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Geomorphology, hydrology, and alluvial stratigraphy in lower Chaco Canyon do not support the possible existence of prehistoric sand-dammed ephemeral lakes

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Abstract

Sand dunes 1–5 m high accumulate on the downwind side of the confluence where Chaco Wash and Escavada Wash form the broad, braided, sandy Chaco River at the northwest end of Chaco Canyon. Sand dunes derived by reworking channel sands are common next to the river and washes. Recently Force et al. (2002) and Force (2004) proposed that a similar set of sand dunes dammed Chaco Wash during Pueblo II occupation (A.D. 900–1150) of Chaco Canyon, forming a small lake. The dynamic geomorphology of the sand dunes and canyon floor, the hydrology of Chaco Wash, and stratigraphic analyses of the locality where lake beds were thought to exist all nullify the hypothesis.

The sand dunes at the canyon mouth and nearby have changed in historic time, so it is likely that the configuration of dunes has changed during the past thousand years. To create a set of dunes across the entire mouth of Chaco Canyon requires that sand be transported and accumulated there, but a ledge of sandstone and gravel terrace projecting southwest at the canyon mouth blocks southwesterly winds from transporting sand to the southern side of lower Chaco Canyon. Chaco Wash flows along or very close to the base of the sandstone ledge. Water discharge along the wash is large and frequent enough that no dune sand presently accumulates in the lee of the ledge or adjacent to the channel. If similar conditions existed in the past, it is doubtful that sand dunes could have blocked the water discharge. The modern dunes have a sand volume of roughly 104,000 m^3; an additional 105,500 m^3 would be necessary to cover the area south of the present dunes to form a dam.

Dune-crest elevations at the mouth of Chaco Canyon rise from the alluvium at the top of Chaco Arroyo toward the northeastern canyon side, ranging from 1 to 5 m above nearby alluvial deposits on the canyon floor. A previously reported radiocarbon age from charcoal buried ~55 cm below the alluvial surface is 1,010 yrs, indicating that only half a meter of sediment has accumulated and is preserved there in more than 1,000 yrs.

The floor of Chaco Canyon upstream from the sand dunes is dominated by alluvial fans from relatively steep northern side-canyon tributaries. Based on a digital elevation model (DEM) of the modern surface of lower Chaco Canyon, if a pond existed behind a 2-m dam with its base at the valley floor, the pond would cover only an area of about 40,000 m^2 and have a volume of 67,000 m^3. A modern peak flow of 141 m^3/sec would fill such a pond in a few minutes. A flood breach in the dunes would occur at the lowest, weakest point, would be catastrophic, and would be difficult to heal.

Force et al. (2002) and Force (2004) indicated that lake beds were exposed at their locality 30 (L30) 900 m upstream from the sand dunes. Half of the sand-dune crests are lower that the exposures of L30, so unless the dunes were much taller in the past, any dune-ponded sediments would not be exposed at L30. The 5-m section at L30 is more complex and apparently older than previously thought. The upper 2 m of the section are on the edge of a larger (5-m deep) paleochannel. Detrital charcoal in the upper sands of the paleochannel fill gave calibrated calendar dates of 138 and 327 B.C. The lower, older part of the section, truncated by erosion of the paleochannel, includes many fine-grained sand, silt, and clay units of probable overbank deposition. Detrital charcoal fragments from a depth of 244 cm, near the top of this older sequence, gave calibrated calendar dates of 834 and 1394 B.C. Although detrital charcoal may be older than the surrounding deposits, the younger dates in each stratum are arguably closer to the true age of the deposits. The absence of potsherds in the sequence also suggests that the channel and underlying deposits are older than Pueblo II. The lower, repetitious, fine-grained units are similar to fine-grained facies seen many kilometers upstream along Chaco Wash in low-energy backwater environments. No unequivocal lacustrine deposits were seen at L30 in 2005.

Until more definitive deposits are described and more specific and favorable conditions for past dams are well defined, we urge that the sand dunes at the mouth of Chaco Canyon simply be called dunes and not a "dune dam." Evidence presented here suggests that a dune dam in lower Chaco Canyon is highly unlikely.

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Introduction

Chaco Canyon, in the semiarid San Juan Basin of northwestern New Mexico (Fig. 1), is known as a cultural center of prehistoric peoples who constructed extensive, well-built, multistoried pueblos throughout the Four Corners region. These large, widespread structures have stimulated curiosity about prehistoric inhabitants, landscape, environment for resources and agriculture, and geology of the canyon beginning with Jackson (1878) and continuing to Hall (2010). Jackson (1878) described a paleochannel with potsherds and human remains within the walls of the present arroyo (later named the Bonito paleochannel) and speculated about the age of the channel and the environment of the past inhabitants. As yet, the ages of initiation and completion of filling of this Pueblo II paleochannel (pottery within ranging from A.D. 950 to 1150) and several other paleochannels are not determined precisely, and past environments within Chaco Canyon are only imprecisely understood. Our paper addresses several related geologic aspects of the physical environment of the past few thousand years in the lower end of Chaco Canyon. We provide (1) a description of the present geology, geomorphology, and hydrology of the northwest end of Chaco Canyon, (2) a description of a stratigraphic profile in alluvium that includes new radiocarbon ages of detrital charcoal, and (3) a discussion of the lack of evidence for a sand-dune-dammed ephemeral lake proposed by Force et al. (2002) and Force (2004) using presently exposed geomorphology and stratigraphy. As this list shows, the reader is forewarned that the following paper concentrates on descriptions that were not presented in previous articles. The details are emphasized in order to show that previous interpretations are not viable.

Force et al. (2002) and Force (2004) hypothesized that a precursor of modern sand dunes at the northwest end of Chaco Canyon dammed Chaco Wash during Pueblo II occupation (A.D. 900–1150) and formed a small lake, fed by the Chaco drainage. This hypothesis led to further speculation regarding the use of the lake by occupants of Chaco Canyon and the possibility that when the dam was breached, the "Bonito" paleochannel cut headward as a deep arroyo and affected the occupants upstream. Force et al. (2002) based their hypothesis on three lines of evidence: (1) the extent of modern sand dunes at the northwest end of Chaco Canyon, (2) fine-grained and gypsum-bearing sediments in a stratigraphic section (Force's locality 30; referred to here as our section L30) interpreted as lacustrine or playa sediments, and (3) an exhumed area of bedrock on the south side of Chaco Canyon interpreted to have been covered by sand dunes in the past. The dune-blockage scenario relies largely on the assumption that the configuration of lower Chaco Canyon has not changed significantly in the past 1,000–1,100 yrs. The assumption has not been tested by gathering critical evidence, including the following: (1) a detailed description of the present geomorphology of the lower end of Chaco Canyon, (2) historical evidence for geomorphic changes in lower Chaco Canyon, (3) investigation of modern and past dune dynamics, (4) age determinations for sand dunes, (5) investigation of the

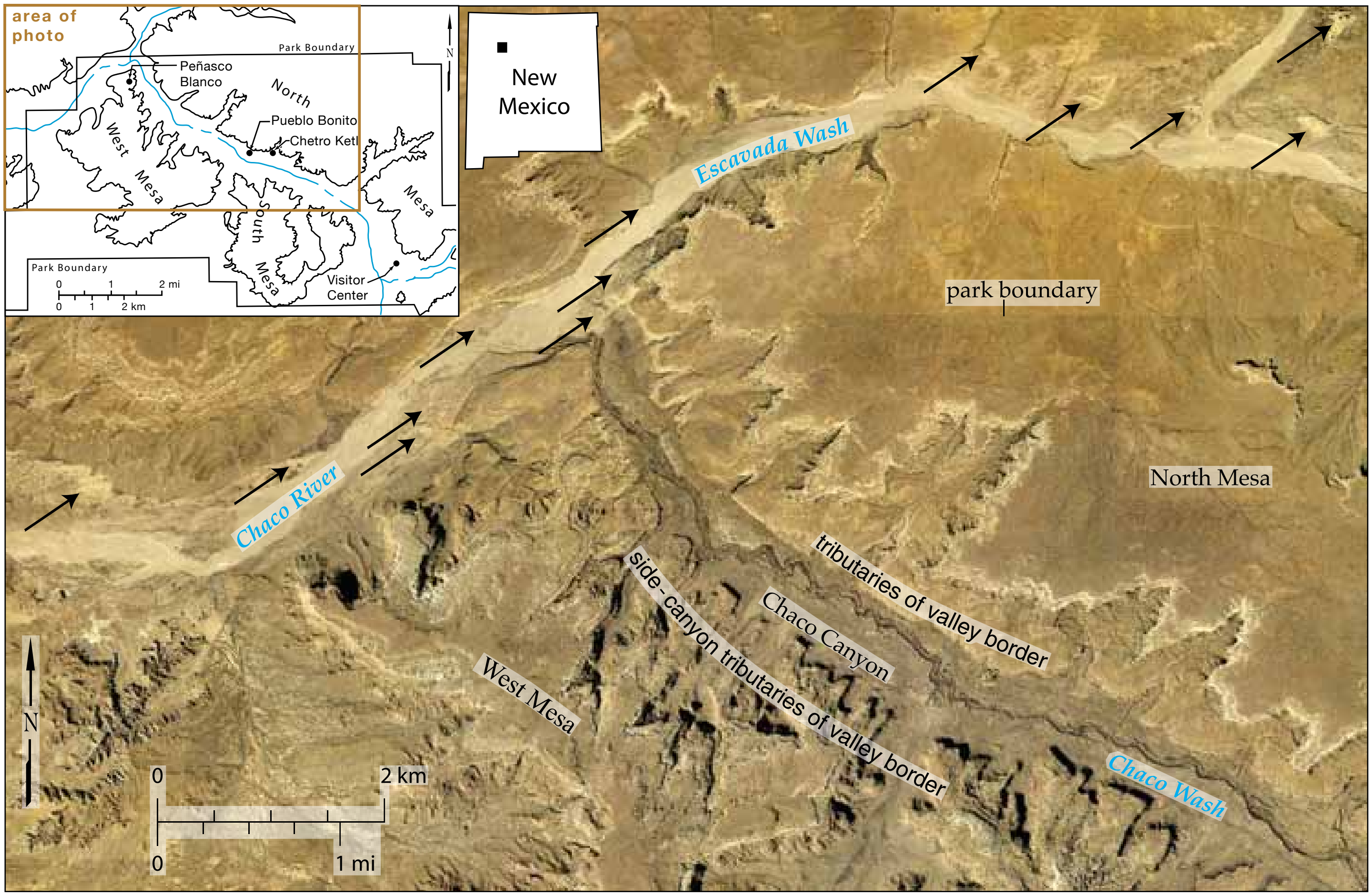

FIGURE 1—Index map showing location of lower Chaco Canyon area in northwestern New Mexico and coverage of digital orthophotograph (in tan box). Courses of Chaco Wash, Escavada Wash, and Chaco River of digital orthophotograph shown in blue. Major geomorphic features are Chaco Canyon and the tributaries of the valley border on both sides of the canyon. Black arrows indicate small eolian sand dune fields that either stop small tributaries or are cut by small tributaries along the major washes. Aerial imagery (2009) by Pictometry International, courtesy of San Juan College, Farmington, New Mexico.

internal bedding of the dunes and the interface between the dunes and alluvium in lower Chaco Canyon, (6) documentation of the size and extent of the sand dunes 1,000-1,100 yrs ago, (7) documentation of unequivocal lake sediments with fossil aquatic organisms near the hypothetical dam and the topographic context of their longitudinal and lateral extent, (8) age determinations for possible lacustrine sediments, (9) consideration of modern stream behavior and possible alternative configurations of streams 1,000–1,100 yrs ago, and (10) consideration of vegetation along streams or on dunes at present or in the past. Obviously, the comprehensive work required to develop knowledge about many of these topics would require many years of effort by field researchers. The main purpose of this article is to describe the geomorphology of northwestern Chaco Canyon, modern water discharge of Chaco Wash, and dune dynamics of lower Chaco Canyon and adjacent areas in order to test the hypothesis that sand dunes could have dammed Chaco Wash to form a lake under present-day conditions. We also present descriptions of Force et al.'s (2002) locality 30 (our section L30) and adjacent arroyo walls as well as ages of detrital charcoal samples from these exposures.

Geologic literature about Chaco Canyon is limited (KellerLynn 2007) and split between studies of Cretaceous bedrock (e.g., Siemers and King 1974; Weide et al. 1979; Scott et al. 1984; Donselaar 1989), studies of modern and past arroyos (Jackson 1878; Bryan 1954; Hall 1977, 2010; Love 1980, 1983), and Quaternary paleoecology (e.g., Hall 1977, 1988, 1997, 2010; Betancourt and Van Devender 1981; Mathien 2005; Benson et al. 2003). Pertinent to describing and interpreting the stratigraphic profile at L30 are the detailed descriptions of modern sedimentary facies related to Chaco Arroyo, particularly those interpreted to represent floodplain slack-water deposits by Love (1980; especially Munsell colors and determinations of grain-size distributions). Previous geologic literature shows that comparable slack-water deposits laid down by large floods vary laterally within a stream's flood zone and have differences in facies from stream to stream (e.g., Patton et al. 1979; Smith 1993; House et al. 2002). In contrast to slack-water deposits, lake and playa deposits in canyon settings in the Four Corners area are described by Pederson (2000) and White (1990, 1992).

The lower, northwestern end of Chaco Canyon is shown in Figures 1 and 2, which can be used to illustrate and define some of the geomorphic terms used in this article. Chaco Canyon is the landform consisting of bedrock cliffs and slopes descending as many as 90 m to its alluvial floor. The bedrock cliffs and colluviated slopes are called the valley border, and ephemeral tributaries descending from the canyon sides are termed side-valley or side-canyon tributaries. The ephemeral stream cutting an incised channel several meters below the alluvial canyon floor is called Chaco Wash on the U.S. Geological Survey Pueblo Bonito 7.5-min topographic map. Because of its small width-to-depth ratio (narrow and deep) many researchers refer to Chaco Wash as an arroyo, and refer to the present channel, floodplain, and high alluvial banks as Chaco Arroyo. The arroyo is a modern landform, and is not necessarily the past form of channel(s) in the canyon. In this paper, we refer to the modern channel as "Chaco Wash" and the whole geomorphic feature of cut banks, channel, and inner floodplain as "Chaco Arroyo." As shown in Figure 1, Escavada Wash is a broad, shallow, sandy, anastomosing or braided complex of channels and bars. Some researchers prefer to limit the term,

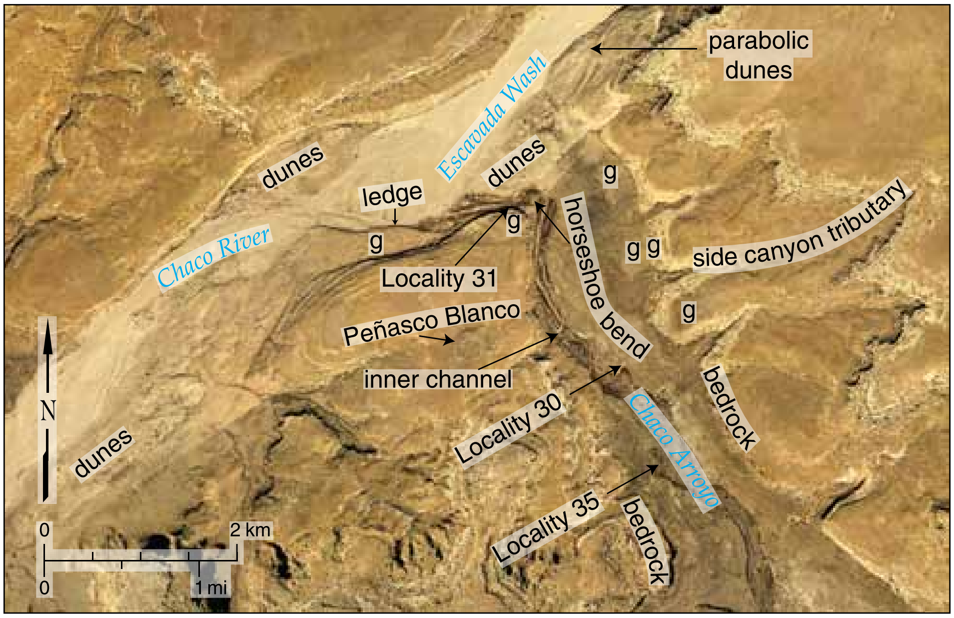

FIGURE 2—Digital orthophotograph covering confluence of Chaco and Escavada Washes to form the Chaco River. Chaco Arroyo upstream from the confluence includes the inset channel and floodplain of Chaco Wash. Gravel terraces and loose gravel on bedrock denoted by "g." Localities 30, 31, and 35 of Force et al. (2002) are indicated. Aerial imagery (2009) by Pictometry International, courtesy of San Juan College, Farmington, New Mexico.

"wash," to such broad, shallow channels. Where Chaco Wash and Escavada Wash join at the western end of Chaco Canyon, the resulting drainage is called the Chaco River or "Rio Chaco," which continues southwest, west, and north to join the San Juan River near Shiprock.

We use the term "facies" to refer to sedimentary deposits of differing character that are spatially organized and reflect different genetically related depositional environments. Deposits within facies may be differentiated by sediment characteristics such as sedimentary structures, grain size, composition, and aggregate color. For example, depositional facies recognized within modern Chaco Arroyo include the crossbedded pebbly sand of the channel and active point bars, channel-margin banks and natural levees, quiet-water back basins, and sand plugs and slack-water deposits of tributary channels and oxbows (Love 1983).

Methods and history of this investigation

Description and sampling at locality 30

The arroyo bank at this locality is approximately 5 m high. Charcoal was noted in the section by Vincent and Love in the summer of 2005, and Gillam collected samples before the bank collapsed. Using a ladder, Gillam (helped by Shattuck and Peterson, NPS personnel) established a vertical scale on the outcrop using a measuring tape, marking 1 m intervals downward (see Results section and figures). Because slump blocks were present along the base of this transect, the lowest part of the primary scale line was offset 2 m laterally to the east by using a sighting level. Sampled beds were arbitrarily identified by single letters and by depths along these vertical scale lines. All markers were left on the arroyo wall to facilitate future work.

Charcoal was removed from the outcrop with metal tools and placed in archival plastic bags. Some of the charcoal samples consisted of a single small chunk that was large enough for dating individually, but most consisted of many small particles taken from specific stratigraphic intervals. These small samples could be combined for dating if necessary.

We focused on sampling charcoal from the sand bed identified as bed "N." However, charcoal was sampled from several other beds as well. Sampled locations were marked on the arroyo bank with light green surveyor's tape showing the letter designating the bed and the sample number. These markers were commonly offset laterally by a few centimeters from the actual sampled points (see Results below). In the case of collections from a larger stratigraphic interval, the markers were roughly centered within the sampled interval. Plain green markers were also placed near a few charcoal fragments that were not collected. The charcoal samples were retained by Chaco Culture National Historical Park (CCNHP) until funding could be secured to obtain AMS ^{14}C dates on pieces of charcoal. Dr. Karen Adams examined the charcoal specimens at the CCNHP visitor center shortly after the samples were taken, identified the plant genera, and added the information to the sample labels (listed in Results section, Table 1).

Several weeks later the measured section at L30 and adjacent arroyo walls were described, sketched, photographed, and sampled by Love, with the assistance of NPS personnel Shattuck and Peterson. Horizontal placement of a tape measure at the top of the arroyo wall facilitated locating units and samples relative to the measured section at L30. Three sections were measured and partially described. Sediment samples were taken to the New Mexico Bureau of Geology and Mineral Resources for further description and were archived.

Sample preparation and treatment for AMS radiocarbon ages

Six samples of charcoal from L30 were submitted by Benson to the Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine. Standard cleaning and acid-base-acid wash pre-treatment procedures were applied. Some samples had noticeable white fibers attached to the charcoal, so a second group of three samples was washed repeatedly with 6 Normal NaOH at 70°C to remove what was thought to be recent fungus. However, the results of the treated group are about 1 sigma standard deviation from the samples with the standard treatment, suggesting that "the fibers are penecontemporaneous to deposition of the charcoal" (unpublished UCI Keck AMS report to Benson 2009).

Aerial photography and additional geomorphic data of lower Chaco Canyon

Stereo aerial photos from 1935 and 2001 were supplemented by digital orthophotographs from the U.S. Geological Survey and 2009 coverage from Pictometry International, provided by San Juan College, Farmington, New Mexico. Analglyphs and a 1 m digital elevation model (DEM) were generated from 2001 aerial photographs by Friedman. Ground-based descriptions and photographs taken during the past 37 yrs that helped with present interpretations can be found online at http://geoinfo.nmt.edu/repository/index.cfm?rid=20110003.

Results: geomorphology and sedimentology of lower Chaco Canyon

Selected present-day geomorphic features and deposits are described in four overlapping areas: stream courses; eroded bedrock and Quaternary stream terraces along lower Chaco Canyon and adjacent Escavada Wash; dune complexes in the confluence area; and alluvial deposits upstream in lower Chaco Canyon. We cannot describe lacustrine or playa deposits on the modern floor of Chaco Canyon because none now exists; instead, back-basin (behind natural levees), oxbow, and tributary-mouth slack-water deposits described by Love (1980, 1983) provide analogs for possible past low-energy, standing-water deposits. Dunes damming and cut by smaller tributary drainages exist along the Chaco River and Escavada Wash but have not been described in previous studies. Historic aerial photographs show that some of these drainages had small ephemeral ponds

TABLE 1—Radiocarbon analyses of samples from locality 30.

Sample name[1]	Lab no. UCIAMS	Depth (cm)	Material	^{14}C age[2]	^{14}C error (yr)	1-Sigma calib. range[3]	1-Sigma calib. age[4]	Calibration age error (yr)
E1c	68761	80–84	*Chrysothamnus*	2110	20	175–102 B.C.	138 B.C.	36
E1j	68762	80–84	*Juniperus*	2175	15	350–305 B.C.	327 B.C.	22
E3	68763	80–84	coal?	54400	3700			
N3j1	68764	244–248	*Juniperus*	3095	20	1412–1377 B.C.	1394 B.C.	18
N3j2	68765	244–248	*Juniperus*	3080	20	1405–1371 B.C.	1388 B.C.	17
N4c	68766	244–248	*Chenopodioideae*	2705	20	894–873 B.C.	834 B.C.	16
E1c6N[5]	68771	80–84	*Chrysothamnus*	2125	20	197–153 B.C.	175 B.C.	22
E1j6N[5]	68772	80–84	*Juniperus*	2200	20	328–285 B.C.	306 B.C.	22
N4c6N[5]	68773	244–248	*Chenopodioideae*	2720	20	895–867 B.C.	881 B.C.	14

[1] Capital letter designation is sedimentary unit at locality 30; number is each charcoal sample; lowercase letter is plant type identified by Karen Adams.
[2] Radocarbon ages determined by accelerator mass spectrometry at the Keck Carbon AMS Facility, University of California, Irvine.
[3] Age calibration done using Stuiver and Reimer (1993) and IntCal 09.
[4] Calibrated age calculated as the center point of the 1-sigma calibrated age range.
[5] Samples E1c, E1j, and N4c contained white fibrous material after a standard pretreatment of 1 N HCl, 1 N NaOH, and 1 N HCl. The fibers were interpreted to be fungus, and aliquots of these samples were treated repeatedly with 6 N NaOH at 70°C until fibers were no longer visible. Results for the two fractions are approximately 1 sigma apart implying the fibers are penecontemporaneous to deposition of the charcoal.

related to eolian activities, but none of them have been studied, and many are now buried by sand.

Confluence of Escavada Wash and Chaco Wash

The junction of these two streams is marked by strong contrasts in channel morphology (Figs. 1, 2, 3, and 4) and belies the notion that a smaller tributary (Escavada) meets a larger stream (Chaco) based on their respective drainage-basin sizes. East of the canyon-mouth dunes, Chaco Wash occupies a relatively narrow trench incised below the broader canyon floor. Its present meandering channel 1–2 m deep and about 20 m wide at bank-full stage, is bordered by an arroyo-bottom floodplain approximately 90 m wide. The arroyo walls rise 2–5 m high above this inset floodplain to the canyon floor. Chaco Wash has a gradient of 2.2 m/km. The valley-floor gradient along the top edge of the arroyo is locally steeper near its mouth, 8.2 m/km, but farther upstream the channel and valley-floor gradients are both about 2.0–2.5 m/km (Love 1980). Much of the sediment transported in Chaco Wash is composed of fine sand (mode = 212 μ; 2 phi; 70 mesh sieve; sieved at ¼ phi intervals). The Chaco drainage area above the canyon mouth is 1,214 km^2, but the lower 261 km^2 follows the strike of underlying bedrock through Chaco Canyon at a relatively low gradient, stores large amounts of sediment as fill beneath the canyon floor, and does not contribute much added runoff to Chaco Wash.

In comparison, Escavada Wash has a shallow, braided, channel 160–380 m wide and a steeper gradient, 8.75 m/km. Its bedload is mostly coarse sand (mode 350 to 500 μ). Although it has a much wider channel than Chaco Wash, its drainage area is only 570 km^2. However, the wash and its tributaries cut across strike of underlying bedrock at steeper gradients and transport coarser sediments. Downstream from the confluence, the Chaco River resembles Escavada Wash.

Water discharge of Chaco Wash was measured between 1976 and 1990 by the U.S. Geological Survey Water Resources Division (Borland et al. 1991, p. 305). Crest-stage discharge estimates have been provided by the U.S. Geological Survey since then. The average annual discharge is 3.85 million m^3/yr. Flows in summer months tend to be flashy, whereas spring snowmelt flows may last for weeks. The largest reported event (140.75 m^3/sec, crest-stage recorder) was on August 23, 2003. A peak discharge of 54.4 m^3/sec and mean daily discharge of 17.6 m^3/sec was reported for September 2, 1988. The third largest recorded discharge (35.7 m^3/sec) followed a rain-on-snow event in January 1979 that scoured and broadened much of the inner channel of Chaco Arroyo (Love 1980).

Adjacent to both Chaco Arroyo and Escavada Wash near their confluence are abandoned channels with attached sand bars that cut across the lower edges of the eolian dune complex and valley-floor alluvium at the mouth of Chaco Canyon (Figs. 2 and 4A). These crosscutting relationships suggest that the low dunes adjacent to the channels are young and have probably been reworked by occasional floods. The 1935 aerial photos show that the channel of Chaco Wash at its confluence with Escavada Wash was much wider and spread out farther north than in 2009 (Fig. 5). Vegetation northeast of the confluence is associated with valley-floor alluvium and thin eolian sand. Tamarisks have taken over much of the present floodplain of Chaco Arroyo, which has developed since 1935.

Bedrock outcrops and terraces at the lower end of Chaco Canyon and Chaco River

Bedrock exposures at and near the mouth of Chaco Canyon consist of Upper Cretaceous marine and coastal-plain strata that dip approximately 2° to the north-northeast. Near the Chaco–Escavada confluence, these rocks have been mapped primarily as Cliff House Sandstone (Scott et al. 1984). However, interfingering with the Cliff House are tongues of underlying Menefee Formation (nonmarine sandstone, shale, and coal) and overlying Lewis Shale (Scott et al. 1984; Donselaar 1989).

Erosion along tongues of softer rocks has separated upper and lower cliffs in the area and has helped to shape features at the confluence that influence the wind currents and dune locations. At the southwestern end of Chaco Canyon, south of the horseshoe bend of Chaco Wash, sandstone beds containing a thin tongue of shale form a cliff approximately 25 m high. The cliff and the ridge above it shelter the lower part of Chaco Canyon from southwesterly winds and any significant eolian sand transport. At the north end of this cliff, erosion along a half-meter tongue of shale has separated a lower sandstone ledge from the upper cliff. This ledge continues to crop out to the southwest where it is capped by stream-terrace gravels and eolian sand. This ledge and terrace, 6–11 m high, confine the south edge of Chaco Wash at its mouth and block most sand transport from the southwest (Fig. 3). The thin eolian sand overlying the terrace gravel indicates that some sand is transported northeastward across the high ground.

Another sandstone ledge on the north side of the mouth of Chaco Canyon and upstream along Escavada Wash protects eolian sand (parabolic dunes) and a low gravel terrace from being eroded (Fig. 2). Buried portions of this ledge may influence the topography of interdune areas.

Other gravel-capped terrace remnants and scattered pebbly lag deposits cover bedrock at several levels near the mouth of Chaco Canyon (Fig. 2). These gravels help stabilize slopes and preserve former Pleistocene positions of the Chaco River. Some of these deposits are cemented by ground water-related coarse calcite, particularly along their basal contacts

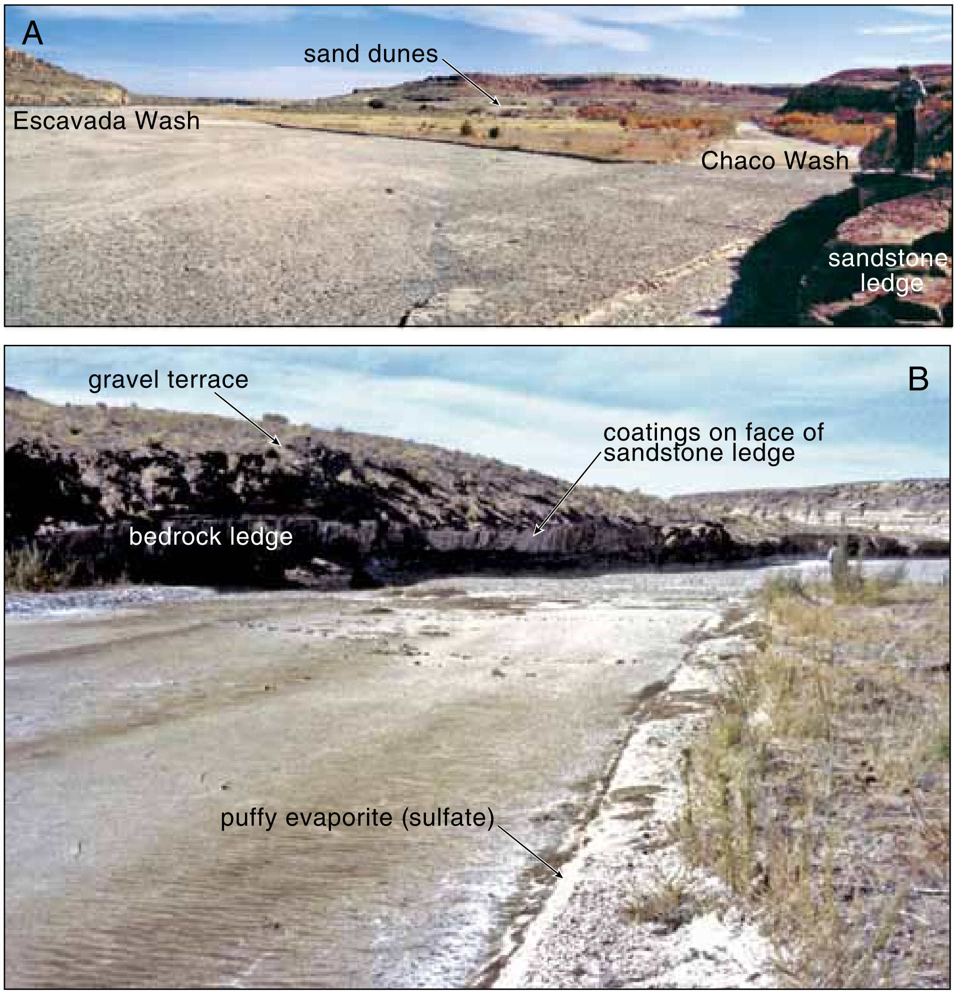

FIGURE 3—**A**—Junction of Escavada Wash (left) and Chaco Wash (right) in 1979. Sand dunes occupy the vegetated area between the two streams and lower cliffs in middle ground. Bedrock (Cretaceous sandstone) ledge with human for scale to right. **B**—Bedrock ledge and terrace viewed downstream across mouth of Chaco Wash in 1979.

with underlying sandstone. Gravel deposits in a terrace position lie between bedrock and eolian deposits on the sandstone ledge at the mouth of Chaco Wash and also form benches above bedrock ledges on the north side of Chaco Canyon.

The subsurface fill of lower Chaco Canyon below present arroyo exposures and sand dunes has not been investigated. Ross (1978) described a seismic study and bore holes on the valley floor ~2.4 km upstream from the confluence of Chaco and Escavada Washes, upstream from Force's locality 30. The thickness of fill at three bore holes across the valley floor is 21–24 m at that location. Farther upstream, a deeper buried inner canyon (at least 34 m below the surface) was also detected seismically and with bore holes (Ross 1978). These limited data suggest that the alluvium and dunes at the mouth of Chaco Canyon are not resting on shallow bedrock, which would have provided a strong, less permeable foundation for a dam.

Sand dunes

The broad, continuous channel of Escavada Wash and Chaco River is subparallel to dominant southwesterly winds and provides an abundant source of loose sand for eolian transport. Small dunes are common along the borders of this channel, on parts of the channel floor, and at the mouth of Chaco Canyon. As illustrated in Figures 2 and 4, the present (2009) dunes at the mouth of Chaco Canyon are a complex of parabolic arms with secondary sinuous crests and parabolic interdune hollows or blowouts, climbing to the north-northeast until the rise in elevation and runoff from the slick-rock cliffs inhibit further accumulation. The large dunes are partially stabilized with vegetation, particularly as coppice dunes beneath bushes. Some eolian sand does cross the slick-rock sandstone to accumulate as isolated dunes midway up the valley border. Partially stabilized blowouts and parabolic arms also continue farther northeastward along the valley border of Escavada Wash covering lower bedrock slopes (Fig. 2).

At the mouth of the canyon in the dune area below the slick rock, dune-crest elevations rise from less than 1,822 m to 1,835 m along a northeast-oriented transect (Fig. 6). Using the 1-m DEM, we estimate volume of the dunes between Chaco Wash, Escavada Wash, the northern bedrock slopes, and the eastern dune edges to be on the order of 104,000 m^3. The slope on the southeast face of the sand pile is not a slip face but consists of overlapping margins of parabolic arms with slopes less than the angle of repose (<30°). Two different processes may limit the extension of sand to the east: (1) wind eddies and vortices related to the high cliffs to the south may commonly stall or divert the transport of sand into lower Chaco Canyon; and (2) runoff along the tributary drainage from the northeast may trim and remove sand when it is blown into its transport area. The features closer to Escavada Wash just upstream from the confluence with Chaco Wash are typical parabolic dunes and blowouts. Some of the "bumps" are large, vegetation-protected coppice dunes. Grain size varies from sand modes of 250 μ on the eastern dunes to 300 μ on the large whiter dunes closer to Escavada Wash (Love 1980).

Smaller, browner parabolic and coppice sand dunes also accumulate adjacent to the present mouth of Chaco Wash (Fig. 4A). These dunes are finer grained with a sand mode of slightly less than 150 μ (Love 1980).

In the earliest aerial photographs, taken in 1935 for the Soil Conservation Service, dunes at and near the mouth of Chaco Canyon were much more active and somewhat differently distributed (Fig. 5) than at present. Eolian sand nearest the confluence of Chaco Wash and Escavada Wash was more sheetlike on vegetated older alluvium. However, oblique transverse dunes, with very little vegetation and active slip faces to the east-northeast, were located farther west and buried more of the bedrock on the northeast side of the canyon. Since 1935, some of that sand has moved eastward to cover the channel bend of the first northeastern tributary ("c" in Fig. 5), and a low bedrock ledge has been re-exposed in a blowout where the sand used to be ("b" in Fig. 5). Similarly, bedrock ledges to the northwest that were covered by transverse or barchanoid ridges in 1935 are now re-exposed, but bedrock farther northeast is now buried by windblown sand. Perhaps four of the largest coppice mounds in 2009 can be correlated to large vegetation seen on the 1935 aerial photographs. Dunes have also migrated northeastward along the valley border of Escavada Wash.

South of the Chaco–Escavada confluence in 2009, at least two generations of climbing dunes approach the lower cliffs, but in general do not pile up against them (Figs. 1 and 7). Rather, there are low areas (including some blowouts) between the parabolic margins of dunes and the trends of the cliffs (suggesting winds are influenced by cliffs). Dune crests are adjacent to cliffs in a few places along the cliffs (Fig. 7, red triangles). Based on the orientation of parabolic arms, winds appear to direct small dunes more northeasterly parallel to the trend of the high cliff. As seen in Figure 7, small, stabilized parabolic dunes are also present on the terrace tread above the bedrock ledges south of the mouth of Chaco Wash. One set of these is cut by two small meandering drainages. A larger dune is overtaking the arms of these parabolae southwest of the

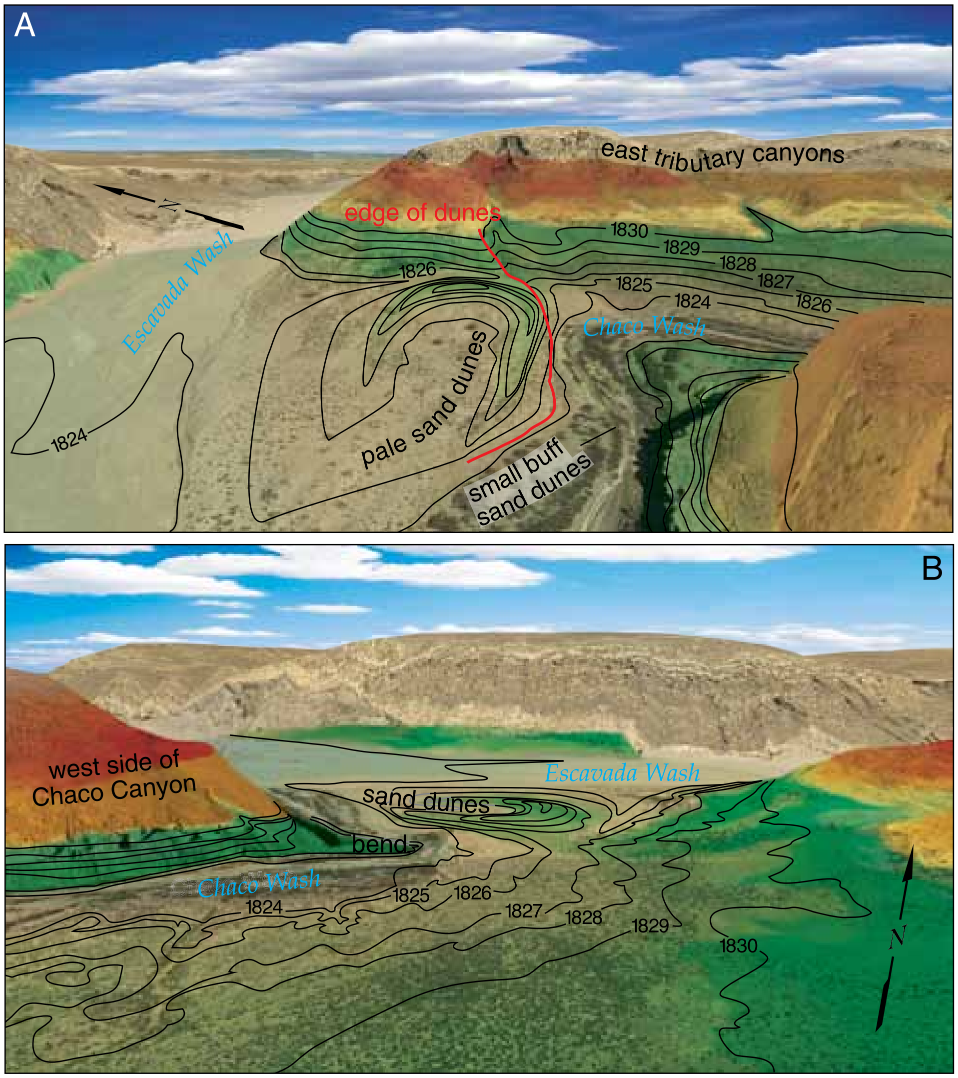

FIGURE 4—Oblique views of dunes and floor of Chaco Canyon generated from digital orthophotographs and digital elevation model with 1-m contours and color ramp superimposed. **A**—View to northeast centered on dune area and horseshoe bend of Chaco Wash. Pale sand dunes become larger to the northeast and are derived from Escavada Wash and Chaco River; small buff sand dunes are on the floodplain adjacent to Chaco Wash and are derived from the channel and inner floodplain. **B**—View to northwest showing sand accumulation, gap between south side of Chaco Canyon and dunes, and limited space for shallow pond having a surface elevation of 1,825 m.

drainages. Two canyon-cutting tributaries from the east disappear in the eolian sand at the mouths of the canyons (Fig. 7).

The 1935 aerial photographs record a very different situation in this area (Fig. 8). Large active blowouts with long parabolic arms south of the eastern tributaries had reworked older sand accumulations and were advancing on low planar-floored blowouts (playa-like) areas that previously formed along the eastern margin of the Chaco River. The base of deflation was probably controlled by a shallow water table. These two eolian-blowout areas are unlike the area envisioned for the reservoir behind the proposed dune dam at the mouth of Chaco Canyon. The two eastern tributaries were diverted into two different blowout playas dammed by eolian sand, although the northern tributary of the two almost reaches the Chaco River. Comparison of 1935 photos with 2009 photos shows that the movement of eolian sand has been dynamic, although vegetation presently is stabilizing most of the sand. Runoff from the two tributaries has not kept pace with the advancing parabolic dunes, and the blowout areas are covered with eolian sand. It should be noted that neither the 1935 blowout playas nor the low ends of 2009 dune-dammed tributaries contained any water at the times the photographs were taken. These could be investigated as possible analogs for ephemeral water storage areas as ponds, although the areas are small and the surrounding sand is apparently very porous.

North of the mouth of Chaco Canyon on the east side of Escavada Wash, dunes with long parabolic arms rise onto a sandstone ledge and bury the slick-rock interval seen to the southeast. Here again, small meandering drainages with headwaters on the bedrock manage to cut part-way or fully across the parabolic dunes (Figs. 1 and 2). Farther north along both sides of this reach of Escavada Wash, multiple generations of small dunes with uneven parabolic arms are coming out of the anastomosing sandy channels of the drainage (Fig. 1).

Many other small dune fields are derived from Chaco River (downstream) and Escavada Wash (upstream) from the confluence of the two streams (Fig. 1). Several of these have small drainages that cross dune fields, are deflected around dunes, are dammed by dunes, or are lost within the dune fields (Figs. 1 and 7). This suggests that further study could possibly determine a minimum size for a drainage basin (as a proxy for water discharge) capable of crossing dunes versus those too small to maintain channels across dunes. The interplay between wet and dry years, each dune field's own dynamics of sand generation, transport, and storage independent of the small drainages would complicate determining the minimum drainage capable of crossing dunes. Based on remotely sensed observations from aerial photographs, digital orthophotographs, and Google Earth™, however, it appears that drainage basins of only a few square kilometers are capable of maintaining or cutting channels across parabolic arms of dunes.

The alluvial floor of lower Chaco Canyon and contributions by northern tributaries

The aggraded alluvial floor of lower Chaco Canyon is 2–6 m above the present channel of Chaco Wash and consists of (1) alluvium transported from upstream by precursors of Chaco Wash and (2) locally derived alluvium from tributaries on both sides of the canyon (Fig. 9). The modern facies of the arroyo and canyon floor were studied in detail and described upstream in the central canyon by Love (1980). Love (1980) also sampled and briefly described some modern deposits in lower Chaco Canyon. He noted that the water table episodically reached the surface in lower Chaco Canyon and suggested possible reasons for its shallow presence.

Most tributaries from the southwestern side of the lower canyon are short and do not have large alluvial fans that extend onto the floor of the canyon. In contrast, the five northeastern side-canyon tributaries all have developed well-vegetated alluvial fans from the base of the cliffs of Cliff House Sandstone to beyond the middle of the canyon floor (Fig. 9). Two of the drainages have entrenched channels all the way to the modern Chaco Arroyo. These channels were present but not continuously entrenched in 1935 (Fig. 5). Gradients on the lower parts of the alluvial fans range from 20 to 28 m/km, whereas upper channel reaches include waterfalls over sandstone cliffs. Size of transported sedimentary grains ranges from pebbles of sandstone and concretions to the fine sand weathered from the Cliff House Sandstone. Although clay is present in the fans, it rarely is preserved as clay drapes. The color of locally derived sand is predominantly light yellowish brown to nearly brownish yellow

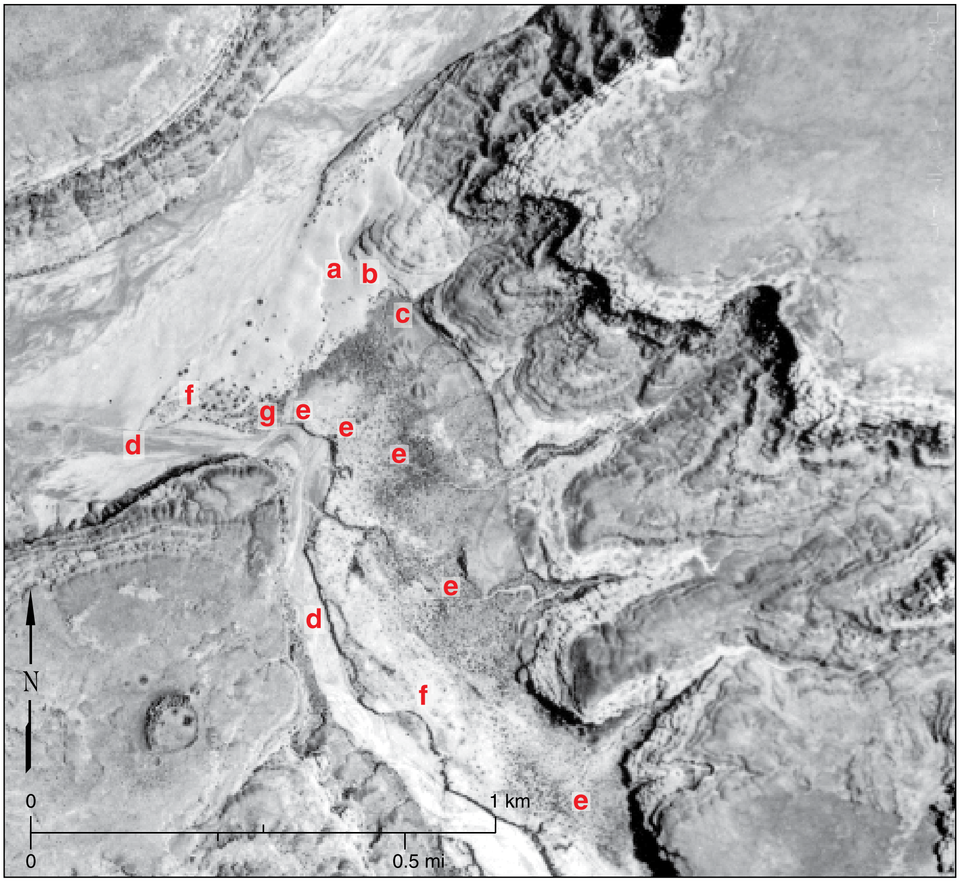

FIGURE 5—Aerial view of the mouth of Chaco Canyon in 1935. Compare with dunes in 2009 of Figure 2: (**a**) oblique crests of active eolian dunes, (**b**) active dune mounting bedrock where blowout now is, (**c**) westward meander of small tributary, (**d**) broad channel and mouth of Chaco Arroyo, (**e**) extent of active channels and alluvial fans of the five northeastern tributaries, (**f**) lack of vegetation on alluvium, and (**g**) extent of alluvial valley floor between horseshoe bend of Chaco Arroyo and the active sand dunes. Photo scan courtesy of Earth Data Analysis Center at the University of New Mexico.

(10 YR 6/4 to 10 YR 6/5). Some eolian reworking of the fans is seen as low coppice dunes, but sheetwash transport and vegetation appear to stabilize the loose sand so large dunes are now absent.

Alluvium derived from erosion of upstream landscapes comprises most of the valley floor between the modern arroyo and the toes of alluvial fans encroaching from the northeast. Based on aerial photos and the 1-m DEM, exposures of alluvium and the valley floor appear to continue westward around the horseshoe bend and to be truncated by historic erosion on the north side of Chaco Arroyo (“g” in Fig. 5; Fig. 6). Recent eolian deposits partially cover the alluvium of the valley floor there. The 1935 aerial photographs also suggest thin eolian sand sheets and low “dome” dunes on valley floor alluvium east of the horseshoe bend. Historically (1935 aerial photos), above the confluence with Escavada Wash, much of Chaco Wash was much less sinuous and the channel was braided. The beginnings of the inner floodplain as attached bars and scrolls inside meander loops are evident (Fig. 5).

Canyon-floor and Chaco Arroyo alluvium ranges from clay to pebbly sand. Sand colors are commonly pale brown to light yellowish brown (10 YR 6/3 to 10YR 6/4). Silt and clay colors are commonly grayish brown to light gray (10 YR 5/2 to 7/2; Appendix; cf. Love 1980). Sedimentary facies of the modern arroyo include several types of channel bedforms, natural levees, back-levee basins, and more generalized overbank floodplains, oxbows, and slack-water deposits in tributaries (Love 1980, 1983). The bedforms, channel-margin deposits, and slack-water deposits all have distinctive grain sizes and/or colors. Because some of these depositional environments had very low flow velocities, fine-grained silts and clays settled from suspension and resemble pond sediments found in nonarid environments. Those fine-grained sediments, coupled with evaporation from the capillary fringe above the modern shallow water table, had produced small nodules and/or bands of evaporite minerals (gypsum and bloedite; Love 1980) in silt and clay that may be mistaken for evaporite minerals formed in playa environments. Aquatic organisms are commonly absent in these depositional settings.

Description of Force’s locality 30

Force et al. (2002) located their section 30 on a map and furnished a photo of the arroyo wall, but did not describe the section in detail and did not put a scale in the photo, nor a depth. We not only measured a section at L30, but also traced units laterally to the southeast and southwest (Figs. 10 and 11). A collapse of the arroyo wall southwest of L30 obscured some of the lower contacts, but provided improved access to the upper part of the outcrop. Details of our measured sections, including Munsell color codes are in the Appendix. Here we describe some of the sedimentary facies and packages of units that we traced laterally.

When studied in 2005, the lowest exposure at L30 (labeled “unit T” in the Appendix) appeared to be a modern bank of Chaco Wash. Even though we dug into the bank, attempting to reach the older base of the arroyo wall, we suspect that the exposed deposit is historic. This unit is mostly fine sand with ripple crossbedding and thin clay drapes. White evaporitic efflorescence coats clayey units to form wavy white bands on exposures.

The lowest unit exposed within the arroyo wall at L30 (unit P; 268–390 cm depth) and farther southeast, consists of light-yellowish-brown fine sand with no preserved sedimentary structures and overlying multiple thin units of upward-fining fine sand, silt, and clay or just gray silt and clay. To the southeast, this unit includes a minor scour-and-fill channel 4 cm deep. Although small charcoal fragments were recovered, no samples were submitted to obtain radiocarbon ages. This package is similar to modern overbank facies of repeated flood events (cf. Love 1980).

The overlying unit N consists of light-yellowish-brown to brownish-yellow very fine sand with detrital fragments of charcoal ranging to 1 cm in diameter (Fig. 12). Even though this bed is only a few cm thick, it can be traced more than 25 m laterally because it is a distinctive sand and both its upper and lower contacts are sharp. It decreases in elevation (relative to the top of the arroyo wall) slightly to the southeast. This unit may have been deposited by the major tributary to the northeast.

More gray clay and upward-fining units of gray sand, silt, and clay overlie unit N from 250 to 202 cm below the surface. To the southeast, this package of thin-bedded units thickens to 275–210 cm below the surface.

Above the thin-bedded unit is consolidated fine sand with calcium carbonate in root casts. To the southeast, this interval consists of nearly structureless churned, gray sand, silt, and clay with only a hint of horizontal bedding. The top of the unit consists of cracked, structureless gray silty clay, which may have been a soil with vertic properties and with gypsum (?) and calcite concentrations.

The overlying unit E, from 77 to 202 cm, consists of ripple-cross-laminated, very fine sand and silt with common detrital charcoal and coal fragments. This unit also contains unidentified fossil snails. It can be traced 8–9 m to the southeast where the crossbedded sands are more prominently exposed and appear to truncate more consolidated, less structured sandy beds farther southeast. To the southwest, this

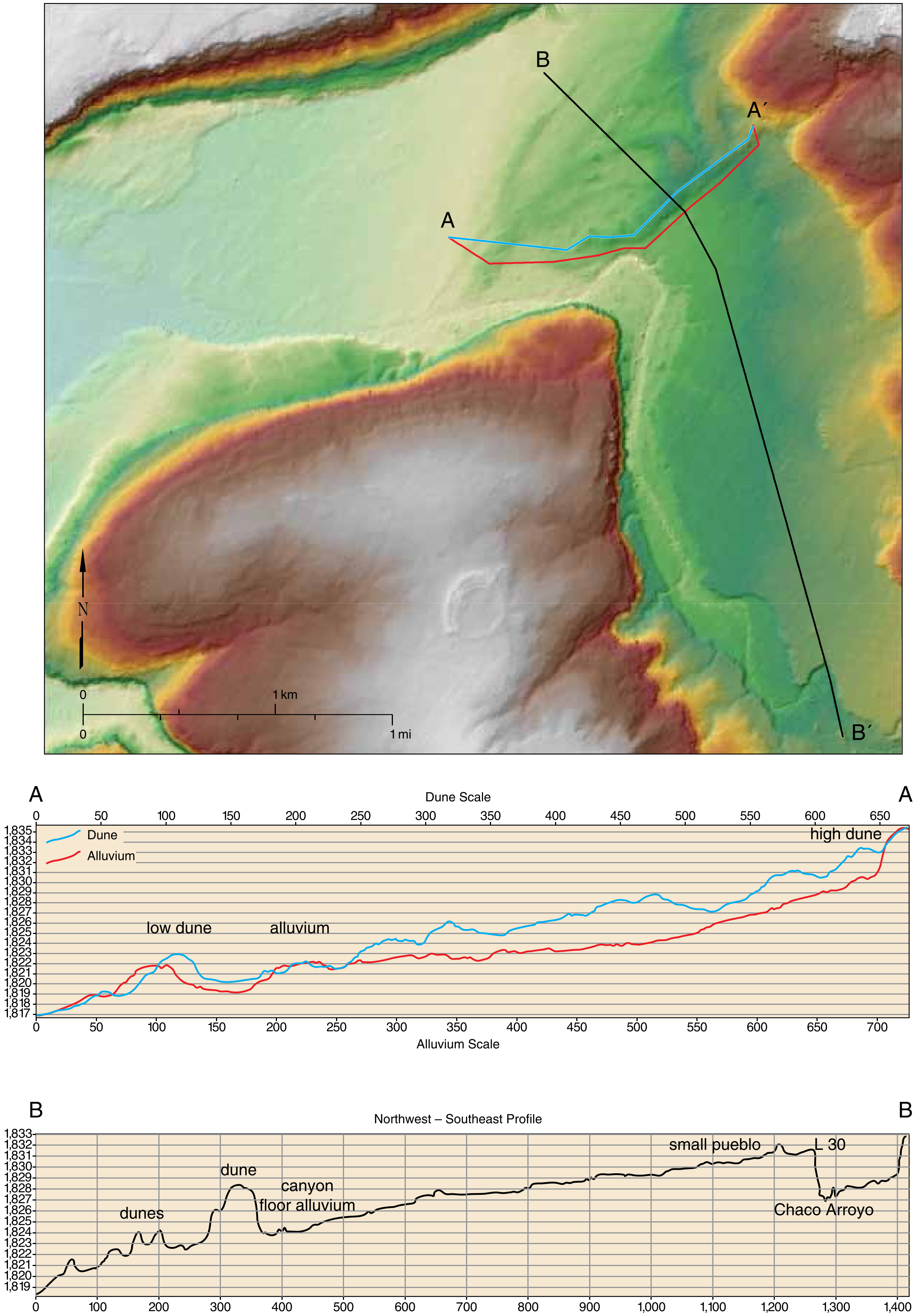

FIGURE 6—Color ramp of 1-m DEM of lower Chaco Canyon showing locations of topographic profiles. **A**—Topographic profiles from Escavada Wash to the dune at the base of the cliffs on the northeast side of lower Chaco Canyon, one along the crest of the dunes (A–A′, blue profile), whereas the other along alluvium at the base of the dunes (red profile). Note separate horizontal scales for dunes and alluvium. **B**—Topographic profile from Escavada Wash across the sand dunes and up the valley floor of lower Chaco Canyon to L30 and across Chaco Arroyo (B–B′).

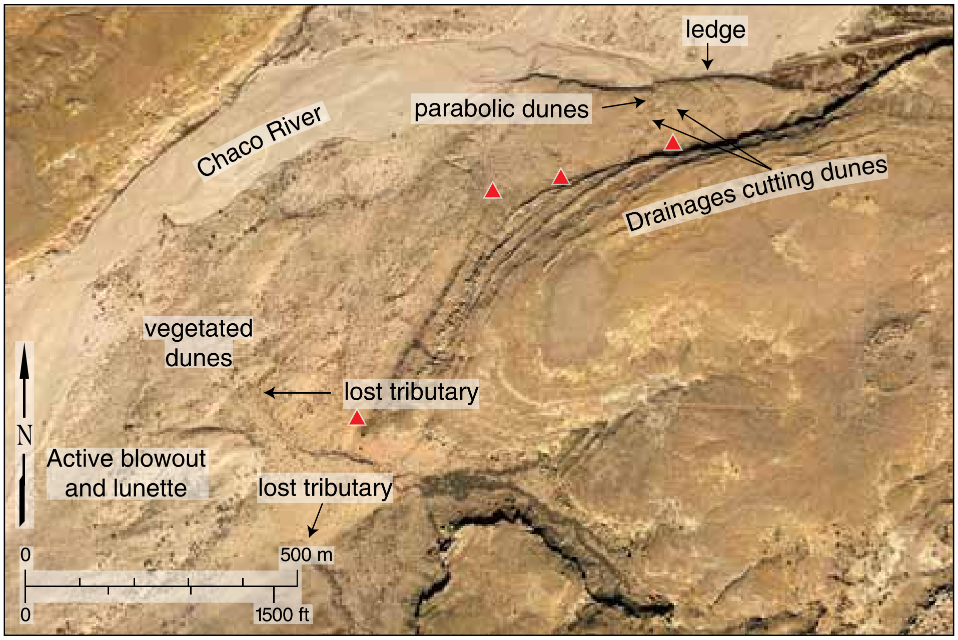

FIGURE 7—Vegetated and active dunes and blowouts along Chaco River southwest of Chaco Canyon. Aerial imagery (2009) by Pictometry International, courtesy of San Juan College, Farmington, New Mexico. Red triangles indicate locations where dune crests are adjacent to cliffs.

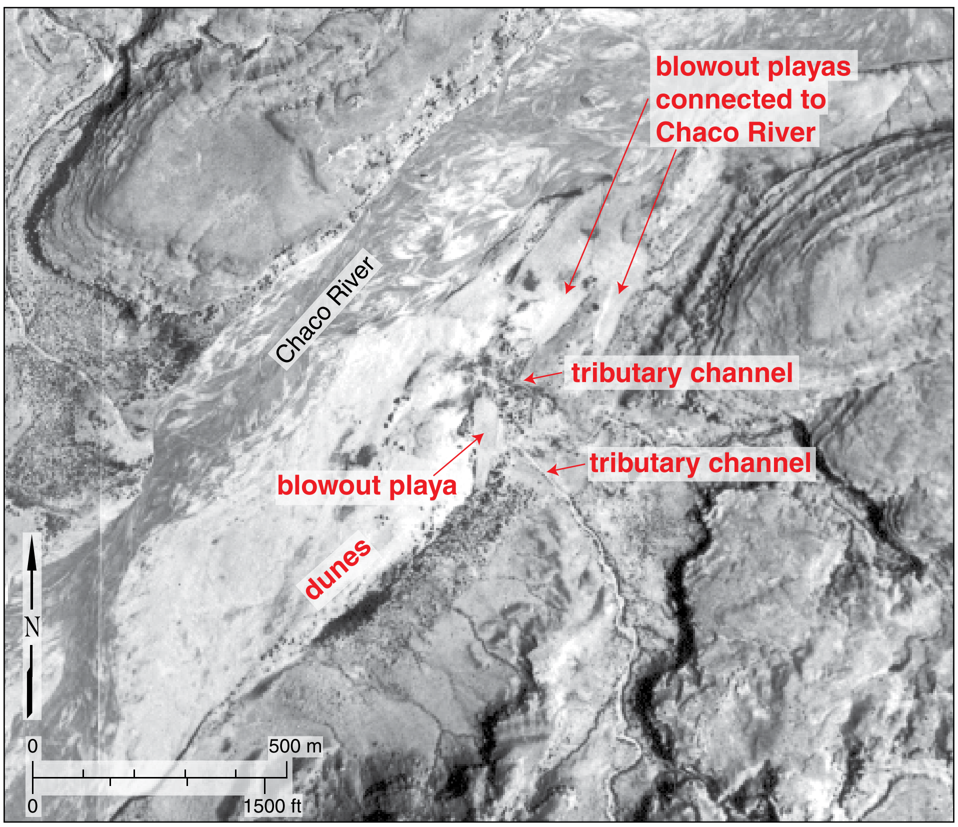

FIGURE 8—Aerial photograph from 1935 showing active dunes and blowouts adjacent to Chaco River.

unit thickens to become part of the fill of a broad, deep, buried channel (Fig. 10).

From 50 to 77 cm below the surface at L30 is a distinctive, relatively thick, structureless, gray silty clay with soft calcium carbonate nodules. The unit can be traced southeastward where it is buried by about 56 cm of sandy alluvium. To the southwest, the sandy alluvium above is much thinner and the top of the clayey unit is within 15 cm of the surface. This clay package appears to be a buried soil with vertic properties.

The uppermost 50 cm at L30 consists of low-angle cross-laminated fine sand and structureless fine sand. This unit is exposed at the surface and can be traced from the edge of the arroyo wall southwestward, westward, and eastward. It is thicker to the east and thinner to the southwest. The crossbeds indicate that at least some of this unit is alluvial, but some may have been reworked at the surface by eolian processes. Based on its position in the landscape, part of this unit may consist of distal alluvial-fan deposits from the side-canyon tributary to the east-southeast.

Beginning about 9 m and continuing beyond 45 m southwest of L30, unit E thickens and truncates underlying units to fill a large arroyo paleochannel. The floor of this paleochannel is below the modern arroyo channel; more than 480 cm below the surface (Figs. 10 and 13). The lowest exposed paleochannel fill consists of moderate-angle crossbeds of light-brown sand and granules of lignite and coal in sets about 25 cm thick. Higher in the section, the sand is more commonly ripple-cross-laminated. Three flat, angular slabs of Cretaceous sandstone slope downward into the channel 16–18 m southwest of L30 at a depth of 320–333 cm. The southern edge of this paleochannel was not seen in these exposures, but on the southwest side of the modern arroyo, 140 m south of L30, additional flat sandstone slabs were noted in local alluvium and colluvium at a similar depth as the slabs 17 m southwest of L30.

Results: radiocarbon

Six samples of detrital "charcoal" and three alternative-treatment replicates were analyzed by the Keck Carbon Cycle AMS Facility at University of California Irvine (Table 1). Because all the charcoal is detrital and some radiocarbon ages are out of sequence vertically, these ages obviously represent maximum ages within each geologic unit.

Discussion

Topics for discussion include (1) several aspects of eolian sand dune behavior, (2) hypothetical dam and reservoir shapes and sizes versus quantities of discharge down Chaco Wash, (3) the location and stratigraphy of L30 upstream from the dunes, and (4) the ages of deposits in the vicinity of the stratigraphic section.

Dynamics of eolian sand dunes and adjacent channels

Comparison of the 1935 and 2009 aerial photos shows that the sand dunes at the mouth of Chaco Canyon and along the Chaco River have changed form and thickness over hectares in 75 yrs. The amount of vegetation stabilizing the dunes has also increased. Active oblique transverse dunes in 1935 have shifted north and east and are now blowouts and parabolic dunes with long, partially stabilized arms. Thick accumulations of eolian sand along the lower cliffs on the northeast side of the canyon have shifted slightly east, and blowouts

FIGURE 9—Aerial photograph of lower Chaco Canyon showing five northeastern tributaries, their alluvial fans, and the alluvial floor of the canyon composed predominantly of alluvium derived from upstream. Aerial imagery (2009) by Pictometry International, courtesy of San Juan College, Farmington, New Mexico.

expose lower cliffs that had been buried in 1935. Sheet runoff from slick-rock sandstone ledges along the canyon margin locally has removed earlier eolian sand. Since 1935 the western parabolic dunes have also migrated north along Escavada Wash a few hundred meters before becoming vegetated and locally removed by erosion along short, steep tributaries. Although accumulations of sand are in similar areas, the amounts of sand in transit have changed. Moreover, floods along the rivers and tributaries have trimmed the edges of eolian sand laterally by many meters. Eolian sand cover on alluvium north and west of the horseshoe bend appears to have increased in volume, but the surface elevation west of the top of the arroyo at the bend is still similar to the exposed alluvium north of the bend.

Because of the differences in eolian activity in just 75 yrs, and the indication that valley-floor alluvium west of the horseshoe bend passes under at least the southern eolian sand, interpretations of the size and shape of eolian sand 1,000–1,100 yrs ago would be very speculative.

The presence of a 6- to 11-m high bedrock ledge and gravel terrace southwest of the mouth of Chaco Canyon helps to concentrate flows within Chaco Wash and prevents southwesterly winds from creating eolian sand dunes in that part of the channel that lies in the lee of the ledge. Minor falling sand from eolian dunes migrating northeastward along the top of the terrace and ledge is likely reworked by frequent flows of Chaco Arroyo.

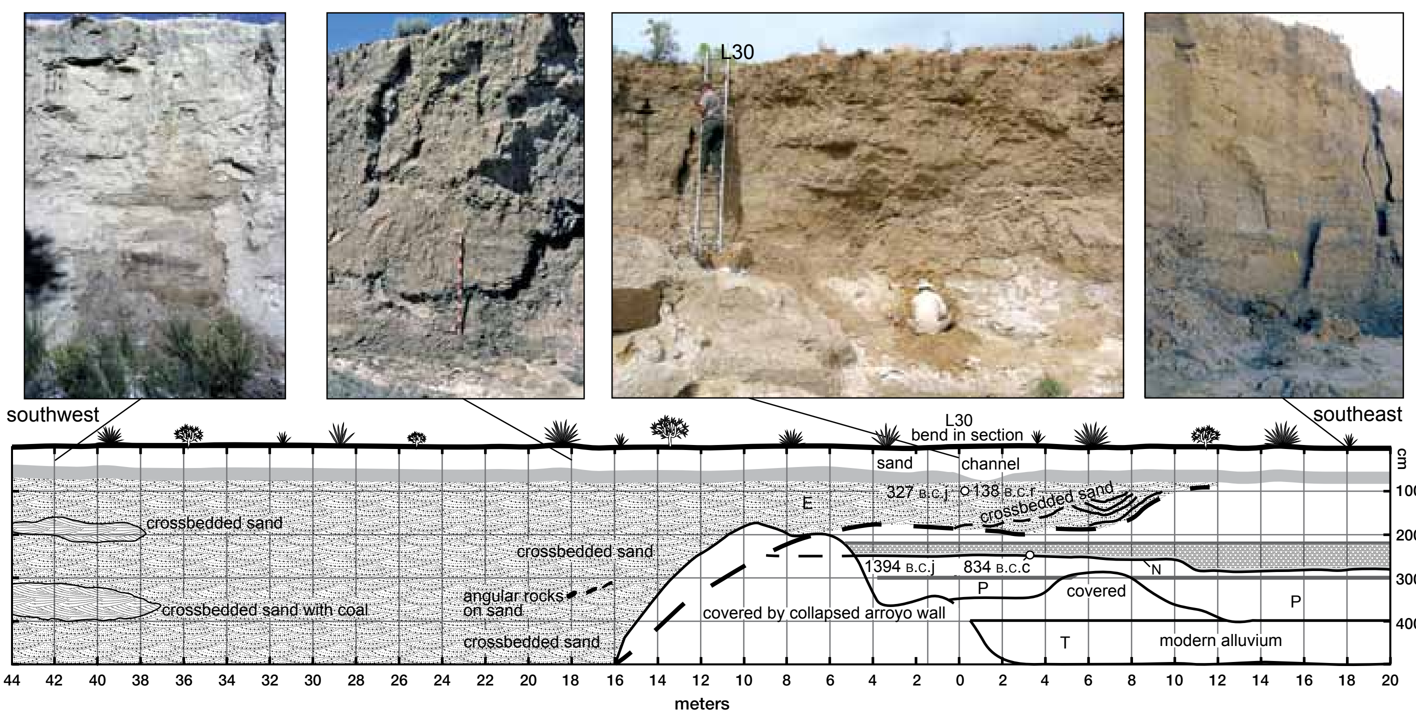

FIGURE 10—Photographs and profile of Chaco Arroyo wall from L30 (0 point) to southeast (20 m) and southwest (44 m). Note that edge of paleochannel cut-and-fill begins a few meters south of L30 and deepens below 5 m to the southwest. Capital letters refer to stratigraphic intervals where charcoal was recovered. The "j," "r," and "c" following the calibrated calendar years (B.C.) refer to "juniper," "rabbit brush," and "chenopod" identifications of charcoal. Descriptions of L30 and related sections are in the Appendix.

FIGURE 11—L30 stratigraphic section measured in September 2005. Pale-green surveyor tape marks detrital charcoal. Blue tape marks depth in meters. The Appendix gives details of measured sections.

As presented above, the volume of sand in the modern dunes is approximately 104,000 m^3. Because these dunes have changed over the past 75 yrs, the volume of the dunes may vary around some value of dynamic equilibrium, with sand being added from downwind and some sand moving up the canyon border away from the dune accumulation. To fill in the present channels (Chaco and Escavada Washes at their confluence) to restore a hypothetical slope to the level of 1,822 m on which to build dunes across the mouth of the canyon, approximately 129,000 m^3 of sediment would be necessary. Building dunes to a comparable height (1,825 m) and width as the current dunes to the north would require another 105,500 m^3. Given the other geomorphic constraints in delivery of eolian sand to the southern half of the canyon mouth, these large additional amounts of sand seem unlikely.

Topographic relationships from sand dunes at the mouth of Chaco Canyon to localities 30 and 35

Based on the 1-m DEM, several topographic profiles were drawn across lower Chaco Canyon. A longitudinal profile from Escavada Wash to Chaco Wash in the vicinity of L30 (profile B–B' in Fig. 6B) shows that the tops of the present dunes near Escavada Wash along the line of this profile and the lower part of the alluvial arroyo-wall exposure at locality L30 are at about the same elevation (~1,828 m for this profile). The contact between the base of the modern dunes and alluvium (elevation ~1,824 m) is below exposures at L30; the lowest exposures there are ~1,827 m. Transverse profiles near the confluence across the dunes are even lower with dune tops at 1,824–1,826 m and the alluvial flat immediately upstream from dunes at 1,823 m. Therefore if flat-lying lacustrine or low-angle-foreset deltaic deposits accumulated upstream from a dune dam near the confluence, they would not be seen at L30. Force et al. (2002, figure 1.7) show laminated silts and clays and ripple-cross-laminated silt at locality 35 and interpret them as playa-lake deposits, but this locality is about 420 m upstream from L30 and is perhaps in a later unit (E. Force, written comm. 2011; Fig. 2). The illustrated horizontal, thinly bedded and laminated silts and clays, overlain by ripple-cross-laminated silt and silty clay are similar to oxbow fill and/or fill behind a sand plug at the mouth of a tributary illustrated by Love (1980). Very similar sedimentary structures are found many kilometers upstream in the walls of Chaco Arroyo and cannot be part of the proposed playa-lake sequence (Love 1980, location 7, figure 62).

Hydrologic considerations of a hypothetical reservoir

As previously described, elevations of the crests of the present dunes increase to the northeast from 1,822 m to nearly 1,835 m from the windward end of the dunes to their highest accumulations near the sandstone bedrock to the northeast (Fig. 6). The dune crest near the lower end of the horseshoe bend of Chaco Arroyo is only 1,824 m and the adjacent alluvium is approximately 1,822 m. On the profile of the small alluvial fan and drainage east of the edge of the dunes (Fig. 6A, red profile), the 1,824 m elevation is reached about 150 m north of the same bend. Similarly, the profile southeastward along the floor of Chaco Canyon reaches the elevation of 1,824 m about 285 m upstream from the eastern edge of the dunes (Fig. 4B). If the lowest elevation of alluvium (1,822 m) extended up canyon 278 m (as it now does) and 285 m of the dunes held backwater across the canyon to the elevation of 1,824 m, that elevation contour shows the possible pool would be approximately 40,000 m^2. The volume of the pool behind such a dam calculated from the present DEM is approximately 67,000 m^3. If the height of the dunes is increased to 1,825 m and the lowest base is 1,822 m, the hypothetical dam would be 3 m high and the maximum pool would be 53,500 m^2. The pool volume would be approximately 195,500 m^3.

As previously given, the annual discharge of Chaco Wash is 3.85 million m^3/yr and maximum recorded discharge is 141 m^3/sec. The pool behind a 2-m dam with a crest at 1,824 m would fill in about 8 minutes if the maximum discharge lasted that long, after which the dam would breach during such a flood. If the dam were 3 m high (from 1,822 to 1,825 m elevation) and the flood pool about 195,500 m^3, the maximum discharge would take about 23 minutes to fill the pool, and an average daily discharge of 17.6 m^3/sec (given by the USGS during the day of the 54.4 m^3/sec peak discharge) would fill the pool and breach the dam in about 3 hours. It should be noted that the 17.6 m^3/sec daily mean flow followed daily flows on 17 previous days and was followed by another week of daily flows. If a flood producing one-fifth of the average annual discharge reached the flood pool and did not infiltrate the underlying sediments, the dam would eventually be breached.

The biggest problem with the notion of dune dams is that overtopping in one small area is all that's needed for water to begin cutting through the dam and soon breach it completely. Once such a dam has been breached, the stream is more apt to maintain the breach than eolian accumulation of sand is able to fill the gap. Also, rather than a filled pond overtopping the dune crests, the loose, permeable sand within dunes can be saturated with water and may liquefy and flow downslope, causing rapid dam failure.

The existence, size, and shape of mainstem channels flowing down Chaco Canyon at various times in the past are not well established. The "Bonito channel," known to exist during Pueblo II time, still has not yielded well-documented ages for its initial incision or complete filling, although multiple levels of potsherds and other cultural debris are well known within parts of the large, broad, backfilled paleochannel (Bryan 1954; Love 1980; Force et al. 2002; Hall 2010). Widespread lateral and longitudinal deposits of gray silt and clay from the headwaters suggest that floods have also spread out on the floor of Chaco Canyon. It is possible to visualize situations where flow was not concentrated in stream

FIGURE 12—Charcoal fragment in unit N. Note light-yellowish-brown color of the fine sand containing this charcoal compared to the underlying gray silty clay and overlying gray rubbly clay. White concentrations are carbonate and sulfate.

channels, and runoff was delivered to the mouth of Chaco Canyon via overland flow (Love 1980, 1983). The dynamics of such flow have not been modeled in detail, and whether such flow events could have been much smaller (in discharge or in channel dimensions) or just of longer duration has not been determined. It is conceivable that no flows reached the lower end of Chaco Canyon at times during dry episodes during the early-middle Holocene (cf. Menking and Anderson 2003; Cook et al. 2007), but the geometry and chronology of Holocene channels and canyon-wide-flow episodes in Chaco Canyon has yet to be documented and accepted. If water from upstream did not reach the lower part of the canyon, the existence of ephemeral ponds there would also be in doubt. The documented large volume and frequency of modern discharges suggest flows must have traversed Chaco Canyon and reached the Chaco River farther west on a regular basis during late Holocene time.

The role of shallow ground water in stabilizing both the alluvial and eolian sediments remains to be determined. The lack of data concerning the origins and flow directions of the ground water makes any discussion speculative.

Lack of evidence of thick eolian sand covering a sandstone bench at locality 31

Force et al. (2002, figure 1.5) present a photograph of an exposure of sandstone on the south side of Chaco Wash where the wash impinges on bedrock downstream from the horseshoe bend (their locality 31; Fig. 2). They suggest that this exposure was once buried by eolian sand. Several problems arise from this interpretation. First, the photo does not document any unequivocal evidence of sand having buried the outcrop. In the photo, it appears that compacted, poorly sorted colluvium with some evaporite-mineral cementation at the contact has been stripped from the steepest part of the exposed sandstone. Second, similar evaporite-mineral coatings at a similar elevation drape down the sandstone ledge at the confluence of Chaco and Escavada Washes (Fig. 3B) and appear to be deposited by seepage of shallow ground water coming from the bedrock. Third, the elevation (from the 1-m DEM) of the sloping sandstone exposure is ~1,825 m, about 1 m above the alluvial floor of Chaco Canyon at the horseshoe bend. These elevations require that accumulation of sand would have to have been much higher than the sand presently seen west of the horseshoe bend. We think that the sandstone exposure at locality 31 is more likely related to very recent stripping of colluvium and is not evidence of a recently removed sand dune. The present course of Chaco Wash at the base of the exposure has led to destabilization of the colluvium causing it to erode and expose the bedrock with discontinuous evaporite-mineral coatings.

Dunes versus small channels in the surrounding area

As shown in Figure 1, small drainages near Chaco Canyon cut across dunes, particularly across parabolic arms. In some places, it appears that the parabolic arms continue to be active on both sides of the drainage, so that streams do not preclude dunes and dunes do not preclude streams (Fig. 7). Clearly elsewhere in the area some side-valley drainages are blocked by sand dunes, particularly by their parabolic arms. Some historic examples are seen on the 1935 aerial photographs southwestward along the Chaco River. Others can be seen north of Chaco Canyon along side valleys of Escavada Wash. It should be pointed out that drainages "blocked" by sand dunes may not yield enough water to pond—the water may soak into or through the dune sand and not leave any playa-like deposits in the drainage. Discharges from the small tributary drainages (a few km^2 of drainage area at most) must, on average, be orders of magnitude less than Chaco Wash, and the dunes must be active to heal breaches. The problems with accumulating water behind dune dams are (1) dunes are loose sand, (2) they are permeable, (3) the substrate may be sandy as well, (4) the eolian sand supply must be larger and more dynamic than the ability of the stream to remove or modify the dune accumulation, and (5) any breach by water effectively cuts a channel through the dune. If a stream transports silt and clay, the permeability of the substrate is reduced and a pool may last longer, but siltation behind a dam reduces the life of the pool and guarantees that the water will overtop the dune

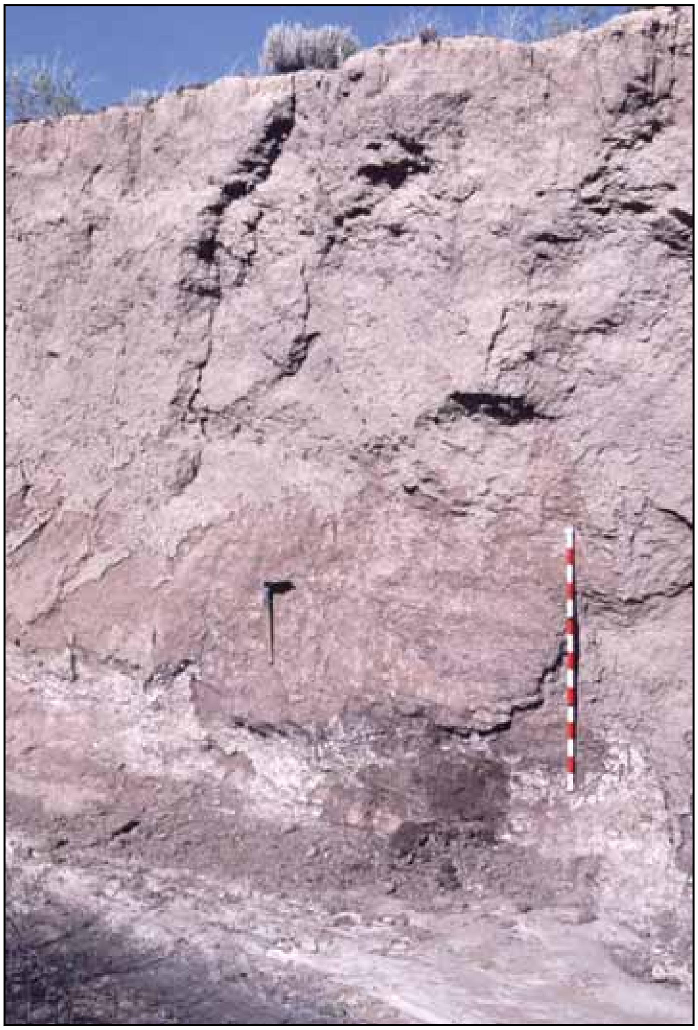

FIGURE 13—Exposure at 18 m south of L30 showing paleochannel cut-and-fill to 4.8 m below the surface with crossbedded lignite clasts and crossbedded sand above. Shovel points to base of slabs of sandstone in the channel fill to right. Note that the lowest exposures are coated with white evaporite mineral efflorescence (sulfates) on surface of moist sand within arroyo wall. Red and white bands on Jacob staff are 10-cm intervals.

in a short time. Eolian sand can also cross dry stream channels as saltating grains or as small ripples or dunes, so evidence of channels crossing dunes may not reflect past dune dams—only that both streams and dunes are dynamic and ephemeral. Comparing 1935 aerial photographs with later photographs shows that where stream channels have shifted, new accumulations of eolian sand have developed.

Age and crosscutting at locality 30

If the detrital charcoal ages of units N and E are close to their true ages, the upper 2.5 m of section at L30 are less than 2,700 yrs old. This thickness of accumulation is similar to the generalized 1 m per 1,000 yrs estimated by Love (1980) for vertical accumulation on the floor of Chaco Canyon away from large paleochannels. As described above, unit E was traced laterally into the upper part of a large buried channel (Fig. 10). Three angular sandstone planar slabs are aligned down the side of the channel, but no other large rocks were seen in present exposures within the channel. The slabs are not imbricated. We suggest that the planar slabs were deliberately placed within the channel by Early Basketmaker occupants of Chaco Canyon. No pottery was found, suggesting that this paleochannel is older than the Bonito paleochannel, which is recognized by abundant potsherds (Jackson 1878; Bryan 1954; Hall 1977, 2010; Force et al. 2002).

Radiocarbon-dated charcoal at L30 consists of burned juniper, rabbit brush, and chenopods. Juniper is a wide-spread but sparse tree, and long-lived. Charcoal from burned juniper could have come from the nearby canyon walls, or it could have washed downstream from anywhere in the headwaters. Smaller vegetation such as rabbit brush and chenopods now grows in locally derived sand. Such plants are short-lived, and charcoal from them is much less likely to withstand long episodes of transport. Charcoal from these plants likely reflects sediment ages more closely than charcoal from junipers contained in headwater-derived silts and clays. Thus the 138 B.C. age of rabbit-brush charcoal in unit E1 is probably closer to the true age of deposition than the older age (327 B.C.) of juniper charcoal. Similarly, the 834 B.C. age from chenopod charcoal from N4c is likely closer to the true age of unit N than the juniper charcoal (1388–1394 B.C.) from N3j in the same thin local unit (Table 1). Despite the differences in ages derived from long-lived trees versus small, locally derived plants, it seems clear that much of the depositional sequence at L30 predates Chacoan Pueblo II occupation by several hundreds of years. These results cast serious doubt on the suggestion that the sequence was deposited in a Pueblo II-age lake.

Carbon sample I-7246 of Hall (1977; also 1 of Hall 2010) was obtained from an in situ burn (hearth?) in clayey silt about 50–55 cm below the surface in a small gully a few meters north of the horseshoe bend of Chaco Arroyo and yielded a radiocarbon age of 1,010 ± 85 yr. This age further suggests that only a half a meter of fine-grained sediments has accumulated and/or has been preserved upstream from the dunes in the past ~1,000 yrs.

Facies at locality 30

Although units are fine-grained sand, silt, and clay derived from local and upstream sources, no unequivocal evidence of lacustrine sediments was observed in this study. The sediments are similar to modern arroyo facies described by Love (1980). In fact, none of the laminated units of silt and clay of L30 approached the bedding style and extent of modern laminated oxbow deposits; most were more like overbank deposits from levee-topping floods. The unidentified snails in unit E are in crossbedded sand and have been reworked from elsewhere. Hall (1980) described both aquatic and land snails from alluvium in Chaco Canyon. Small gypsum concentrations and crystals were noted below about 107 cm depth in both sand and finer units (Appendix). Evaporite mineral efflorescence on the lower, damp arroyo walls and on previously troweled surfaces near the base of the section shows that such minerals can grow rapidly during evaporation of interstitial water high in sulfate. These evaporite minerals do not indicate lacustrine conditions.

Although we do not see lacustrine deposits in lower Chaco Canyon, a dam and lacustrine sediments in a canyon environment with a high water table are described by Pederson (2000). In Lake Canyon, Utah, Holocene deltaic, subaerial littoral, subaqueous littoral, proximal pelagic, and distal pelagic facies progress down-canyon. Fossil aquatic organisms such as gastropods and diatoms indicated perennial lake facies. The damming mechanism in Lake Canyon was interepreted as a dune dam by Graf (1989), but Pederson (2000) determined that aggrading sandy alluvium from tributary canyons, despite their permeable sandy make-up, were responsible for damming the lakes. The high water table upstream fed the episodically perennial lakes. A large flood in 1915 caused the historic lake to breach the alluvial dam, causing headcutting through both the dam and the lake deposits. A progression of lake facies in maars of the Hopi Buttes area of Arizona was described by White (1990, 1992). The deposits include alluvial, deltaic, and banded lacustrine units. The lacustrine units included fossils of aquatic organisms. These examples show that exposures of suspected lake deposits should be documented over longitudinal and lateral distances and not at a few selected locations. Remains of aquatic organisms would help establish conditions of perennial water.

Conclusions

The geomorphology of stream channels, alluvial fans, and eolian dunes, and their vegetative cover at the lower end of Chaco Canyon show that these systems can change rapidly over a few decades. The present dunes at the lower end of Chaco Canyon vary in height but are not close to functioning as a dam for the major drainage of Chaco Wash. The volume of accumulated sand would have to be more than twice as much for a dam to reach the height of 1,825 m. Unless the dunes were much larger and more continuous in the past, it is unlikely that they ever acted as a dam. In the future, the modern sand dunes should be referred to as sand dunes and not as a "dune dam."

Modern dunes cannot block Chaco Wash for two reasons, first, a 6- to 11-m high ledge (bedrock and gravel terrace capped by parabolic dunes) downstream from the confluence of Chaco and Escavada Washes blocks southwesterly winds, greatly reducing eolian sand deposition in the channel, and concentrates stream flow, enabling removal of whatever eolian sand may accumulate. Second, northeast of the cliff and along Chaco Wash there is practically no fetch and probably only a small eolian capacity to transport sand via saltation. Therefore, no mechanism would allow quick and large accumulations of eolian sand in this reach of Chaco Wash. Modern dunes gradually increase in height and in canyonward extent downwind from the junction of the two streams. As seen by the low channel-marginal bars, which cross the lowest areas of dunes at the mouth of Chaco Wash and along Escavada Wash, the streams are able to spread out and rework sand dunes and sand sheets when flows are high. The eastern edges of the largely stabilized parabolic dunes appear to be controlled by possible vortices downwind from the high cliffs on the southwest side of the canyon. Upwind from the streams' confluence, most modern dunes do not pile up against the high northeast-trending cliff, apparently because airflow has vortices parallel to the cliff—not up against it.

The volume of modern water discharge and consequent sediment transport by Chaco Wash is orders of magnitude larger than the estimated volume of a flood pool behind a hypothetical dune dam. Assuming that a dune dam as high as 3 m above the valley floor could be created, breaching it at its weakest point would proceed catastrophically with the magnitudes of modern floods, or with longer flows ponding to equal one-fifth of the historic annual discharge of Chaco Wash.

Stratigraphy and alluvial facies at L30 do not support the presence of lake deposits here. Most of the alluvial section is higher (1827–1830.5 m) than the elevation of about half of the modern crests of dunes. Much of the lower part of the exposed section consists of sand and upward-fining sequences of alluvial silt and clay similar to deposits in modern back basins behind levees and on overbank floodplains along Chaco Arroyo. Radiocarbon ages of detrital charcoal of local plant species at two levels within the section (138 B.C. at 0.84 m and 834 B.C. at 2.48 m below surface) and the lack of potsherds suggest that much of the section predates Pueblo II time. Laterally, a large (>5 m deep) channel without pottery cuts the lower 3 m of section and aggrades to within 1 m of the surface. The younger radiocarbon age is within this unit. A separate radiocarbon age on charcoal burned in situ in fine-grained alluvium obtained by Hall (1977) a few meters upstream from the sand dunes shows that only 55 cm of sediment accumulation has occurred there in the past 1,000 yrs.

Our descriptive details of the modern geomorphology and dynamic nature of the confluence of Chaco and Escavada Washes, and the sand dunes near the mouth of Chaco Canyon suggest that the dunes could not have formed a resistant dam for the discharges of Chaco Wash. Based on the observed geomorphology and stratigraphy, including that presented by Force et al. (2002), we see no evidence, actual or theoretical, of lacustrine depositional environments in lower Chaco Canyon.

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Appendix

Description of locality 30 stratigraphy (October 29, 2010). Colors are on dry samples unless otherwise noted. Samples designated by bed letters "E1," etc., obtained by M. L. Gillam for charcoal content; these samples are archived at Chaco Culture National Historical Park; sediment characterization samples designated by "DWL 3," etc., obtained by D. W. Love later; these samples are archived at New Mexico Bureau of Geology and Mineral Resources.

Depth (cm)	Description
0–47	Top of section at surface above arroyo wall. Loose fine sand (most 125–177 μ), 10Y 6/3 [DWL 2].
47–50	Low-angle cross-laminated fine sand (most 177–250 μ) 10YR 6/3 [DWL 3].
50–63	Fine sand similar to above.
63–77	Distinctive, relatively thick structureless silty clay with uncommon 1–2 mm soft carbonate nodules, 10YR 5/3 (m) to 10YR 6/3 (d) [DWL 4]; unit to east is buried by 56 cm of sandy alluvium; unit to south is shallower, from 10 to 50 cm below the surface.
80–84	Ripple-cross-laminated silt and very fine sand with detrital charcoal; 10YR 6/2 to 6/3; bed E of MLG: Sample E1—two chunks of charcoal about 6 cm apart vertically. Sample E2—many small charcoal fragments, combined.
91–95	Lower part of bed E, as above [DWL 5]. Sample E3—many small charcoal fragments, combined. Note: Bed contains at least two species of fossil snails; examples are in either Sample E2 or E3.
107	Structureless silty gray clay with gypsum (?) and calcite concentrations to 2 mm; 10YR 6/2 [DWL 6].
144	Very finely laminated, ripple-laminated, and structureless silty gray clay; 10YR 6/2 to 7.2 [DWL 7].
168–170	Structureless, cracked, clayey and silty very fine sand; gypsum nodules to 2 mm; slight fizz indicating calcium carbonate; 10YR 6/2 [DWL 8].
190–195	Consolidated fine sand; calcium carbonate in root casts, gypsum nodules to 2 mm; 125–177 μ sand; 10YR 6/3 to 5/3; unit may rise to east and descend to south [DWL 9].
226	Very finely laminated clay and silty clay; 10YR 6/2 [DWL 10].
244–248	Consolidated very fine sand and silt (not much clay); angular, hard calcium carbonate nodules less than 1 mm in diameter; unit 3–4 cm thick, depth varies slightly but can be traced laterally to east for at least 30 m. 10YR 6/4 to 6/5; bed N; note that some samples labeled "N" are from slightly above or below this bed; [DWL 11]. Sample N1—single charcoal fragment from middle of bed N (Fig. 12). Sample N2—many small charcoal fragments from bed N, combined. Sample N3—single charcoal fragment from about 1 cm above top of bed N. Sample N4—single charcoal fragment from basal contact of bed (photo of charcoal fragment can be found online: < http://geoinfo.nmt.edu/repository/index.cfm?rid=20110003 >). Sample N5—many small charcoal fragments from bed about 1 cm thick, directly below bed N (see photo in repository). Sample N6—about 1 cm below bed N. Sample N7—three small charcoal fragments, close together, in middle of bed N.
248–268	Rubbly-weathering gray clay and gray sandy clay; local clay-flake rip-up clasts and transported charcoal at top, overlying gray sand and clay.
268–298	Bed P; at the vertical scale line this is a composite unit consisting of three upward-fining beds, each composed of about 90% sand and 10% silty clay. Where sampled about 15 m farther upstream, the clayey layers are much thinner or absent, and this is a dominantly sandy interval. Sample P1—several small charcoal fragments, combined in gray silty clay 18 m upstream.
300	Consolidated clay (~30%) with silt and very fine sand; gypsum nodules to 2 mm; slight-moderate fizz from $CaCO_3$; 10YR 6/2.
306	Sample O1 charcoal in unit P.
310	Consolidated very fine sand (125 μ; sparse clay); gypsum nodules and slight fizz; 10YR 6/4 [DWL 13].
400–490	Thick sandy interval excavated at base of exposure; unit T of MLG; highly likely to be modern sandy bank with arroyo wall fall at top; at 400, fine sand (125–177 μ; sparse clay) 10YR 6/4 [DWL 14].
422–432	Sample T2—several small charcoal fragments combined from this interval.
450–463	Sample T1—several small charcoal fragments combined from this interval.
465	Ripple-cross-laminated fine sand (125–177 μ) with thin clay drape coated with white efflorescence; roots; fizzes mildly 10YR 6/4 to 6/6.
480	Compact fine sand (125–177 μ); barely fizzes; 10YR 6/4.

Description of locality 30 stratigraphy in paleochannel 43 m south of original locality. Colors are dry unless otherwise noted. “e” designates estimate of depth. Samples designated by “DWL 3,” etc., obtained by D. W. Love; samples archived at New Mexico Bureau of Geology and Mineral Resources.

Depth (cm)	Description
0–15e	Top of section at surface above arroyo wall. Loose fine sand (most 125–177 μ), 10Y 6/3; similar to [DWL 2].
15–50e	Distinctive, relatively thick structureless silty clay with uncommon 1–2 mm soft carbonate nodules, 10YR 6/3; equivalent to [DWL 4].
50e–196	Inaccessible fine sand.
196–200	Crossbedded medium sand (177–250 μ; sparse clay); slight fizz; 10YR 6/3-6/4 [DWL 24]; may be traced to similar sand to north.
200–305	Low-angle crossbedded fine sand (125–177 μ); 10YR 6/4 [DWL 23].
380	Crossbedded fine sand with angular granules of black organic matter (lignite and coal) [DWL 22].
405	Moderate-angle crossbeds 25 cm thick of angular coarse granules of black organic matter (lignite and coal) in scoured local channel within larger channel.
422	Crossbedded medium sand and abundant sand-sized clay flakes (177–250 μ); slow fizz; 10YR 6/3 to 6/4 and 10YR 5/2 [DWL 21].
450	Base of exposure at modern arroyo floor.

Description of locality 30 stratigraphy 18 m east of original locality 30.

Depth (cm)	Description
0–56	Top of section at surface above arroyo wall. Loose fine sand similar to [DWL 2].
56–75	Distinctive, relatively thick structureless silty clay with uncommon 1–2 mm soft carbonate nodules equivalent to [DWL 4].
75–120	Light-brown fine sand and clay.
120–210	Nearly structureless hard, compacted, churned sand, silt, and clay with only a hint of horizontal bedding; basal contact is sharp with underlying unit.
210–275	Multiple cycles of consolidated light-brown sand and gray clay with darker laminated clay and lighter silty clay 4–8 cm thick near base.
275–279	N layer of pale-brown, very fine sand that can be traced laterally to same N bed of 244–248 cm depth at locality 30.
279–292	Low-angle, very thinly laminated silt and gray clay.
292–299	Dark-medium gray, structureless, blocky clay (vertisol).
299–300	Unit P1 of gray silty clay with detrital charcoal.
300–324	Multiple cycles of silt-clay drapes.
324–328	Minor channel scour filled with fine sand, silt, and clay.
324–350	Multiple silt-clay drapes, fining upward; probably overbank.
350–390	Pale-brown sand, structureless with gray-stained root molds.
390	Base of section is top of modern stream bank.