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ARCHITECTURE OF BURIED BLUFF LINES: A RECORD OF THE INCISING ANCESTRAL RIO GRANDE AND ABO ARROYO FROM THE PLEISTOCENE TO HISTORICAL TIMES

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Abstract—Approximately 6 km east of the mouth of Abo Arroyo on the active floodplain of the Rio Grande, New Mexico, a 400-m exposure in the arroyo wall shows five preserved bluffs with buttress unconformities between Abo Arroyo and ancestral Rio Grande-derived sediments. The sources of sediments are identified by sediment color, clast types and bedding fabric. Ancestral Rio Grande sediments are pale, moderately well-sorted, and, where exposed, have basal straths immediately overlain by very well-rounded quartzite-bearing gravels and cobbles. Abo Arroyo sediments are red, show east-to-west inclined bedding in some places, are poorly sorted, and, in coarse facies, have subangular clasts from the catchment area. The oldest sediments, which Bluff 1 cross-cuts, are approximately 2.2 Ma, and the most recent sediments, younger than Bluff 5, have been deposited in the last century. The depositional history between Bluff 1 and Bluff 5 is difficult to interpret because of lack of age control, but cross-cutting relationships indicate the following. The oldest sediments in Bluff 1 were deposited during the aggrading period of the ancestral Rio Grande that ended at 800 ka. During the following 800 ky, the ancestral Rio Grande cut Bluffs 1-4. After cutting each bluff, the ancestral Rio Grande aggraded slightly and deposited floodplain sediments. The floodplain and distal Abo Arroyo fan deposits are interbedded, and grade upward into coarser Abo Arroyo pebbly sands. Bluff 1 was not exposed long enough to develop a wedge of colluvium before being buried. Bluffs 2 and 3 were buried by colluvium. Between Bluffs 2 and 3, it appears that there are continuous ancestral Rio Grande floodplain deposits, Abo Arroyo muds and steepening-upward fan deposits. Bluff 3 formed west of an older natural levee. Bluff 4 does not have colluvium and was rapidly buried by Abo Arroyo deposits. Bluff 5 was formed during recent (historical) incision by Abo Arroyo. This sequence shows the complex stratigraphic heterogeneity along the margin of axial river systems. It is difficult, if not impossible, to predict the subsurface depth to good aquifers in these sediments, given the intercalation of marginal tributary fans and streams with axial river bluff lines.

INTRODUCTION

Erosional and depositional interactions between axial rivers and tributaries lead to geometrically complicated contacts (Leeder, 2011). Deposits of the two systems may interfinger, showing finely preserved sedimentary structures, or may exhibit buttress unconformities along incised, and commonly colluviated bluff lines. The depositional history of river/tributary interfaces may also help to interpret the regional history of the river system. However, most mapping necessarily simplifies the finer-scale, three-dimensional geometric features of the axial and transverse river interfaces. The geometry of these junctions can challenge our interpretations of the activity of both axial rivers and tributaries, and complicate subsurface fluid flow paths after burial. Preserved buttress unconformities can act as traps or aquitards. They can also cause fluid flow—and the transport of contaminants—to deviate from regional head gradients (i.e., Davis et al., 1993; Love et al., 1999). To better understand the range of possible complications to fluid flow, detailed descriptions of such contacts between axial river deposits and tributary alluvial deposits are needed.

Detailed descriptions of interacting axial river/tributary deposits are also necessary to inform our understanding of geomorphic processes, such as terrace formation. Strath terrace formation is a complicated process that is thought to reflect climate cycles (Gile et al., 1981; Bull, 1991; Hancock and Anderson, 2002; Delong et al., 2008; Mack et al., 2011). Conceptually, strath terraces are thought to form when a stream overtops neighboring deposits because of high sediment and water flows, then erodes down into those deposits and leaves a gravel lag that is subsequently buried by sand and muds as sediment fluxes drop. At some point, the river incises down, leaving a bluff line, and the cycle is thought to repeat in a narrower confinement. This conceptual model assumes that tectonism is slow compared to the climate-driven geomorphic activity of the river (Gile et al., 1981; Bull, 1994; Hancock and Anderson, 2002).

Interaction of transverse rivers with axial rivers complicates this conceptual model. Leeder and Mack (2001) summarize a conceptual model for “toe-cutting”, or lateral erosion of alluvial fans and transverse river deposits by larger axial rivers. In this case, the axial river does not overtop the neighboring alluvial fan, but rather erodes away the deposits closest to the river as the axial river avulses laterally. The river leaves a terrace, possibly a strath terrace, behind. The conceptual model is that climate changes—that impact both water and sediment fluxes in the axial and transverse rivers—lead to the lateral erosion of the transverse stream and alluvial fan deposits. This is supported by recent experimental work by Kim et al. (2011), where they found, roughly, that the location of a simulated axial drainage within a slowly subsiding basin is controlled largely by the relative sediment transport capacity of the axial river, and the sediment fluxes of both east- and west-flowing transverse drainages. Kim et al. (2011) argue that the axial river can behave similarly to longshore currents along coastlines—acting to sweep away incoming sediments up to their capacity. If the axial river cannot move enough sediment, then the alluvial fans prograde, shifting the river away from the transverse drainage; if the axial river has the capacity, it will shift laterally and erode the alluvial fan deposits (Kim et al., 2011). Because this conceptual model explicitly depends on the transport capacity and sediment loading of the rivers involved, it supports the original conceptual model of alluvial fan-axial river interaction of Gile et al. (1981).

To that end, we describe a remarkable outcrop of five bluff lines exposed along the alluvial walls of lower Abo Arroyo (Fig. 1). Approximately 6-km upstream from where the modern Abo Arroyo spills onto the Rio Grande floodplain, and 40 m higher, is a 400-m-long exposure of deposits of the ancestral Rio Grande and Abo Arroyo where they repeatedly cross-cut and are interlayered at their interface. Six different levels of ancestral Rio Grande channels, overlying floodplains and Abo Arroyo fan deposits, and five preserved bluff lines crop out in this small area (Fig. 2). The buried bluff lines show a complicated set of contacts between ancestral Rio Grande deposition and erosion, and incision and deposition of alluvium by Abo Arroyo and its alluvial fan.

For an overview of the Abo Arroyo drainage and previous work, see Love and Rinehart (a; this guidebook). This paper is organized into: 1) a brief summary of the local geologic framework, 2) a description of the units and contacts in the outcrop in Abo Arroyo along with available age constraints, 3) an inferred depositional history of the outcrop, 4) possible linkages to the regional history of the ancestral Rio Grande, and 5) implications for aquifer and reservoir compartmentalization.

GEOLOGIC FRAMEWORK

Abo Arroyo (1073 km^2) descends from Abo Canyon westward into the southeastern portion of the Albuquerque basin of

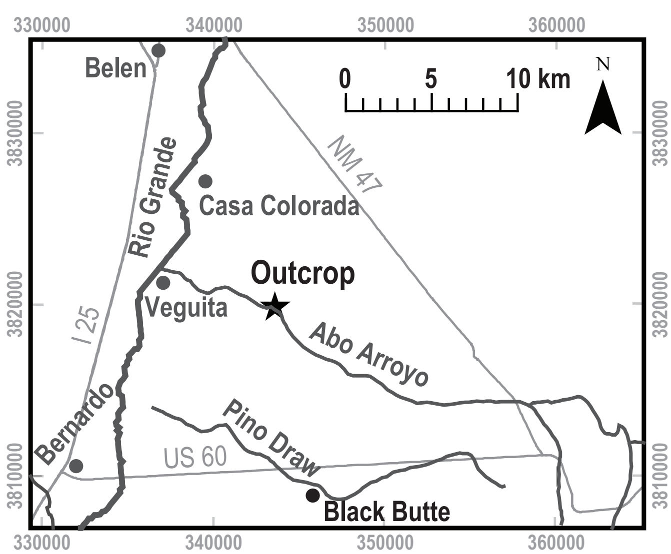

FIGURE 1. Location of outcrop (star), Black Butte (black circle), rivers and arroyos (dark gray lines), towns (gray circles), and major highways (light gray lines). Coordinates in UTM 13N, NAD83.

the Rio Grande rift. Based on clast provenance and cross-cutting relationships, Rinehart et al. (2014) found that Abo Arroyo has been spilling into the Albuquerque basin with roughly this contributing area since before the ancestral Rio Grande reached its maximum level of aggradation (0.8 Ma; Connell et al., 2013). In the past, the stream deposited a large alluvial fan approximately 25-km long and at least 9-km wide along the eastern edge of the Rio Grande valley, 3-5 km east of the modern river.

The Albuquerque basin is a large extensional sedimentary basin (7,925 km^2) formed in the Rio Grande rift (Connell, 2004). The rift has been active from Oligocene through Quaternary time. Early in its evolution, the Albuquerque basin was closed, filling with a combination of lacustrine/playa floor sediments and piedmont sediments shed from the surrounding mountains. Beginning about 5 Ma, the ancestral Rio Grande integrated southward from the northern Albuquerque basin to a large lake in the vicinity of Las Cruces to Fort Quitman, southeast of El Paso, Texas (Connell et al., 2005). After integration, the Albuquerque basin continued to fill with fluvial sediments of the ancestral Rio Grande and piedmont sediments. These sediments form the Plio-Pleistocene upper Santa Group. About 0.8 Ma, the ancestral Rio Grande reached its highest elevation and began to incise (Connell et al., 2013).

Two types of bluff lines are reported in the Albuquerque basin—those buried in basin fill, and those inset against basin fill. Bluff lines buried within basin fill are documented by Davis et al. (1993) and Morgan et al. (2009). The buried bluff lines may occur at multiple levels within the fill. Bluff lines related to Pleistocene terraces along the Rio Grande are described by McCraw et al. (2006), Connell et al. (2007), and Love et al. (2009). In the Albuquerque area, Connell et al. (2007) described five levels of bluff lines at the valley-margin edges of Pleistocene terraces. None of the levels show multiple bluff lines with only subtle (<5 m) vertical separation. The top of aggradation of the ancestral Rio Grande is about 125 m above the present Rio Grande floodplain. The oldest terrace (Lomatas Negras Formation) contains the 640-ka Lava Creek B ash and has a basal strath ranging from 65 to 75 m above the river. The next oldest terrace (Edith Formation) has a basal strath 12-24 m above the floodplain and aggraded fluvial deposits up to 12 m thick. It contains Rancholabrean fauna and therefore is younger than about 300 ka. The Los Duranes Formation formed about 120 ka and has a basal strath about 6 m above the floodplain and aggraded 42-48 m above the floodplain. The fourth bluff line is formed by the Menaul Member of the Los Duranes Formation at 26-36 m above the floodplain, although Connell et al. (2007) concede that the member is problematic in its placement within the sequence. The most recent terrace bluff line, the late Pleistocene Arenal Formation, has a basal strath 10-11 m above the floodplain cut into the Los Duranes Formation and is 3-6 m thick.

Inset Rio Grande terraces and bluff lines in the southern Albuquerque basin are delineated by McCraw et al. (2006) and Love et al. (2009). The top of ancestral Rio Grande aggradation in the area is 105-110 m above the floodplain, although fault offsets have lowered the top to less than 100 m in some areas.

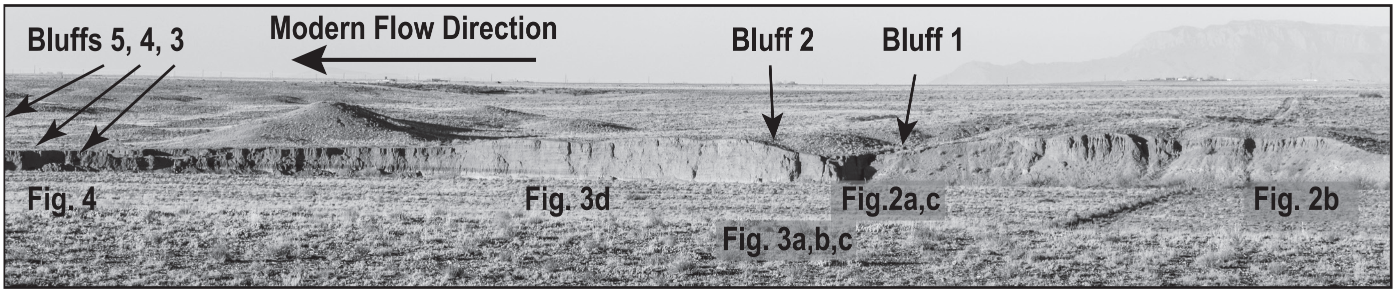

FIGURE 2. Looking north at the entire outcrop (approx. 400-m long and 10-m tall). Location of bluffs and the location of following figures are indicated.

The highest basal strath of an inset terrace is about 50 m above the floodplain. The basal terrace deposit is up to 15 m thick and is comprised of coarse gravel of well-rounded quartzites and volcanic clasts. The next highest gravelly basal strath is about 38 m above the floodplain, and the deposit is truncated by thick valley-border alluvium graded downslope to the next lowest terrace. That terrace has a basal strath at floodplain level and a tread about 27 m above the river. Lower terraces are evident farther south, but not in this area.

The Rio Grande axial-fluvial deposits mostly consist of medium- to coarse-grained, moderately well sorted, white to buff, subarkosic litharenites, poorly consolidated sands and beds of well-rounded, resistant, coarse gravels composed of siliceous clasts. Sands and gravels are commonly trough cross-bedded at a scale of centimeters to meters; finer sands exhibit plane beds and ripple cross-laminations. The resistant siliceous clasts include quartzites, other metamorphic and plutonic rocks, volcanic rocks from northern New Mexico, and chert and petrified wood reworked from older bedrock. Older (early Pliocene-Pleistocene) sandy fluvial deposits in sections of basin fill commonly have meters-wide and -thick zones with extensive poikilotopic cements.

Most Abo Arroyo sediments ("Abo-derived") are poorly sorted, fine-to coarse-grained, pale- to deep-red, lithic-rich, unconsolidated sandy gravel with coarse-pebble to cobble-sized clasts of subangular to subrounded limestone; red sandstone; metamorphic quartzite, schists and gneiss; and granitic rocks. In the active channel, which has recently narrowed and incised, clasts are commonly subangular cobble- to boulder-sized with a similar range of lithologies (Love and Rinehart (b), this guidebook).

Based on cross-cutting relationships in exposures beneath the level of maximum aggradation of the ancestral Rio Grande, the Abo Arroyo alluvial fan has been interacting with the river for more than 1.6 Ma based on Guaje pumice pebbles found locally in Sierra Ladrones Formation deposits, and the Abo Arroyo fan was deposited on top of both axial-river and eastern-piedmont upper Santa Fe Group sediments after 0.8 Ma (Rinehart et al., 2014). The fan spills northwest across and south of the Hubbell Bench and north of the Joyita Bench (Grauch and Connell, 2014) into the Belen sub-basin of the Albuquerque basin, crossing a series of subtle Quaternary faults and upper Santa Fe Group sediments (McCraw et al., 2006; Rinehart et al., 2014). Lobes of the Abo Arroyo fan complex have been deposited on the surface of maximum Rio Grande aggradation. Episodic deposition of terraces inset along its valley have followed episodic incision of the ancestral Rio Grande from middle to late Pleistocene time (McCraw et al., 2006; Rinehart et al., 2014) and, most recently, in the 20th century (Love and Rinehart (b), this guidebook). With the exception of the outcrop described below, few if any good exposures of past terraces or basin fill exist along the Abo Arroyo valley.

METHODS

The sediments and sedimentary structures of the outcrop were described based on the methods outlined in Boggs (2006). Beds are strata greater than 1-mm thick, and laminations are strata less than 1-mm thick. We used the field descriptors of particle size (mud vs. sand textures) of Folk (1954). We did not relate the observed colors to a color chart, and are necessarily vague in our color description.

Stream elevations were estimated from the USGS 10 m DEM of the area, which was derived from a 20-ft contour topographical map. Elevations above the Abo Arroyo channel were estimated using a Nikon range finder that measures both true distance and horizontal distance. The heights above the Abo Arroyo channel are estimated from the average of at least 3 estimates using the range finder.

DESCRIPTION OF THE OUTCROP

In Figure 2, the entire 400-m long and 10-m tall outcrop is shown looking to the north with the bluff lines and locations of additional figures indicated. We identify five major bluff lines from east to west. Within the valley of Abo Arroyo and to the north of the outcrop, the low hills are composed of Abo-derived sand, gravel and cobbles. The hills are mantled by subangular clasts of sandstone, limestone, quartzite, schist, gneiss, and granite with a poorly sorted, red, medium-grained sandy matrix. Inset against the hills within the valley is a surface with a moderate slope toward the modern valley. This slope has small tributaries leading to the historical channel of Abo Arroyo (see Love and Rinehart (a,b), this guidebook). The inset surface also consists of colluvium and aggrading eolian deposits. The valley-margin alluvium is Abo-derived with no or extremely rare clasts of reworked Rio Grande gravel.

The base of all of the bluff lines is approximately 40 m above the modern Rio Grande floodplain, with the top of the bluff lines being greater than 50 m (Bluffs 1 and 2) to between

41 and 44 m above the modern floodplain (Bluffs 3, 4 and 5). These bluffs are located 150 m to 200 m to the west of mapped down-to-west normal faults (Rinehart et al., 2014; C. Cikoski, personal communication). Using the surface of maximum aggradation of the ancestral Rio Grande, which these faults cut to the south, the maximum vertical throw of the faults is between 10 and 20 m in the last 0.8 Myr (Rinehart et al., 2014). None of the beds spilling over the bluff lines onto the lower surface show warping or disruption of bedding that would be expected from faulting—especially with 10s of meters of displacement.

Farthest to the east, Bluff 1 (Fig. 3) is a buttress unconformity between white- to buff-colored, partially cemented, pebbly sandstone (the bluff), and an inset (west of the bluff-line), red-colored, poorly-sorted, medium- to coarse-grained, fine- to medium-bedded sand overlying non-cemented buff-colored sands and well-rounded gravels. The buff-colored pebbly sands cut by the buried bluff have well-cemented sandstone lenses and late-Blancan vertebrate fossils dating to approximately 2.2 Ma (Love et al., 2013). Above the cemented pebbly sand is a thicker than 1-m bed of non-cemented coarse, well-rounded, gravels and cobbles (Fig. 3b). Above the gravel are beds of Abo-derived pebbly sand. The well-rounded pebbles are reworked down the bluff to the west into the red, subangular, Abo-derived gravels (Fig. 3a, c). The red sand units west of the bluff overlie interbedded red and white mud (Fig. 3a, c). At the base of the interbedded muds is a faintly bedded, white to pale gray sandy mud bed (Fig. 3a, c), underlain by a medi-

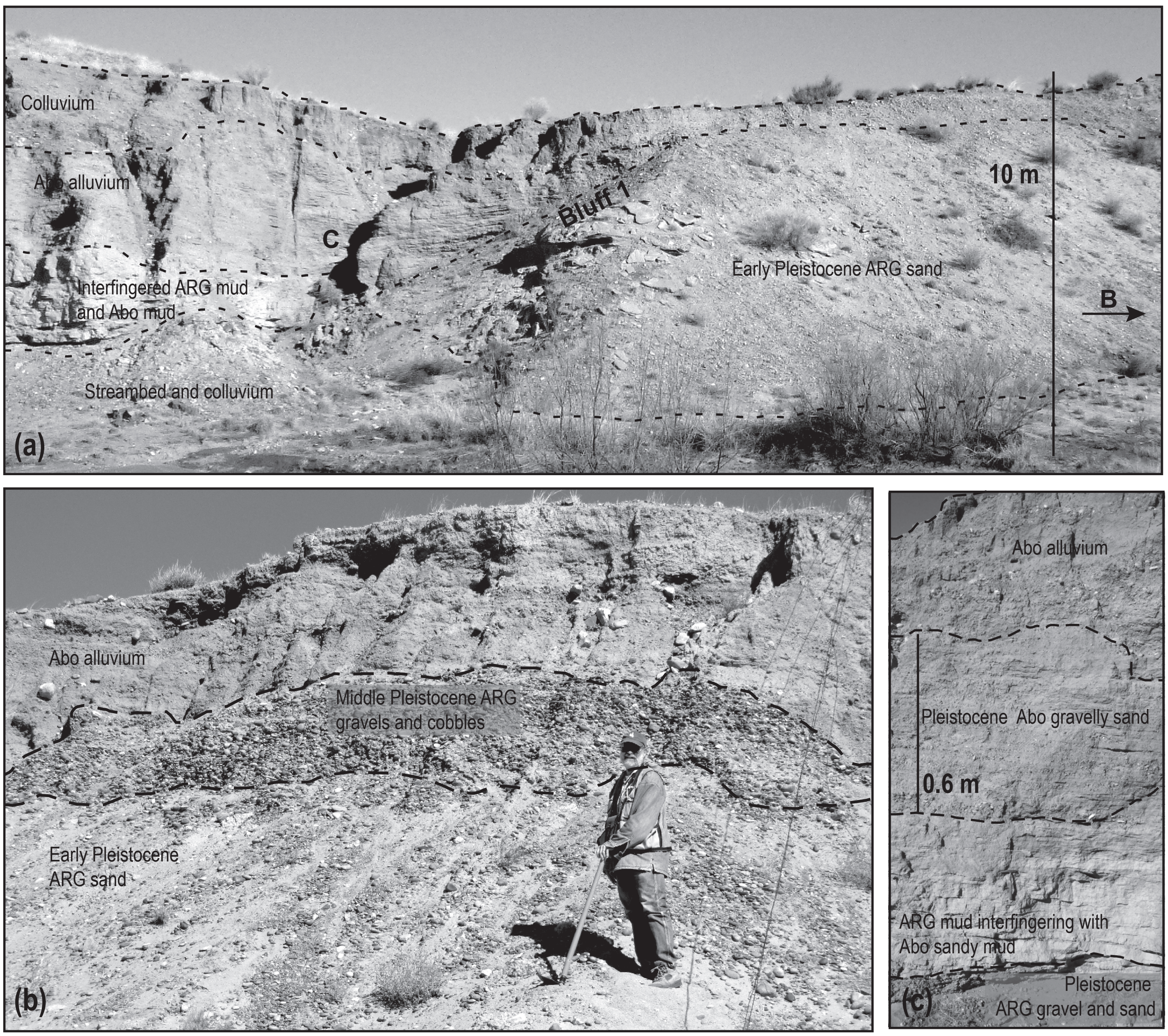

FIGURE 3. Annotated photographs of Bluff 1 and the underlying (to the right) and overlying (to the left) deposits. ARG = ancestral Rio Grande. **a**) Bluff 1 with contacts between in situ deposits with source interpreted. **b**) Series of early Pleistocene (approx. 2.2 Ma; Love et al., 2013) ARG sand (lowest), ARG gravels (middle), and Pleistocene (?) Abo-derived alluvium (top). **c**) West-looking outcrop of deposits lying against Bluff 1. Abo alluvium is younger than in (b).

um- to coarse-grained, cross-laminated, white sandstone with some well-rounded quartzite gravels (Fig. 3c). In the white- to buff-colored sands and poorly exposed gravel beds west of the bluff, we were unable to find diagnostic clasts indicating ages, such as obsidian or other volcanic rocks, or fossils. The buttress itself does not show a colluvial wedge, but has a steepening-upward series of beds that grade from horizontal to the slope of the Bluff 1 (Fig. 3a).

The second buttress unconformity, Bluff 2 (Fig. 4), is found approximately 15 m downstream of Bluff 1 (Fig. 2). Bluff 2 has a wedge of pale sandy mud colluvium on top of the reddish sediments and intercalated red- and white-mud beds that are inset against Bluff 1 (Fig. 4a). The sandy mud colluvium shows no bedding structure, but has a slightly diffuse bottom and has a stiffness similar to a Stage II carbonate horizon (Gile et al., 1981); it is difficult to identify it as a paleosol because of (a) lack of development, and (b) clay minerals interfering with significant carbonate preservation (Gile et al., 1995). The relationship of white laminated sands between Bluffs 1 and 2 and very similar sands between Bluffs 3 and 4 is buried, but the former appear to be 1-1.5 m higher than the similar sands to the west (Fig. 3c).

We tentatively posit that the sands between Bluffs 1 and 2 are older than the sands between Bluffs 3 and 4. The deposits west of the buttress unconformity of Bluff 2 are, from bottom to top: 1) coarse, very well rounded quartzitic gravel (Fig. 4b); 2) a ripple cross-bedded , moderately well-sorted medium to coarse white sand overlying a layer of white sandy mud (Fig. 4c); 3) interbedded white and red sandy muds grading from pure white muds to all red muds (Fig. 3c-d); 4) slightly dipping, interbedded, red, fine- to medium-bedded, poorly-sorted sands and red sandy muds; and 5) reddish, poorly-sorted, gravelly bedded sand (Fig. 4a-b). The dipping muddy and sandy red-colored beds steepen upwards against and over Bluff 2, though the Abo deposits overtopping Bluff 2 have been truncated more recently.

Between Bluff 2 and Bluff 3 (Figs. 2 and 4), the lower muddy red beds coalesce into a single, approximately 1-m thick layer that also darkens. Similarly, some of the sandy red beds above either coalesce or pinch out between Bluffs 2 and 3. In the thickened red mud layer, irregular masses of white calcite-cemented sediment are found (concretions; Fig. 4d). There are rare krotovina-shaped cemented sediments as well in the red muds and penetrating the white muds. Additionally, the darkening of the muds indicates the integration and preservation of more organic matter than closer to Bluff 2. This is consistent with a low degree of soil development. In the pale sands, there are uncommon to rare rust-coated grains. As the outcrop continues to the west from Bluff 2, the zone of interbedded white and red muds decreases in thickness to less than 0.2 m. The white muds form the pale bed seen in Figure 2 at the bottom of the outcrop. Also, the sandy red alluvial beds flatten

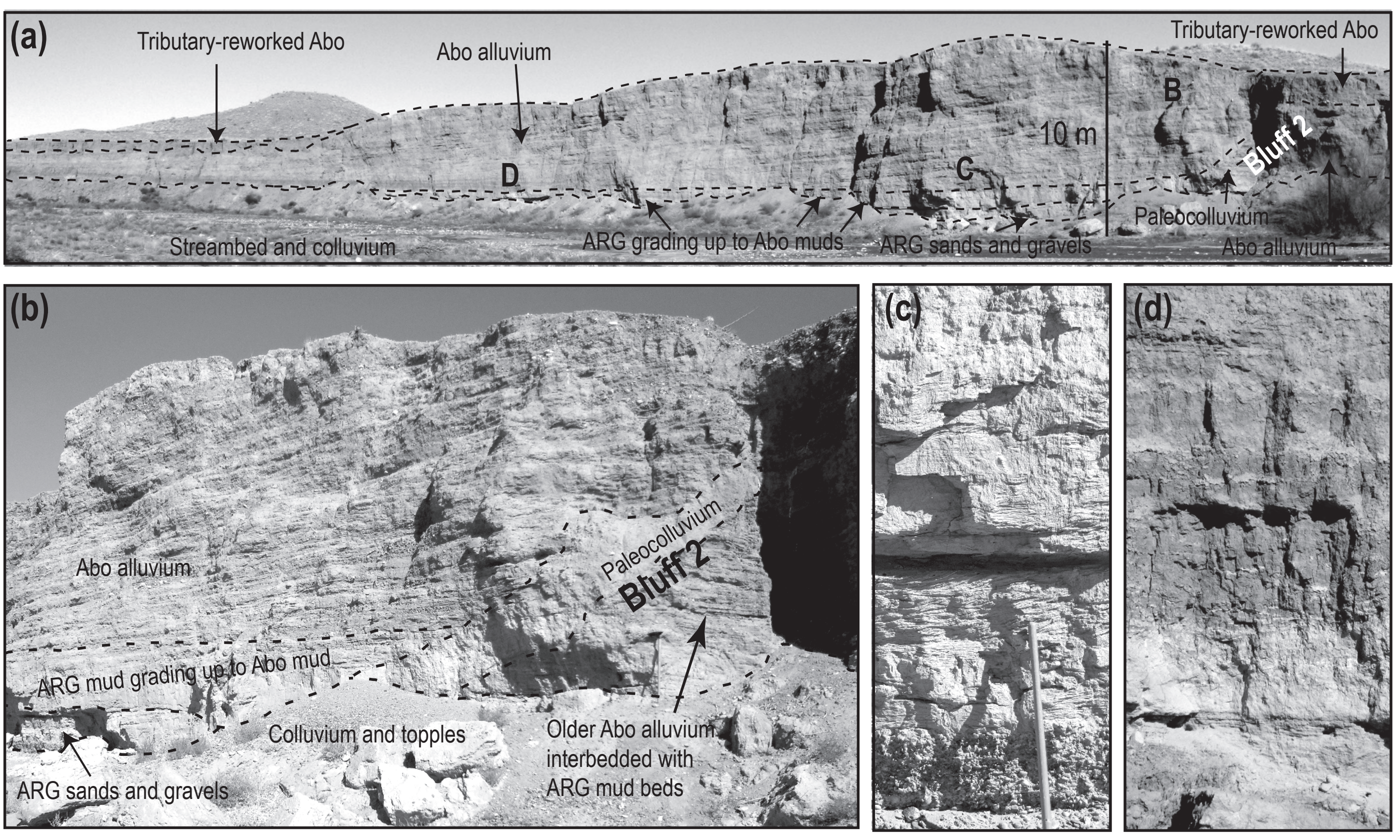

FIGURE 4. Annotated images of Bluff 2 and younger deposits to the west. **a**) Overview of Bluff 2 and surrounding deposits, with locations of subfigures (b-d) indicated. **b**) Close-up of Bluff 2 and younger deposits. Outcrop is 10-m tall. **c**) White colored ancestral Rio Grande sediments to the west of Bluff 2. Handle is 0.9-m tall, 3-cm across. **d**) Interbedded red and white sandy muds grading up to poorly sorted red sand. Image is 0.5-m across.

to nearly horizontal approaching Bluff 3. Approximately 100 m from Bluff 2, a 1- to 2-m layer of tributary-reworked red sands is cut into the older (Pleistocene) red sands (Figure 5a). These reworked sands form the surface of the historical Abo Arroyo floodplain (Fig. 5; Love and Rinehart (b), this guidebook).

At the western end of the outcrop, the coalesced reddish mud bed continues above the pale sandy mud unit and gravel beds, and Bluffs 3, 4 and 5 are found within 20 m of each other (Fig. 5). The base of Bluff 3 is formed by the truncation of the basal gravel unit and pale sandy mud traced laterally from Bluff 2. The top of Bluff 3 is in poorly sorted, faintly bedded, Abo-derived pebbly sand. The red mud layer, so traceable from the northeast, ends in an unconformity below the poorly sorted, almost "massive" red pebbly sand (Fig. 5b). Southwest of Bluff 3, the exposed basal unit is a bedded pale sandy mud unit overlain by bedded pebbly, poorly-sorted, pale sandy mud and red mud layers. Below the pale sandy mud to the southwest is another basal gravel unit, lower than the gravel west of Bluff 2.

About 10-m downstream (southwest) from Bluff 3, Bluff 4 is formed by truncating the units southwest of Bluff 3; above the unconformity, younger (late Pleistocene to Holocene) poorly sorted Abo-derived reddish gravel, sand and loess is deposited along the sloping bluff line and subsequently aggraded to form the alluvial floor of the lower Abo valley. Another 8 to 10 m to the west, Bluff 5 is formed by truncating the late Pleistocene to latest Holocene poorly sorted Abo-derived reddish gravelly sand. A red pebbly sand deposited in the late 20th century (Love and Rinehart (b), this guidebook) is inset against the poorly sorted red alluvium and loess of the valley floor (Fig. 5c). Bluff 5 cuts down into a coarse, very well rounded gravel package and a laminated pale sand (Fig. 5c) that may be a remnant of the lower part of units at the base west of Bluff 3. Based on Love and Rinehart (b; this guidebook), lack of bedding, and vertical lineations seen in outcrop, the top of the outcrop is covered by historical colluvium and loess (Fig. 5c). This colluvium is red colored and derived from Abo Arroyo sediments.

DEPOSITIONAL INTERPRETATIONS AND POSSIBLE CORRELATIONS

Based on color, clast types, geometric relations on outcrop, and correlations to previous mapping and section summary descriptions (Connell, 2004; McCraw et al., 2006; Rinehart et al., 2014), we identify the pale sediments in the outcrop as sourced from the ancestral Rio Grande, and the red and darker sediments as sourced from an ancestral Abo Arroyo. Most of the red sands show some bedding and are likely alluvium. They are also likely directly associated with Abo Arroyo, rather than being from small intra-valley tributaries that reworked older deposits. The sedimentary packages on the inset sides of each of the buttress unconformities are very similar. The sediments at the base of the buttress unconformities where the ancestral

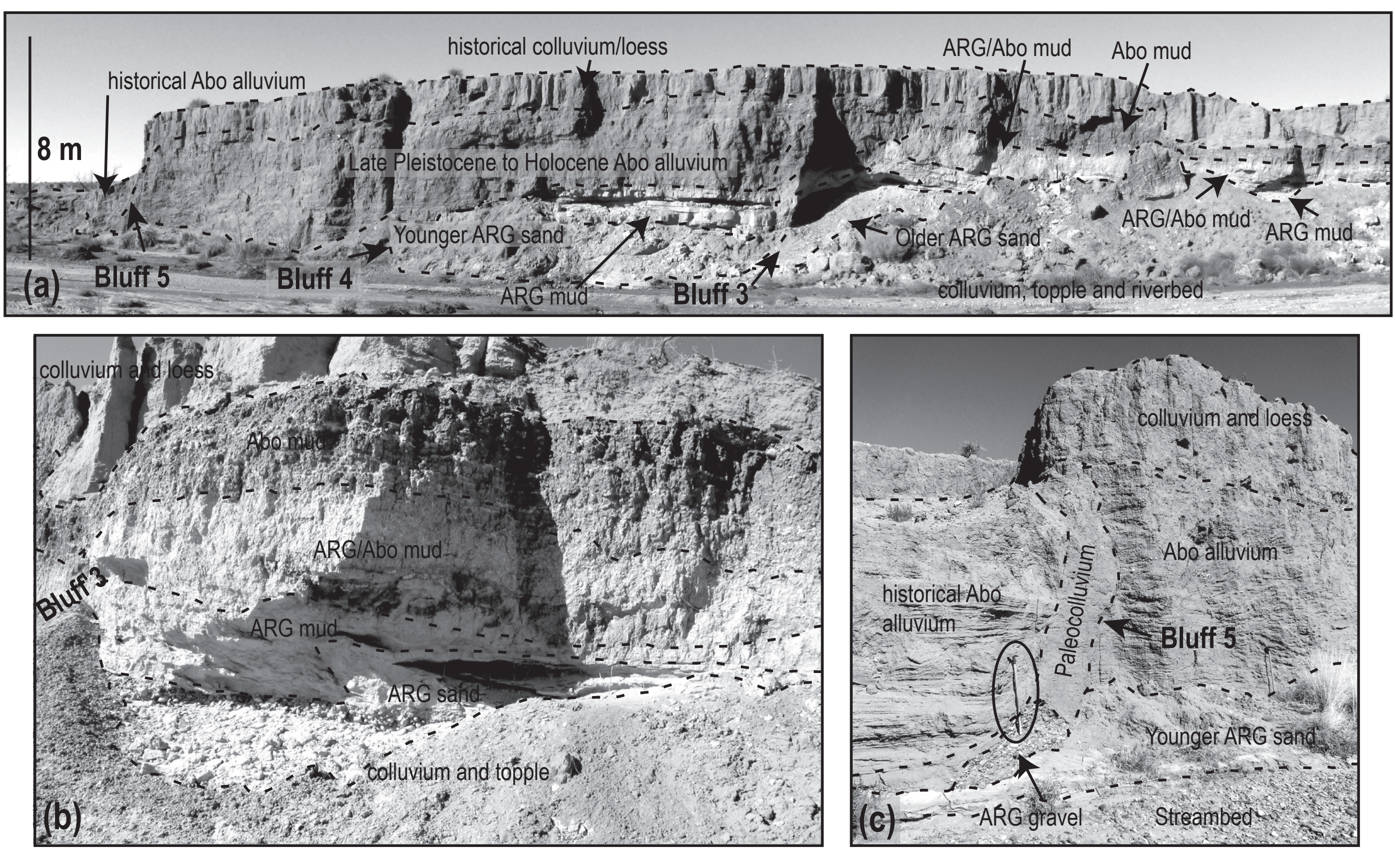

FIGURE 5. Bluffs 3, 4 and 5 of the outcrop, with ancestral Rio Grande (ARG) and Abo Arroyo deposits interfingering. **a**) Overview of bluffs, contacts and deposits. Height is approximately 8 m. **b**) Detailed view of levee, distal fan deposit, and Bluff 3. **c**) Architecture of Bluff 5. Pick is approximately 0.9-m long.

Rio Grande cut into the older deposits to form a bluff have a basal unit of well-sorted gravel 1 to 2 m thick, overlain by finer-grained sand and mud layers 1 to 2 m thick. The fine-grained "floodplain" sediments alternate upward with fine-grained red deposits prograding westward from the ancestral Abo Arroyo.

Both the floodplain sediments and the Abo Arroyo sediments commonly are draped upward against the bluffs. In most (Bluffs 2, 3 and 5) of the bluff margins above the gravel at each unconformity are colluvium reworked from the upper faces of the bluffs and sandy deposits draped against the bluff. The overlying sediments from Abo Arroyo have sloping sets of bedded sand and gravel that become more parallel to the underlying floodplain sediments farther from the bluffs—in particular, Bluffs 1 and 2. The distal red-brown clay units merge toward the west into one thick, structureless unit. The implication of the basal gravels of each of the packages stepping 1 to 3 m down to the west will be discussed below.

The detailed relative depositional history of the outcrop is based on stratigraphic position and cross-cutting relationships, but it is difficult to place in an absolute time context because of the lack of age control. Figure 6 shows a summary of the stratigraphic relationships of the units we have described, including the cuts made by the different bluffs. The ancestral Rio Grande deposits east of Bluff 1 contain fossils with ages of approximately 2.2 Ma, but the rest of the outcrop is free of age constraints until the very youngest deposits of Bluffs 4 and 5 that are demonstrated to be historical by Love and Rinehart (b; this guidebook) based on observed incision from aerial photography in the last 80 years. The other sediments of both sources are markedly unconsolidated, whereas the older 2.2-Ma and 1.6-Ma ancestral Rio Grande basin fill to the south (unit Qsxo of Rinehart et al., 2014) is prevalently cemented. Moreover, the top of basin fill is about 60 m higher than this outcrop and is considered to have been abandoned about 0.8 Ma as the Rio Grande began to incise its present valley.

To the south, Rinehart et al. (2014) mapped a middle Pleistocene Abo fan deposit (map unit Qaom) graded to the top of the 27-m Rio Grande terrace tread of McCraw et al. (2006). This unit (Qaom) has a similar landscape position as unit Qam2 of McCraw et al. (2006). McCraw et al. (2006) and Love et al. (2009) correlated this tread to similar terraces in Albuquerque and Socorro that are estimated to be about 120 ka. Similar to our study, McCraw et al. (2006) document a separate, poorly exposed Rio Grande gravelly terrace strath at 38 m above the Rio Grande floodplain and beneath Qam2. The outcrop of that unit is not extensive enough to determine whether it too has multiple bluff lines, but it overlies older, partially cemented Rio Grande basin fill facies. Although this terrace is similar in elevation to the Menaul Member in Albuquerque (Connell et al. 2007), we suggest that the Abo Arroyo set of outcrops are older than that member and may be placed somewhere in age between the ages of the Edith Formation (<300 ka) and the Lomatas Negras Formation (~640 ka).

The oldest depositional unit is ancestral Rio Grande pebbly sand sediments, with early Pleistocene fossils. Presumably similar sediments continued to accumulate another 50-60 m to form the wide-spread surface of maximum Rio Grande aggradation. Then, after the ancestral Rio Grande began incising after 800 ka, a bench was cut on ancestral fluvial sediments approximately 50 m above the modern floodplain by a middle-Pleistocene Rio Grande that deposited coarse, well-rounded, well-sorted resistant gravels (Fig. 3b). That deposit was subsequently overtopped by Abo Arroyo-derived alluvial sediments. This gravelly bench corresponds to the 50-m terrace of McCraw et al. (2006), and its bluff line would be east of these exposures. If this is the case, then only the gravel deposit would be part of the terrace, and the lower ancestral Rio Grande sandstone would be part of the basin fill. Alternatively, the 50-m gravel strath in this exposure is part of the basin fill and is unrelated to the Pleistocene terraces of the Albuquerque basin. It is difficult to tell how high the gravels aggraded because they have been truncated by late Pleistocene to Holocene Abo Arroyo alluvium.

The middle Pleistocene (?) Rio Grande likely cut Bluff 1 after the river incised to a 44-m level and migrated laterally into older sediments. This can be seen by the juxtaposition

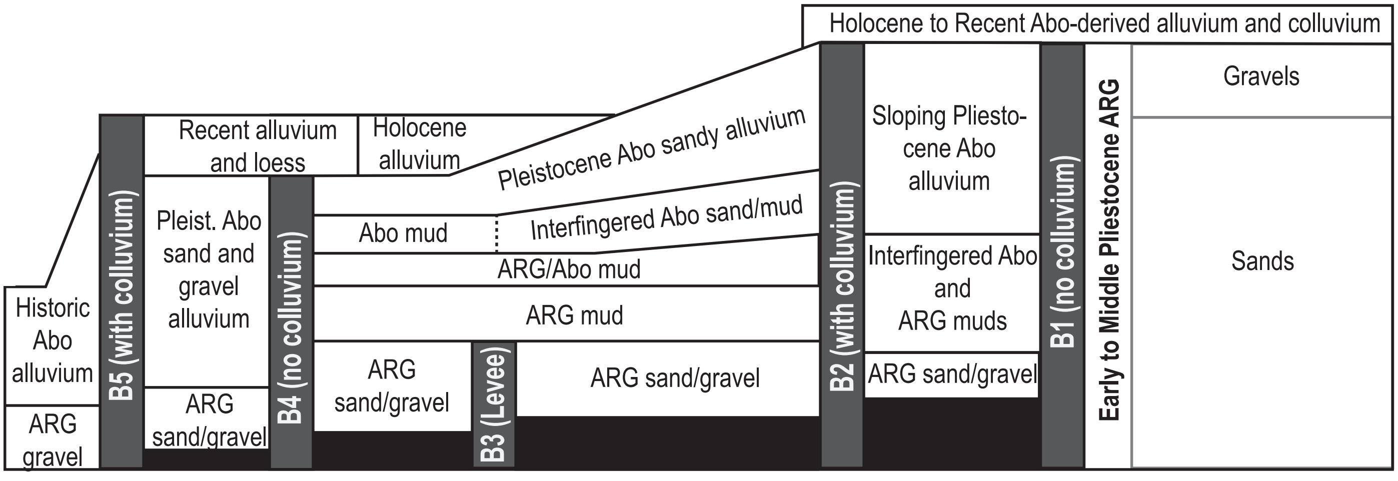

FIGURE 6. Stratigraphic schematic of outcrop showing deposits (clear boxes), bluff lines (gray), and unseen regions underlying basal ancestral Rio Grande (ARG) sand and gravels. Not to scale.

of younger ancestral Rio Grande sands and floodplain muds against the bluff. Then, Abo Arroyo spilled onto that floodplain and eventually overtopped the bluff, even as ancestral Rio Grande deposition continued. This is supported by the interbedding of distal alluvial fan muds from Abo Arroyo with both the ancestral Rio Grande floodplain deposits, and with the eventual overtopping of bedded alluvial sands. The Abo Arroyo alluvial fan became coarser grained up section, probably due to progradation from distal to medial positions through time (Leeder, 2011).

At some later time, the ancestral Rio Grande once again cut to the east, forming Bluff 2. This bluff line was not immediately overtopped by Abo Arroyo. This is supported by the formation of the colluvium on Bluff 2. It is unclear what the relationship between the ancestral Rio Grande sands and gravels east of Bluff 2 are with those between Bluff 1 and 2; they are not related to the older 2.2 Ma sands, judging by consolidation and cementation.

The tops of Bluffs 1 and 2 have been beveled by the Holocene to historical Abo Arroyo, limiting information based on paleosols of these surfaces. Neither preserved bluff has recognizable soil development, though the slightly diffuse bottom boundary of the colluvium of Bluff 2 along with subtle textural features suggests it may have reached Stage I+ soil development (Gile et al., 1981) before being buried.

Bluff 3 forms a critical relationship in this series of buttress unconformities. It appears that the ancestral Rio Grande floodplain muds between Bluffs 2 and 3 are continuous through the outcrop (Figs. 2, 4, and 5). This implies that the alluvial Abo Arroyo-derived sediment seen onlapping Bluff 2 also extends to Bluff 3. There is a complex interbedding of red alluvial muds and ancestral Rio Grande muds between Bluffs 2 and 3. The sand, pale mud, and dark clay units become thicker and higher just before becoming truncated by Bluff 3. We interpret that this was a natural levee adjacent on the east side of the ancestral Rio Grande channel while the colluvium of Bluff 2 was forming and continued to be a levee as Abo Arroyo onlapped on the ancestral Rio Grande floodplain. The onlapping of an Abo Arroyo alluvial fan is further supported by the continuous red mud beds first coming together between Bluffs 2 and 3, and then separating above the bedded pure ancestral Rio Grande sand and mud east of Bluff 3. It is also supported by the increase in bedding angle of higher and sandier Abo Arroyo sediments.

The ancestral Rio Grande sands near the base of exposures between Bluffs 3 and 4 are inset 2-3 m and probably are much younger than those between Bluffs 2 and 3. However, this story is complicated by the extension of Abo Arroyo muds past the highest point of the levee onto the ancestral Rio Grande floodplain. This implies that the active ancestral Rio Grande channel had incised to some extent to the west, allowing the distal Abo Arroyo fans to aggrade over the levee and onto a floodplain further to the west.

Incision to form Bluff 4 truncated the Rio Grande sands at a level lower than Bluff 3. An ancestral Abo Arroyo incised into the distal alluvial fan and ancestral Rio Grande deposits and aggraded above the level of dark red muds of the package between Bluffs 2 and 3. The upper 1 to 3 m along the exposure between Bluffs 2 and 3 shows an erosional unconformity with 1 to 4 m of relief. The fill above the unconformity is probably related to aggradation of the historical valley floor of lower Abo Arroyo (Love and Rinehart, b; this guidebook). It is unclear how much higher the Pleistocene Abo fan aggraded. It could have been up to the historical elevation 10 m above the modern channel, or, more likely in our opinion, it could have been up to the Qaom surface of Rinehart et al. (2014) approximately 30 m above the modern channel, and then cut back down before aggrading the historical floodplain documented in Love and Rinehart (b; this guidebook). Then, recently, the historical Abo Arroyo was cut into the Abo valley alluvium. This recent incision eroded through Abo Arroyo deposits and down into ancestral Rio Grande deposits to form the buttress unconformity at Bluff 5. The modern floodplain of Abo Arroyo has aggraded up to 1.5 m of reddish sandy sediment since 1954 (Fig. 5c).

DISCUSSION

This outcrop shows a complicated record of the interaction of the ancestral Rio Grande channel, the ancestral Rio Grande floodplain, the channel of Abo Arroyo, and the fan of Abo Arroyo. Both channels, at different points in time, eroded previous fill and then re-aggraded alluvium from the channels, the floodplain, and/or the alluvial fan. This interaction stretches back as far as 2.2 Ma and extends, in the space of a 400-m long outcrop, to historical times. Much of this interaction has provisionally been in the last 0.8 Ma since the Rio Grande began to incise. It is possible that the regional 50-plus-m bluff lines of McCraw et al. (2006) and Connell et al. (2007) were buried by deposits of Abo Arroyo, which were then incised by the ancestral Rio Grande, reburied by Abo alluvium, and reincised three more times until the river shifted farther to the west.

Only Bluff 5, which was cut and then filled by Abo Arroyo, can be thought of as possibly representative of the traditional cut-and-fill architecture of semi-arid tributary arroyos. The rest of the outcrop preserves the relatively rapid (given the lack of plant fossils and bioturbation, and little soil development) aggradation of ancestral Rio Grande and Abo Arroyo sediments through a series of ancestral Rio Grande incisions. The size of Abo Arroyo is large enough to strongly interact with the Rio Grande, at least on the floodplain. Additionally, the zone of interaction of the Rio Grande and Abo Arroyo has apparently been restricted between Bluff 1 and points west since the formation of Bluff 1. If the gravel at the top of the exposure of Bluff 1 overlies a strath correlating with the 50-m terrace of McCraw et al. (2006) and the Lomatas Negras Formation of Connell et al. (2007), this would imply that the Rio Grande has occupied points to the west of Bluff 1 for at least 640 ky.

Studies of Rio Grande terrace bluff lines in the Albuquerque area and farther south have not described multiple bluff lines at nearly the same level, but slightly stepped toward the river valley, as observed along Abo Arroyo. However, Mack et al. (2011, fig. 3) illustrate four stepped, inset bluff lines and terrace treads in a 5-m vertical interval along the Rio Grande valley between Truth or Consequences and Caballo Reservoir. Although they only show the terrace treads and not the terrace fluvial bodies or basal straths, they imply that each of the stepped terraces has a basal strath that also stepped laterally and down about 5 m over an interval of 12,400 years. These latest-Pleistocene and Holocene low bluffs related to migration of the Rio Grande may be a good analogy for the Abo Arroyo bluffs and may suggest that the Abo Arroyo bluffs formed during an interglacial episode as the Rio Grande migrated to progressively slightly lower levels over the time interval of a few to tens of thousands of years.

The depositional sequence interpreted from the outcrop provides a rare example of repeated toe-cutting and lateral movement of the axial-transverse river interface. Whether the Bluffs 1-4 were cut as part of a Middle Pleistocene incision, or were cut as the basin filled to the level of maximum aggradation, the bluffs represent a period of repeated erosion-deposition exchanges between the ancestral Rio Grande and Abo Arroyo. Each bluff shows a lateral cutting into Abo deposits and ancestral Rio Grande fill, indicating, in the vein of Leeder and Mack (2001) and Kim et al. (2011), that Abo Arroyo was no longer transporting enough sediment on a long-term basis to swamp out the ancestral Rio Grande and its nearly annual spring floods. Either Abo Arroyo had a decrease in sediment loads, or the ancestral Rio Grande had an increase in carrying capacity relative to the Abo Arroyo sediment flux. Another hypothesis is that the ancestral Rio Grande could have been captured to the west by episodic fault offsets down to the west along the Contreras Cemetery fault of McCraw et al. (2006) after which the Rio Grande eroded laterally to the east again.

In either case, after Bluffs 1 through 4 were cut, the ancestral Rio Grande shifted back to the west, initially filling the eroded volume with its own sands and capping itself with floodplain muds, and then interbedding with deposits of Abo Arroyo until the axial stream moved far enough to the west so that Abo Arroyo onlapped over interbedded axial and transverse alluvial deposits. We tentatively state that this cycle represents a "see-saw"-ing between Abo Arroyo and the ancestral Rio Grande sediment fluxes and carrying capacities over a short time (less than 10s of kyr). Possible causes of this during glacial cycles include increases in water fluxes (and increases in axial river sediment carrying capacity) during interpluvials, whereas in Abo Arroyo headwaters, rocks are weathered and sediments are stored in place during pluvial cycles and are released and transported during interpluvials with less vegetation and more flashy discharges during monsoonal climate .

In terms of fluid flow, be it water or other liquids, this outcrop indicates that the top boundary of good aquifers in axial river deposits may be more complicated than traditionally thought. Here, within a tributary arroyo and 6 km away from the modern floodplain, we have a set of local seals over part of the outcrop (clay-dominant floodplain and distal fan deposits on ancestral Rio Grande sands and gravels), but much of the good aquifer and reservoir to the east is relatively unsealed by poorly sorted Abo Arroyo sands. This means that the aquifer would behave semiconfined with compartments of flow possible between Bluffs 2 and 3. Additionally, without this exposure we would have no idea that this complication existed. This implies that leaks of contaminants from hydrocarbon pipelines, gas stations, or other sources along the margins of an axial river valley may find an unexpectedly tortuous path into and through the aquifer.

The possibility of the actual buried bluffs forming either aquitards or conduits is not reflected by differences in cementation or alteration along the contacts. A possible explanation for the lack of cementation is that the deposits were only occasionally saturated with shallow groundwater, predominantly from Abo Arroyo after initial deposition. If the lower Abo drainage during an interglacial was a losing stream and flowed for only brief intervals during floods, the deposits were only intermittently saturated and may have drained downward between floods. Perhaps the level of shallow groundwater within the Rio Grande floodplain continued to be lowered as the river shifted westward and incised.

In short, the interaction of an axial river depositional system with a large tributary channel and alluvial fan system has led to the beautiful and complicated history of depositional and erosional interaction exposed in this outcrop.

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