±0.4)	Mesa Carrizo	K-Ar on basalt	Bachman and Mehnert (1978)
4.0 (±0.3)	Socorro area (miniumum date of through-flowing Rio Grande south of Albuquerque Basin)	K-Ar on basalt	Bachman and Mehnert (1978)
7.2 (±0.6)	Mesa Gallina (Sierra Lucero)	K-Ar on basalt	Bachman and Mehnert (1978)
8-11	Gabaldon Badlands	late Clarendonian fossil fauna	Tedford (1981)

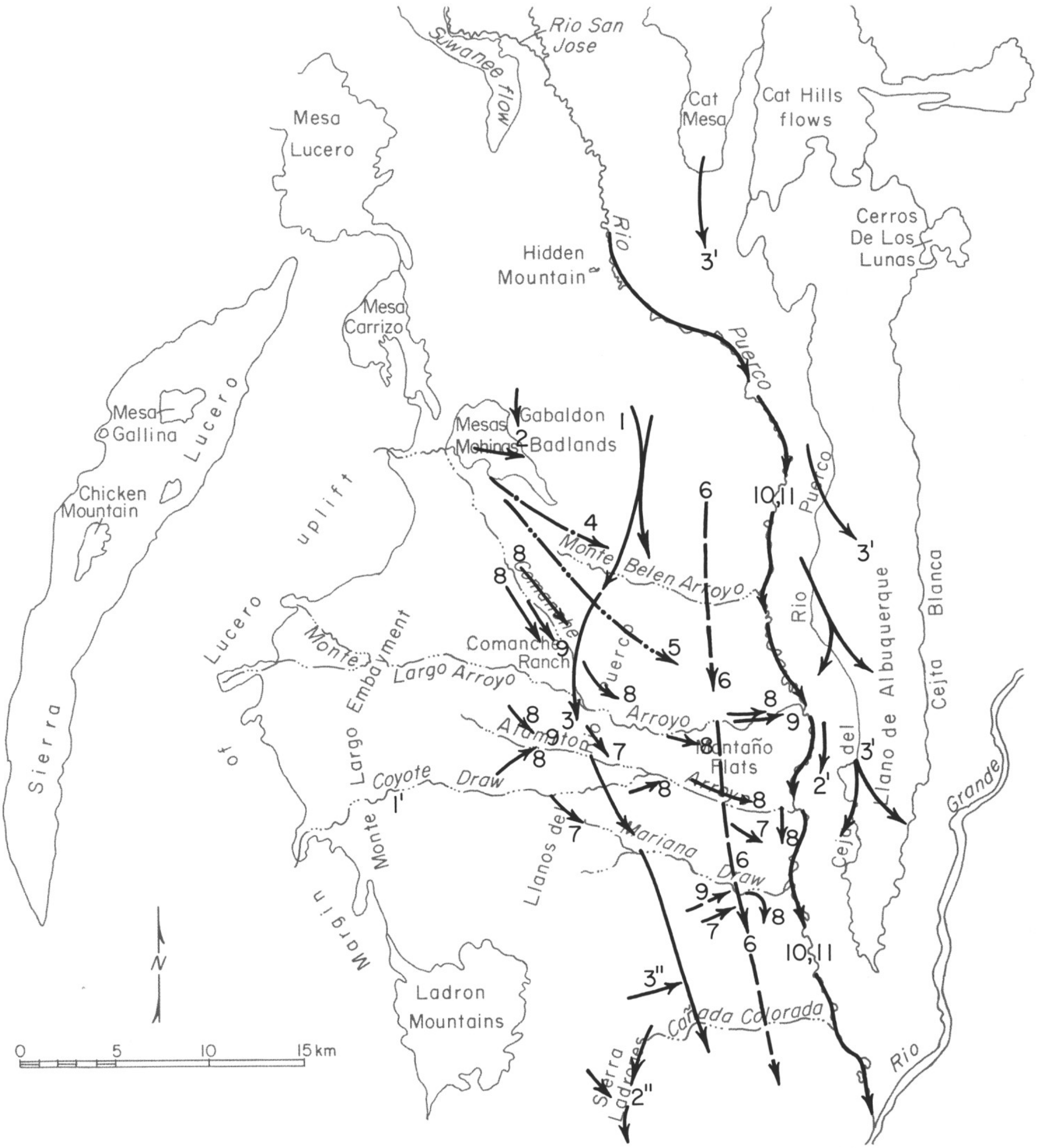

Figure 1. Late Cenozoic geomorphic features, deposits, and generalized patterns of sediment movement in the area of the lower Rio Puerco, New Mexico. Numbers and arrows indicate chronological sequence of deposits and transport directions discussed in text.

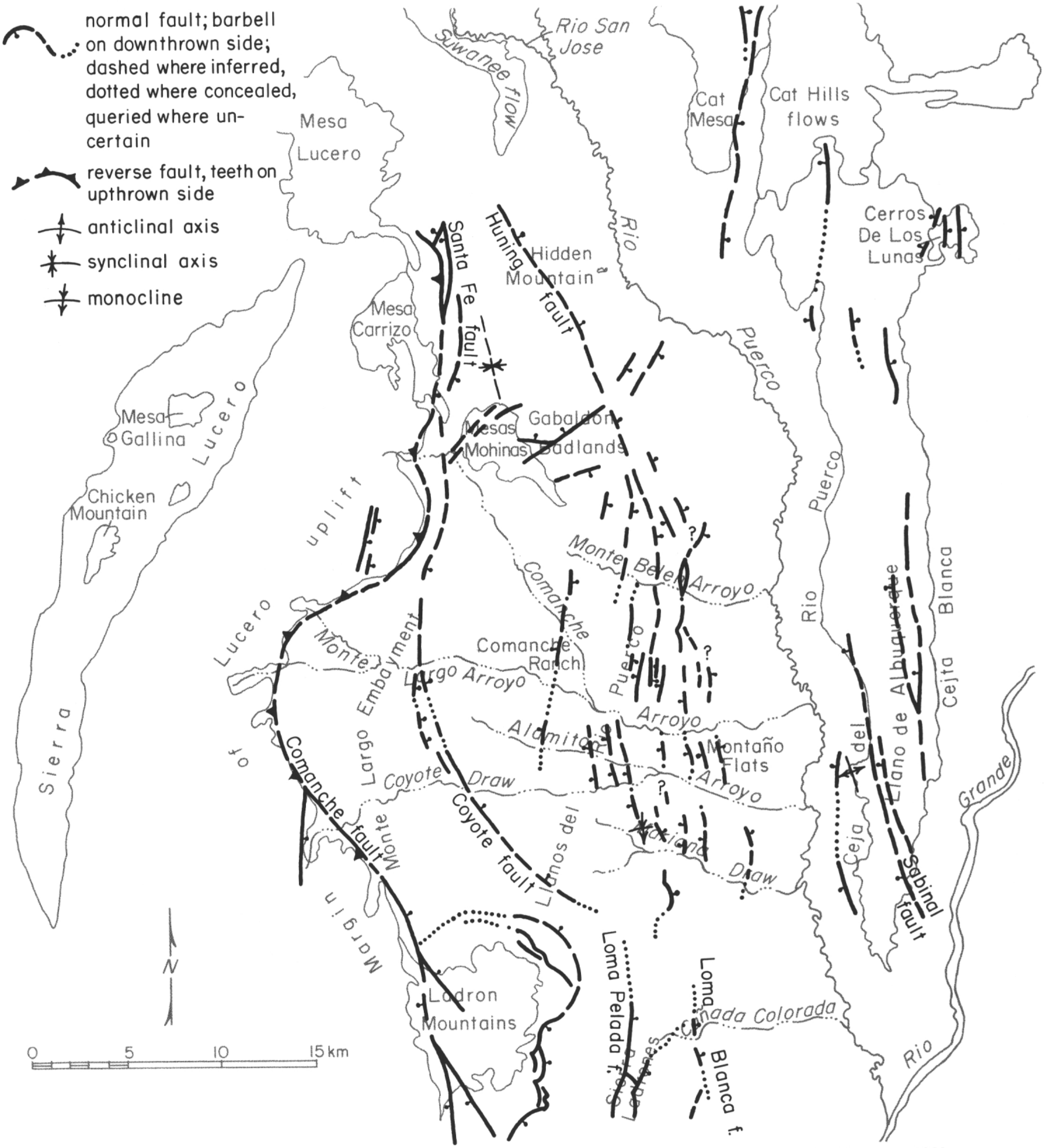

Figure 2. Late Cenozoic faults and folds of the lower Rio Puerco area (modified from Kelley, 1977; Machette, 1982).

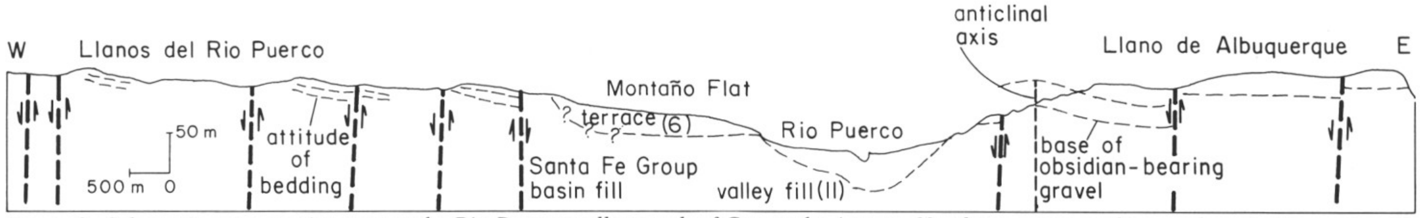

Figure 3. Schematic cross section across the Rio Puerco valley south of Comanche Arroyo. Numbers correspond to numbers in Figure 1 and to deposits discussed in text.

general pattern of sediment transport and locations of deposition through time are shown in Figure 1 in numbered sequence and are described below from oldest to youngest. Cross sections showing cross-cutting relationships of deposits exposed along the valley borders are illustrated in Figures 3 and 4. Numbers given to the events and correlative deposits are also used as informal designations for stratigraphic and morphostratigraphic units in the descriptions and discussion. For example, number (8) at several locations in Figure 1 and shown in the cross section in Figure 4 refers to deposits forming a fill terrace (8), while the surface of the terrace is referred to as topographic level (8).

Upper Popotosa Formation

Fine-grained deposits exposed in the lower part of the Gabaldon Badlands (location 1 of fig. I; Wright, 1946; Kelley, 1977; Tedford, 1981) and limited exposures of similar units at Coyote Springs (fig. I; location 1') reflect playa-like deposition between about 11 and 8 m.y. ago. These beds are considered a northward extension of the Popotosa Formation. Unlike exposures of piedmont facies in the Popotosa Formation southeast of the Ladron Mountains (Machette, 1978b), no sedimentologic indicators of major topographic relief of uplifts to the west or south are present in the Gabaldon Badlands. Sediment appears to have been contained within the closed Albuquerque Basin. Overlying intercalated sandstones and mudstones (Wright, 1946; Kelley, 1977) mark the beginning of prograding fans from the basin margins. Present dips range from 15 to 33 degrees to the west and southwest (Kelley, 1977) in the Gabaldon Badlands and approximately 20 degrees to the east at Coyote Springs.

Lower Sierra Ladrones Formation

The upper part of the section in the Gabaldon Badlands to the top of Mesas Mohinas (location 2 in fig. 1) consists of interbedded sandstones, conglomeratic sandstones, mudstones, and unconsolidated mud, sand, and sandy gravel (Kelley, 1977). Gravel beds as much as 4 m thick at the top of the section include clasts from both the adjacent Lucero uplift (basalt, limestone, and sandstone cobbles and boulders) and from distant sources to the north and west (cobbles and well-rounded pebbles of siliceous sediments, Precambrian plutonic and metamorphic rocks, and Cretaceous sandstone concretions and fossil shells). Significantly, no Grants obsidian has been recovered from these units. The units are interpreted to be braided-stream deposits from the north with local incursions of sediments derived from the Lucero uplift. These deposits are correlated with the Sierra Ladrones Formation to the south (Machette, 1978b; see below). Dips in the upper units generally are approximately 3 degrees to the southwest (Kelley, 1977).

To the east, in exposures along the base of the Llano de Albuquerque (fig. 1; location 2'), similar gravel beds with clasts from the north and northwest are intercalated with finer-grained reddish-brown sand and mud. Commonly the gravelly sand units are partially cemented with calcite. These lowermost units contain no Grants obsidian.

To the south, exposed in Sierra Ladrones (fig. 1; 2"), the Sierra Ladrones Formation is a thick sequence of fluvial sand and gravel interbedded with finer-grained units and intercalated with piedmont facies from the Ladron Mountains (Machette, 1978b). The fluvial unit indicates a major south-flowing axial stream. These deposits are thought to be related to other fluvial deposits older than 3 m.y. (fig. 1; 2) because no Grants obsidian has been reported from them and because they cannot be traced from Sierra Ladrones northward to Canada Colorada, where later obsidian-bearing deposits and correlative piedmont deposits interfinger farther to the east.

Upper Sierra Ladrones Formation

Sometime after eruptions of obsidian and perlite near Grants about 3 m.y. ago (Table 1), clasts of obsidian began to appear in gravel-bearing channels along with the suite of well-rounded siliceous sediments, Precambrian metamorphic and plutonic rocks, Cretaceous sandstone and fossil shells, and minor limestone and basalt. The channel fills range up to several meters thick with flow-direction indicators oriented to the south, southeast, and southwest, but the channels are laterally discontinuous over several hundred meters. Obsidian-bearing channel fills occur from a level of at least 26 m below the Llano de Albuquerque surface to the top, and range laterally from Cat Mesa on the north to at least Canada Colorada to the south, and from Comanche (Huning) Ranch on the west (fig. 1; 3) to the Cejita Blanca scarp on the east. Cementation of the gravel-bearing units decreases upward in sections exposed along the flanks of the Llano de Albuquerque (fig. 1; 3'). Along westernmost exposures, gravels derived from the Lucero and Ladron Mountains intertongue with gravels from the north. Locally derived gravels also include flat-pebble clasts composed of earlier cemented basin fill (fig. 1; 3"). The gravelly sand facies exposed at upper stratigraphic levels throughout the Albuquerque Basin indicates an extensive alluvial plain coursed by south-southeastward-flowing streams.

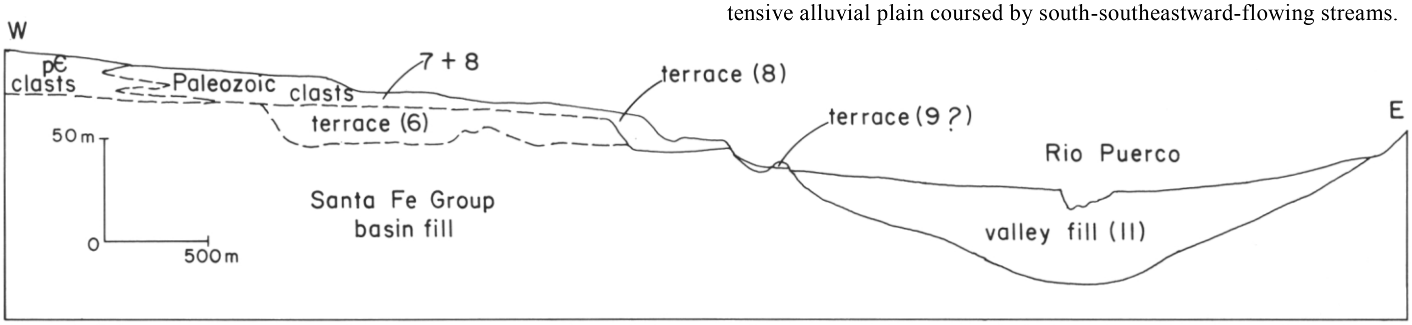

Figure 4. Schematic cross section of the western margin of the Rio Puerco valley south of the mouth of Mariano Draw. Numbers refer to deposits discussed in text.

The braided streams shifted laterally across the basin, locally filling in low areas in the southwest corner of the basin. Interfluve areas developed finer-grained facies, soils, and local arroyo-like channels, but aggradation dominated the entire basin. During at least the late stages of basin aggradation, the Rio Grande dominated the east-central part of the basin but apparently did not shift west of the central Llano de Albuquerque. Aggradation of these channels and the related fine-grained facies was the culmination of filling of the southwestern and south-central Albuquerque Basin. The Llano de Albuquerque geomorphic surface is a remnant of the top of this fill, which is thought to be between 500,000 and 1 ,000 ,000 yrs old (Bachman and Machette, 1977; see below).

Incision of the Rio Puerco

Initial incision of the Rio Puerco may have been due to several factors, including increased, concentrated discharge, tectonics, and increased gradient from changing regime of the Rio Grande. The uppermost channel deposits preserved on Cat Mesa and on the east flank of Mesas Mohinas are particularly coarse grained and laterally extensive, with flow directions predominantly to the south. Further increases in discharge may have initiated cutting of the Rio Puerco valley.

Denny (1941) and Wright (1946) suggested that faulting along the Rio Puerco diverted drainages southward and caused incision of the Rio Puerco valley. Faults parallel to and adjacent to the lower Rio Puerco valley (figs. 2 and 3; see below) indicate a poorly defined graben straddling the valley. The river may have been confined in this fault-controlled low area.

When the Rio Grande began to incise its present valley, the Rio Puerco may have begun to incise in response to lowered base level. Possibly the junction between the Rio Puerco and the Rio Grande shifted to the north, causing a steeper gradient and incision along the lower reaches of the Rio Puerco.

Unpaired High Terraces of Comanche Arroyo

After southward-flowing channels no longer contributed sediment to the Comanche Ranch area, ancestral channels of Comanche Arroyo flowed from the Lucero uplift across fine-grained reddish-brown basin fill exposed on the southwest flank of Mesas Mohinas (fig. 1; 4) and further south (fig. 1; 5) across obsidian-bearing deposits toward the Rio Puerco. No topographically equivalent deposits exist south or west of the present course of Comanche Arroyo, nor known correlative levels of a slightly incised Rio Puerco.

Terraces of the Rio Puerco and Deposits along Tributary Drainages

Possible terrace remnants along the Rio Puerco occur at 55-61 m, 35-40 m, 24-30 m, 6-8 m, and 3 m above the present valley floor, but the first major aggradational terrace (fig. 1; 6) occurs from 10-42 m above the valley floor, forming Montano Flats (approximately 50 m below the surface of the Llano de Albuquerque, figs. 3 and 4). Fill consists of gravel channels 2-3 m thick intercalated with pebbly channel sand, unconsolidated reddish-brown sand, silt, and clay very similar to basin-fill sediments. Clasts in the gravel channels include boulders and cobbles of cemented basin fill, as well as well-rounded cobbles and pebbles of siliceous rocks, Precambrian plutonic and metamorphic rocks, limestone, sandstone, basalt, and obsidian. The gravel units are uncemented except in rare local areas. Tributary-channel facies are also cemented locally.

Deposits occurring on modern drainage divides of western tributaries (fig. 1; 7) consist of clasts from the Ladron and Lucero Mountains. These deposits probably are not synchronous, but appear to be related to terrace deposits described above (fig. 1; 6) or below (fig. 1; 8). Locally, tributary or piedmont deposits of (fig. 1; 7) overlie terrace deposits of (fig. 1; 6). Deposits along divides south of Comanche Ranch indicate a lack of incised drainages in this area at that time, perhaps analogous to the present anastomosing channels of the Monte Largo embayment. To the east none of the highest interfluves between tributaries from the Lucero Mountains are capped with clasts from the mountains. The interfluves are underlain by facies of the earlier southward-flowing streams.

Terrace deposits (fig. 1; locs. 8; fig. 4, deposit 8) cross-cutting the major terrace (fig. 4; deposit 6) are primarily preserved along tributary drainages, but overlap a low gravel terrace of the Rio Puerco at the mouths of some tributaries. Deposits range up to 20 m thick and locally are well indurated. Depositional units consist of gravelly sand (or conglomeratic sandstone) 1-2 m thick intercalated with fine-grained reddish-brown sand and clay. Clasts of limestone, basalt, and reddish-brown sandstone predominate in terraces of the tributaries. Some transport of clasts of Precambrian rocks from the Ladron Mountains north to Alamito Arroyo may have taken place at this time (fig. 1).

The deposits of the two major terraces (fig. 1; 6 and 8) indicate that even though the fluvial systems became confined in stream valleys, streams continued to flow in coarse-grained braided channels with fine-grained interchannel areas similar to the facies of the previous unconfined alluvial plain.

At least one lower unconsolidated terrace occurs along tributaries (fig. 1; 9). The terrace fill is at least 13 m thick. The deposits consist of crossbedded gravelly sand similar to coarse-grained modern arroyo deposits. Facies in the lowest terrace near the mouth of Comanche Arroyo suggest a change in fluvial regime closer to conditions of modern tributary arroyo channels. Like present tributary arroyo channels, fluvial sorting of fine- and coarse-grained sediments into separate facies within the terrace is incomplete, so that individual crossbedded units contain clasts ranging from clay to boulders. Correlative deposits along the Rio Puerco have yet to be recognized.

Rio Puerco Valley Floor

Sometime after aggradation of valley floors to level (fig. 4; 9), the valley of the Rio Puerco and tributary valleys were incised, and most of the previous fill was removed (fig. 1; 10). Along the Rio Puerco the depth of incision is at least 41 m below the present valley floor. Cobbly gravel and coarse sand, similar to basal sections of previous terraces, have not been penetrated in auger holes. Aggradation of the valley floor to its present level apparently proceeded in a series of cuts and fills with depositional facies consisting of sand, silt, and clay of flow regimes similar to modern conditions (see Heath, this guidebook).

Channel facies within fill beneath the valley floor are consistently more fine grained than older channels, and facies of silt and clay are more dominant than in earlier fluvial regimes. Although similar facies may be found locally in earlier deposits, the breadth and thickness of the relatively fine-grained deposits confined to the valley floor is without precedent.

Cuts and Fills Exposed in the Valley Fill

In the uppermost 11 m of fill exposed along the Rio Puerco and its tributaries, several buried channels of cycles of cut-and-fill may be traced (fig. 5). Although most of the deposits remain to be dated, archeological sites buried within 1-2 m of the present valley floor are 2,000-3,000 yrs old, indicating that most of the valley floor aggraded prior to 3,000 yrs ago. At least three major channels have cut and filled during the past 3,000 yrs and other major channels are more deeply buried in the fill (fig. 5). Two of the youngest channels are more than 8 m deep and 40 m wide and are filled predominantly with sand. Sedimentary structures in the channel dated about 150 B.C. (I of fig. 5) suggest conditions similar to the modern inner channel and inner floodplain (minus most vegetation such as tamarisk; Heath, this guide-

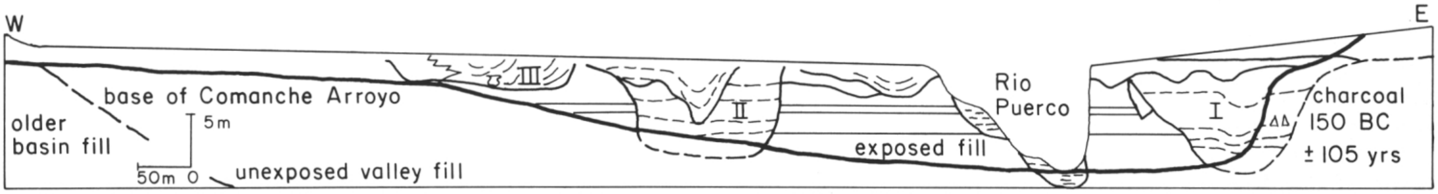

Figure 5. Schematic cross section of Rio Puerco valley fill near the mouth of Comanche Arroyo. Numbered channels are discussed in text.

book). Sedimentary structures in the younger sandy channel (II of fig. 5) suggest that it aggraded by depositing almost horizontal sheets as much as 1 m thick as a braided, sandy stream confined by arroyo banks. The youngest buried channels recognized so far (III of fig. 5) are as much as 6 m deep and have pottery in their fill. At Pottery Mound, a large Pueblo IV site along the banks of the Rio Puerco northeast of the Gabaldon Badlands, a buried channel with a well-sorted, crossbedded sandy base contains pottery dated between A.D. 1325 and 1450. Two buried tributary channels related to this buried channel are filled with locally eroded deposits and trash from the pueblo; one has adobe structures built on top of it.

Near the mouth of Comanche Arroyo (fig. 5), a 4-m deep channel similar to the main buried channel at Pottery Mound has potsherds of Pueblo age (A.D. 900 to 1250). These may have been reworked into the channel later, so the buried channel may correlate with the buried channels at Pottery Mound, or this channel may have been active earlier.

These buried shallow channels all have cross-laminated sand along their base, but are dominated by silt and clay in point-bar deposits. The facies indicate extensive lateral shifts of the channels, reworking the upper part of the valley fill. Apparently the channels were part of a tightly meandering stream system along the valley floor.

Entrenchment of Present Rio Puerco Arroyo

The entrenchment of the lower Rio Puerco to form the present arroyo apparently took place episodically since at least the 1760's. There was a gully near the present junction of the Rio Puerco and Rio San Jose mentioned in letters by Spanish settlers written in 1761-1765 (Betancourt, 1980; F. Wosniak, 1983, personal commun.). Anglo explorers and surveyors of the middle and late 1800's reported depths of 6 m for the incised channel of the lower Rio Puerco (Betancourt, 1980).

Later episodic incision to depths as much as 13 m postdate 1880 (clinker from the railroad and glass in the deposits) and apparently are related to large floods. Channel stabilization is due to periods of low flow and to growth of tamarisk (see Heath, this guidebook).

GEOMORPHIC SURFACES OF THE LOWER RIO PUERCO

Denny (1941, 1967) and Wright (1946) described four pediment surfaces in the southern Albuquerque Basin based on reconnaissance, interpretation of aerial photographs, and correlation to earlier work by Bryan (1932). As suggested by Wright (1946), further work (M. Machette, 1980, personal commun.) and this study indicate that the surfaces are more complicated than a fourfold division. Machette felt that regional correlation of only four pediment surfaces and use of previously proposed names could not be justified because numerous relatively planar geomorphic features have developed in different ways (most are not pediments) at different times and are not necessarily related. For example, on the north side of the Ladron Mountains, the two younger pediments mapped by Denny are essentially the same deposit separated by the Coyote fault (Kelley, 1977; Machette, 1982). Other pediment remnants are bounded by faults as well. Therefore these remnant pediments are not related to geomorphic processes in dynamic equilibrium, as suggested by Denny (1967). Some piedmont areas have been stable enough to develop stage III to stage IV k-horizons in soils (Gile and others, 1966), while other piedmonts at similar topographic positions continue to be active areas of sedimentation and erosion. In local areas near the Ladron Mountains, piedmont surfaces have been uplifted and appear tilted more steeply away from the mountains than present gradients of streams and alluvial fans. A relative sequence of piedmont deposition, faulting, and erosion occurs along the base of the Ladron and Lucero Mountains, but determining the order of the sequence will require more detailed work. The relationship of these piedmont deposits to terrace deposits along the Rio Puerco remains to be determined as well.

Recognizable geomorphic surfaces marking the upper limits of aggradational sequences nearer the center of the Albuquerque basin and along the Rio Puerco include the Llano de Albuquerque (Bachman and Machette, 1977), Montatio Flats and their northward and southward extensions, the inset terraces of (fig. 4; 8) and (fig. 4; 9), and the present valley floor (fig. 4; 11). These may be related to terrace levels along the Rio Grande (Lambert and others, 1982; Machette, 1978b, 1978c; Lozinsky, 1982; Gile and others, 1981). The Llano de Albuquerque may be traced northward to Albuquerque, whereas lower, inset terraces along both the Rio Puerco and Rio Grande are discontinuous. The Llano de Albuquerque is correlative with the major La Mesa surface of the Rio Grande valley of southern New Mexico (Hawley, 1978).

Although no major terrace has been noted along the lower Rio Puerco that could be correlative with the Tercero Alto surface (Bachman and Machette, 1977) 73 m above the Rio Grande near Albuquerque or the high terraces east of Belen (Titus, 1963; Hawley and others, 1982), the deposits beneath the Suwanee basalt flow 75 m above the present valley floor may be about the same age.

Montano Flats have approximately the same relative topographic position above the Rio Puerco (40 m) as the Segundo Alto has above the Rio Grande (40 m) near Albuquerque and farther south. The alluvial facies beneath Montafio Flats are similar to the facies of Los Duranes alluvium, which underlies Segundo Alto. Both Montalio Flats and Segundo Alto may be correlated with unit E of Machette (1978b) and with the Tortugas geomorphic surface of southern New Mexico. Locally, the Tortugas is a complex of at least two surfaces (Gile and others, 1981). Along the Rio Puerco, younger terrace deposits (fig. 4; 8) attain the same level as the older terrace deposits (fig. 4; 6) of Montafio Flats. The surface of the deposits of (fig. 4; 8) may be correlative with alluvial unit D of Machette (1978b) and with the younger of the two Tortugas surfaces, or with the Picacho surface. A twofold division of Los Duranes alluvium near Albuquerque has not been recognized.

The terrace underlain by deposits (9) may be related to Edith and Menaul alluvial deposits of the Albuquerque area, to alluvial unit C of Machette (1978b), and to deposits beneath the Picacho surface of southern New Mexico. Alternatively, correlations of the terraces along the Rio Puerco with Rio Grande terraces may be shifted back to the next older terraces along the Rio Grande. Recognition of more complex crosscutting stratigraphy within the terraces of the Rio Puerco is also possible.

RELATIONSHIPS OF DEPOSITS TO TECTONICS OF THE SOUTHWEST ALBUQUERQUE BASIN

Although the ages of most of the deposits of the lower Rio Puerco are only crudely estimated, they are useful in evaluating timing and style of tectonics in the southwest corner of the Albuquerque Basin. Faults and other tectonic features affecting deposits of the lower Rio Puerco are shown in Figure 2. Deformation in the area is discussed chronologically in terms of the deposits described above.

Deposits in the lower part of the Gabaldon Badlands are dated between about 8 and 11 m.y. ago (Tedford, 1981). Correlative deposits probably are buried hundreds of meters beneath the Llano de Albuquerque (based on correlations discussed below). The playa-like deposits give no indication of the Lucero uplift to the west. However, the basalts resting on the crest of the Sierra Lucero dated at 7.2 ± 0.6 m.y. (Bachman and Mehnert, 1978) are separated from deposits in the Gabaldon Badlands that may be correlative by approximately 800 m of vertical relief. Some of this topographic relief may have existed at the time of eruption of the basalts, but some separation appears to be due to tectonics after 7 m.y. ago.

The basalts along the crest of Sierra Lucero are separated topographically from basalts of Mesa Carrizo (radiometrically dated at 3.7 ± 0.4 m.y.; Bachman and Mehnert, 1978) by approximately 490 m of relief. No known major faults exist between the two basalt-capped mesas, and although tectonic upwarping may exist, the topographic relief is mainly due to erosion. Because the original topographic position of the basalts presently on the crest of the Sierra Lucero is not known, the amount of topographic relief developed between 7.2 and 3.7 m.y. ago remains to be determined.

The lower deposits of the Gabaldon Badlands dip 15-33 degrees to the southwest (Kelley, 1977), whereas possibly correlative deposits near Coyote Springs dip approximately 20 degrees to the east-northeast, and Upper Paleozoic bedrock east of the uplift-bounding Comanche fault in the Monte Large embayment dips approximately 40 degrees to the east (Callender and Zilinski, 1976, fig. 8). These dips imply a flexure or fault south of Mesas Mohinas, perhaps just southwest of Comanche Ranch.

The uppermost deposits preserved in the Gabaldon Badlands (location 2 of fig. 1) contain boulders of basalts and locally derived clasts of Paleozoic sedimentary rocks, as well as clasts from a fluvial system from the north. The basalt boulders are probably derived from the nearby flows of Mesa Carrizo (3.7 m.y.), but the streams from the north carried no Grants obsidian (as contained in deposits less than 3 m.y. old). The uppermost deposits of the Gabaldon Badlands are separated from the Mesa Carrizo flows by approximately 120 m of vertical relief and 3-7 km horizontal distance. Although this separation possibly represents actual topographic relief and steep local stream gradients of that time, the eastern flows of Mesa Carrizo are cut by faults and downdropped into the Albuquerque Basin 12-25 m. Other possible faults east of the Mesa Carrizo flows could have dropped the Gabaldon deposits even farther, but uplift of the Gabaldon Badlands also occurred (see below).

Farther east in the Albuquerque Basin (2' in fig. 1), pre-obsidian deposits occur approximately 200 m below similar deposits of Mesas Mohinas (upper Gabaldon Badlands). Because both deposits contain laterally extensive braided-stream sand and gravel from the north, vertical separation probably is due to tectonics rather than to stream gradients. Several lines of evidence indicate uplift and westward tilting of the Gabaldon Badlands relative to the rest of the Albuquerque Basin. First, the playa-like sediments exposed in the lower badlands are not exposed in most of the Albuquerque Basin. Second, obsidian-bearing gravels aggrade to similar elevations on both sides of the Rio Puerco along the Llano de Albuquerque and Comanche Ranch area south of the badlands, indicating that late basin fill reached a common final depositional level. Sufficient uplift of the Gabaldon block apparently terminated deposition on the crest of the block prior to the onset of deposition of obsidian-bearing gravels in the remainder of the southern Albuquerque Basin. Third, obsidian-bearing gravels along the east flank of the Gabaldon Badlands are 60 m higher than the Llano de Albuquerque. Fourth, at least two levels of deposits (4 and 5 of fig. 1) of ancestral Comanche Arroyo occur on the southwest slope of Mesas Mohinas. These levels have no correlative levels southwest of Comanche Arroyo, because the entire landscape is lower to the south.

Sometime near the cessation of deposition of obsidian-bearing gravel, but prior to subsequent development of extensive piedmont deposits from the Lucero and northern Ladron Mountains, several faults cut the Llanos del Rio Puerco. Major movements along at least five of these faults involved separations with the west sides down and tilting of the blocks to the east (figs. 2 and 3). Initial movements of these faults isolated interfluves of tributaries so that these areas were not covered with sediments derived from the Ladron or Lucero Mountains. Movement along the faults may have been recurrent, with some offset (2 m or less?) of terraces (8) or (9) occurring in late Pleistocene time. Machette and McGimsey (1983) suggest mid-Pleistocene or younger movement along these faults, based on subdued slopes of the scarps.

Machette (1982) and Machette and McGimsey (1983) estimated latest Pleistocene to possibly early Holocene movement on part of Coyote fault (Kelley, 1977) north of the Ladron Mountains and late Pleistocene movement on parts of the Loma Peleda, Loma Blanca, Cliff, and Sabinal faults (fig. 2), based on scarp morphology and soil development.

The faults and the attitudes of exposed beds east of the Lucero uplift and south of Comanche Ranch suggest that the Monte Largo embayment and Llanos del Rio Puerco area are underlain by faulted, basinward-dipping (eastward) strata including prebasin units. This interpretation is consistent with cross sections prepared by Kelley and Wood (1946), Kelley (1977), Brown and others (1980), and a gravity model presented by Cape and others (1983). The attitudes of exposed beds and faults do not corroborate the attitude of subsurface strata and faults interpreted by Cape and others (1983).

The upper part of the basin fill is folded into broad, open anticlines, synclines, and monoclines in at least three places in the study area (fig. 2). A broad anticline trends northwest-southeast along the Ceja del Rio Puerco east of Alamito Arroyo. A syncline trends northwest-southeast north of Mesas Mohinas (Kelley, 1977), and a south-facing monocline occurs on the north side of Mariano Draw. Local folds occur as drag adjacent to faults.

Deformation in the southern Albuquerque Basin has influenced some stream courses and deposition. As discussed above, the position of the lower Rio Puerco valley may have been due to faulting. Minor tributary drainages of the major east-west arroyos crossing the Llanos del Rio Puerco follow north-south-trending faults. Deposition of obsidian-bearing gravels has been influenced by the Huning fault on the east and northeast sides of the Gabaldon Badlands. In this area, no obsidian occurs west of the fault. Machette (1978a, 1982) has used sedimentation and soil development on the down-faulted sides of faults to determine ages of movement for recurrent faults in the area.

SUMMARY

Late Tertiary to Quaternary deposits exposed along the lower Rio Puerco show the sedimentologic and geomorphic development of the southern Albuquerque Basin and later tectonic deformation. The lowest exposed deposits (upper Popotosa Formation) are fine-grained playa deposits which range from 8 to 11 m.y. old, yet show no indication of nearby uplifts, in contrast to piedmont deposits developed farther to the south (Machette, 1978b). Later, fluvial deposits from the northwest spread across the southern Albuquerque Basin, interfingering with piedmont deposits from the Lucero and Ladron uplifts. Prior to 3 m.y. ago, the Mesas Mohinas area began to be uplifted and tilted to the southwest. Fluvial deposits containing obsidian from Grants flowed around the

uplifted block and continued to fill the Albuquerque Basin. After aggradation of the basin ceased, the geomorphic surface marking the top of basin fill was cut by several north-trending recurrent faults and locally was folded. Initial incision of the Rio Puerco valley about 0.5-1.0 m.y. ago could have been due to increased discharge, concentration of flow along a north-trending graben, or increased gradient following downcutting of the Rio Grande at the mouth of the Rio Puerco. Terraces along the Rio Puerco and its tributaries reflect episodes of aggradation within the valley, which correspond to terrace levels along the Rio Grande. Clasts within terraces of tributaries of the Rio Puerco indicate lateral shifts of contributary drainages in the western part of the basin. Unpaired high terrace-like deposits along the north side of Comanche Arroyo are uplifted and tilted along the Mesas Mohinas block. Lower terraces may be slightly offset by recurrent movement on faults.

Fill of the present valley floor is more than 41 m thick, consisting of fine sand, silt, and clay with minor amounts of gravel reworked from the valley borders. Numerous cuts and fills are evident within the exposed valley fill of the Rio Puerco. At least three major channels postdate 2,100 yrs ago. These indicate three modes of channel behavior for the Rio Puerco, depending on the amount of sand, silt, and clay available to the channel, The present 8- to 13-m incision of the Rio Puerco was initiated by 1765 and has been cut in stages. Documented large floods during the 20th century are responsible for further incision, while periods of low flow and growth of vegetation have stabilized the present channel level.

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