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NEW INTERPRETATIONS OF ALLUVIAL AND PALEO-VEGETATION RECORDS FROM CHACO CANYON, NEW MEXICO

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Abstract—The alluvial stratigraphy, vegetation history, and paleoecology of Chaco Canyon are re-evaluated. The alluvial units are Fajada (middle-late Pleistocene), Pre-Gallo (undated), Gallo (6.7 to 2.8 ka), Chaco (2.1 to 1.0 ka), and Bonito (0.8 to 0.1 ka). A new alluvial unit, Pre-Gallo, is a small erosional remnant that may be late Pleistocene or early Holocene in age. The hot-dry climate of the mid-Holocene and accompanying low stream flow resulted in the accumulation of local sand in the canyon, forming the Gallo unit. A shift to less arid climate by 2.5 ka and increased stream flow flushed out much of the Gallo sand. Greater stream flow throughout the drainage basin resulted in clay overbank deposition across the canyon floor, forming the Chaco unit. The canyon floor provided a habitat for a molluscan fauna consisting of two freshwater snails and six terrestrial snails. The end of the accumulation of the Chaco unit occurred ca. 1.0 ka with a shift in climate to dry conditions and the downcutting of the Bonito channel. The Bonito channel was filling by ca. 0.8 ka, based on buried potsherds. The vegetation of the Chaco area has been a desert-shrub grassland since the end of the Pleistocene. Within that framework, a pinyon-juniper woodland thrived on sandstone substrates during the late Pleistocene-early Holocene. However, mid-Holocene aridity led to the demise of the woodlands, leaving behind a few individuals of pinyon pine and juniper on sandstone escarpments. Reduced rainfall, high evaporation, and increased soil alkalinity promoted the expansion of chenopod shrubs during the mid-Holocene. Moister conditions by 2.5 ka resulted in a reduction in chenopod shrubs and expansion of pinyon pine and juniper in isolated stands on local escarpments and in higher areas of sandy soils within the desert shrub grassland, similar to present-day vegetation patterns. Slight shifts in regional climate after ca. 1.0 ka to dry then wet conditions, while significant to fluvial geomorphology, does not show up in the local vegetation record.

INTRODUCTION

Travelers are drawn to Chaco Canyon because of the legendary ruins, first described in 1849 (McNitt, 1964). From AD 850 to 1250, Chaco Canyon was a center of prehistoric Puebloan culture in the American Southwest. Chaco is famous for its multi-storied stone buildings, such as Pueblo Bonito, that were constructed in alignment with solar and lunar cycles. The major pueblos in the canyon are included in Chaco Culture National Historical Park; the park was designated a UNESCO World Heritage Site in 1987. The history of geological observations began in 1877 with William H. Jackson's visit to the canyon. The first systematic fieldwork on the geology of the valley fill was conducted in 1924 and 1925 by Kirk Bryan (1954) in conjunction with the National Geographic Society's Pueblo Bonito Expeditions. Subsequently, Hall (1977) and Love (1980) expanded upon Bryan's studies, refining the geologic picture of the alluvial fill in the canyon. In the following discussions, I present new information and interpretations, building on my 1972 and 1973 fieldwork at Chaco Canyon (Hall, 1977).

ALLUVIAL CHRONOLOGY

A firm chronology is essential to place geological events and associated strata into the continuum of earth's history. This is especially true for the late Quaternary, where geological and archaeological sequences coalesce. When the study of the alluvial geology at Chaco was initiated in 1972, virtually no information was available on the age of the canyon fill. The only direction at that time was the presence of various prehistoric sites, features, and artifacts buried in the alluvium, the age of which was tied in with the Basketmaker-Puebloan cultural sequence using pottery types dated by tree-ring studies (discussed by Bryan, 1954).

Radiocarbon dating

The 1972-73 study was in the era before accelerator mass spectrometry (AMS) dating, and a comparatively large amount of charcoal was needed to produce a reliable radiocarbon date. Eighteen charcoal samples were collected from the Gallo and Chaco units for conventional radiocarbon dating. The samples were from buried archaeological features or from natural burns with associated fire-reddened sediment. Reddened sediment from local brush fires can be common and has been documented in Holocene alluvium in the Rio Puerco drainage (French et al., 2009). Experimental data indicate that the firing temperature and chemistry of sediments that exhibit reddening are somewhat variable, although reddening appears to occur with temperatures exceeding 500°C (Canti and Linford, 2000). Isolated pieces of charcoal were observed in most alluvial exposures at Chaco but were not collected for dating because the isolated charcoal had been transported to the site of deposition and, potentially, could be too old for the age of the alluvium in which it occurs. Also, prior to AMS dating, large samples of isolated charcoal would have been required for conventional radiocarbon dating, and it was impractical and perhaps not possible to collect that much charcoal from a narrow stratigraphic zone. Charcoal from in-place natural burns or buried prehistoric features was not discovered in the Bonito unit although reworked charcoal is present throughout the Bonito channel fill. The radiocarbon dates reported by Hall (1977) provide at present the only isotopic ages for the Holocene alluvium at Chaco Canyon (Fig. 1, Table 1) except for a date

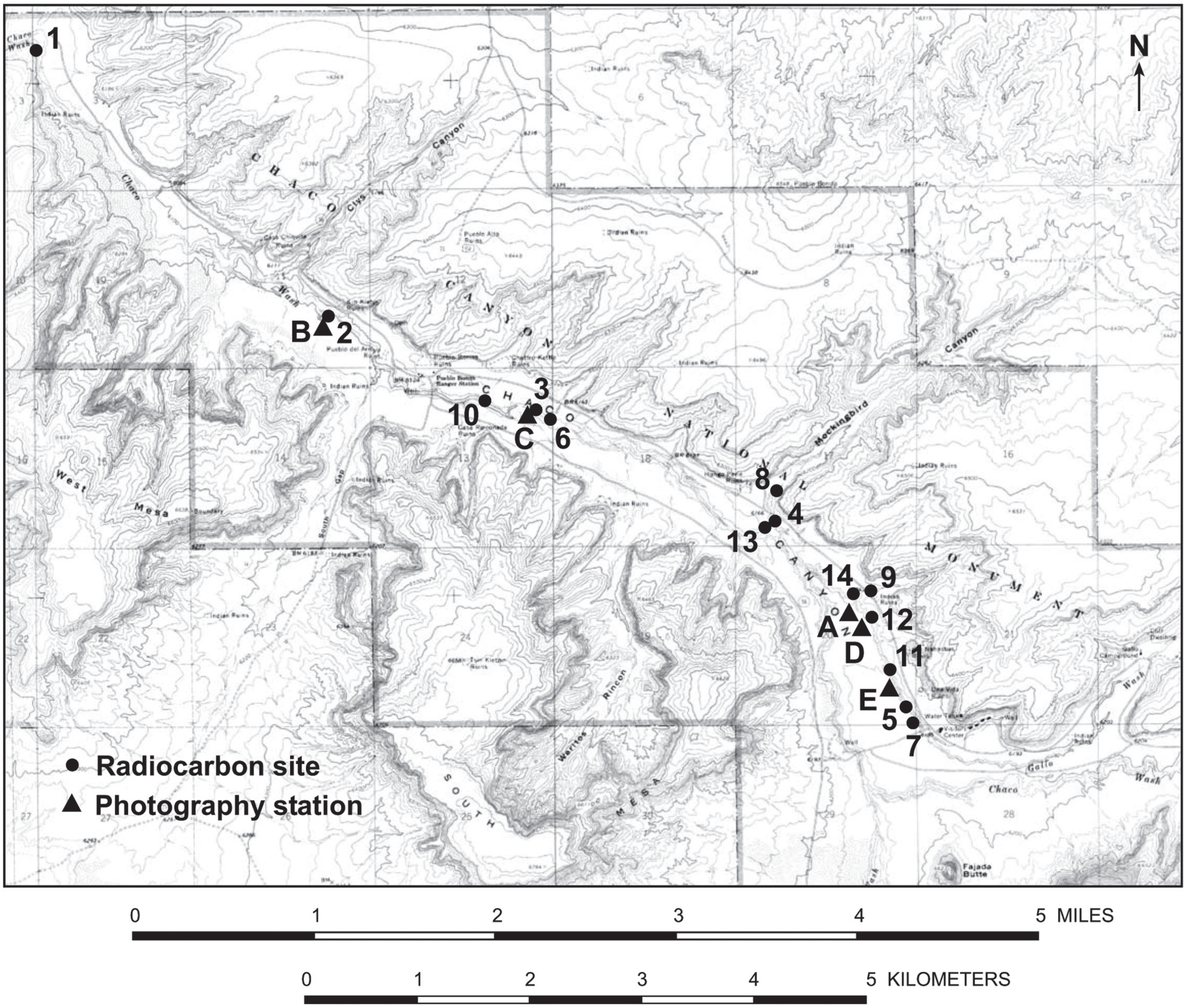

FIGURE 1. Topographic map of Chaco Canyon showing number locations of radiocarbon dating sites (numbers) (Table 1) and photography stations (letters); from Pueblo Bonito 7.5-minute quadrangle, 1966.

reported by Love (1980, p. 184-186) of 3700 ± 240 ^{14}C years BP on in-place charcoal at 6.1 m depth.

The radiocarbon ages were determined by Teledyne Isotopes. All of the charcoal samples were pretreated to remove carbonate and soluble humates, except three samples that were too small for alkali pretreatment. Prior to submitting the charcoal for radiocarbon dating, I inspected each charcoal particle, using a binocular microscope at 10X and 30X, for cellulose structure and the special reflection of light or luster characteristic of charred wood. Particles without these properties were discarded from the samples. Coal and carbonaceous shale from the Menefee Formation (Upper Cretaceous) are exposed along the escarpments in Chaco Canyon. It was anticipated that the time-consuming effort with the binocular microscope to eliminate particles that lack charred wood properties would avoid potential contamination of the radiocarbon samples by coal and carbonaceous particles.

ALLUVIAL STRATIGRAPHY

The stratigraphy of the alluvium at Chaco Canyon was investigated during the summers of 1972 and 1973. The entire Chaco Wash and its tributaries within the park boundary were walked and all segments of the arroyo walls were closely examined to identify the stratigraphy and to discover dateable materials. The alluvial geology and the several measured sections reported by Bryan (1954) were inspected, although many of the alluvial features and buried archaeology he described in 1924-25 were no longer visible in 1972-73. Indeed, some of the cutbank sections that were described by Hall in 1972-73 have since collapsed.

The alluvial units introduced by Hall (1977) are the Fajada,

Table 1. Radiocarbon dates from alluvium, Chaco Canyon, New Mexico.

Map Index No.*	Lab No.†	Material Dated	Measured Radiocarbon Age‡	Sample location
Chaco Unit				
1	I-7246	Charcoal	1010 ± 85	50-55 cm depth, small hearth, west end of canyon
2	I-7304	Charcoal	1010 ± 90	80-90 cm depth, buried site (29SJ672) (Fig. 8)
3	I-7247	Charcoal	1025 ± 85	150 cm depth, trash midden (29SJ903) with Red Mesa Black-on-white pottery, Chaco Wash IV pollen section (Fig. 4)
4	I-7249	Charcoal	1185 ± 85	215 cm depth, buried trash midden, jct. Mockingbird Canyon, Coolidge Corrugated pottery
5	I-7090	Charcoal	1390 ± 90	330 cm depth, small buried hearth with maize, Gallo Wash
3	I-7301	Charcoal	1655 ± 85	205 cm depth, buried hearth, Chaco Wash IV pollen section (Fig. 4)
6	I-7092	Charcoal	1935 ± 100	220 cm depth, buried shallow depression 1-2 m wide
7	I-7248	Charcoal	2110 ± 85	310 cm depth, buried bell-shaped pit, Gallo Wash (29SJ1987)
3	I-7303	Charcoal	2170 ± 110	173-183 cm depth, buried trash midden with Lino Gray pottery, stratigraphically above dated buried hearth (I-7301); radiocarbon age too early; Chaco Wash IV pollen section (Fig. 4)
Gallo Unit				
8	I-7245	Charcoal	2805 ± 90	410 cm depth, mixed charcoal and reddened sand matrix, near mouth of Mockingbird Canyon
9	I-7171§	Charcoal	2900 ± 330	390 cm depth, possible hearth with reddened sand matrix, north tributary to Gallo Wash
NA	I-7170	Charcoal	3005 ± 210	475 cm depth, 510 m upstream from east boundary fence, reddened sediment (Fig. 6)
10	I-7173§	Charcoal	4115 ± 500	450 cm depth, reddened sediment, possible hearth or natural burn, south of Chetro Ketl ruin
11	I-7302	Charcoal	5680 ± 120	490 cm depth, associated with reddened matrix of natural burn, Gallo Wash south of Una Vida ruin
12	I-7172§	Charcoal	5860 ± 700	620 cm depth, isolated charcoal not associated with baked sediment, Gallo Wash I pollen section (Fig. 3)
13	I-7091	Charcoal	6290 ± 115	670 cm depth, associated with reddened sediment of natural burn, near jct. with Mockingbird Canyon
14	I-7174	Charcoal	6725 ± 110	650 cm depth, associated with reddened sediment of natural burn, Gallo Wash

* Figure 1.
† Teledyne Isotopes, Westwood Laboratories, Westwood, NJ; radiocarbon analyses in 1973; charcoal collected in 1972 and 1973; reported in Hall, 1977, p. 1600-1601.
‡ Conventional radiocarbon date; not corrected for $\delta^{13}C$; Libby half-life of 5568 years; one-sigma value of these conventional ages is largely determined by sample size
§ These samples could not be pretreated to remove possible humic acids because of their small size; all other samples pretreated to remove carbonates and humic acids

Gallo, Chaco, Post-Bonito, and Historic. A new unit, provisionally called Pre-Gallo in this report, is described below. The units were defined on the presence of bounding erosional unconformities, compatible with the criteria for lithostratigraphic units at that time (American Commission on Stratigraphic Nomenclature, 1970) and, more recently, for allostratigraphic units (North American Commission on Stratigraphic Nomenclature, 2005). A summary chart of the alluvial stratigraphy reported by Bryan (1941, 1954), Hall (1977), and re-interpreted in this paper is presented in Figure 2. Sedimentary beds within each unit can be traced for short distances, but are eventually discontinuous. Even though the Gallo and Chaco units are distinct in the core of the study area, the units exhibit variability when traced upstream and downstream in the canyon and are difficult to identify solely on lithology. It should be noted that the alluvial fill in the canyon extends to 30 m depth (Love, 1983a); stratigraphic studies of the alluvium have been restricted to the upper 6-8 m of deposits that are exposed in arroyo walls of Chaco Wash and its tributaries. Previously unpublished textural data from the alluvium are given in Table 2.

Fajada unit, middle-late Pleistocene

The Fajada unit is a 5-meter thick pebble to boulder gravel composed of iron-stained, dark reddish brown sandstone clasts with minor components of shale, quartz, quartzite, chert, jasper, agate, and petrified wood. It is best exposed in a gravel quarry along Chaco Wash near the visitor center. The red, calcic Fajada paleosol occurs in eolian fine sand at the top of the gravel and has stage II carbonate morphology. Although not directly dated, the gravel may be middle Pleistocene in age based on geomorphic considerations and the presence of the paleosol at the top of the sequence (Love, 1983a). The Fajada gravel and associated paleosol are topics for future research.

Table 2. Sediment data from Chaco Canyon, New Mexico

SAND										DRY
v. c.	coarse	med.	fine	v. fine	SAND	SILT	CLAY	OC	$CaCO_3$	COLOR
Bonito unit										
Cross-bedded sand at Bryan's section 16*										
0	0.1	1.7	41.8	56.4	69	18	13	0.14	3.4	10YR 6/3
Chaco unit										
Laminar fill, shallow channel, light-colored bed										
0	0	0.5	27.4	72.1	19	33	48	0.26	6.9	10YR 5/2
Laminar fill, shallow channel, dark-colored bed										
0.1	0	1.2	41.3	57.4	8	25	67	0.23	8.5	10YR 4/2
Overbank alluvium										
0.7	4.8	14.0	37.3	43.2	8	20	72	0.26	8.2	10YR 5/2
Sand beneath overbank alluvium										
0	0.1	0.8	44.1	55.0	56	20	24	0.27	4.8	10YR 5/3
Gallo unit										
Overbank alluvium										
0.2	0	0.5	32.0	67.3	10	35	55	0.24	7.3	10YR 5/2
Sand, upper, massive										
0	0.1	2.2	35.7	62.0	75	16	9	0.09	6.7	10YR 5/4
Sand, lower, massive										
0	0	0.1	22.1	77.8	49	35	16	0.21	5.2	10YR 6/3

Note: Numbers are percentages; Wentworth scale; OC = organic carbon determined by Walkley-Black method; carbonate determined by Chittick method; dry color from Munsell® Soil-Color Charts (2009); analyses by Milwaukee Soil Laboratory, 6917 W. Oklahoma Ave., Milwaukee, WI 53219.
* Bryan, 1954, p. 26, and Hall, 1977, p. 1597.

Pre-Gallo unit, late Pleistocene-early Holocene (?)

The "pine pollen zone" was defined initially on comparatively high percentages of *Pinus* pollen that occur in a very pale brown

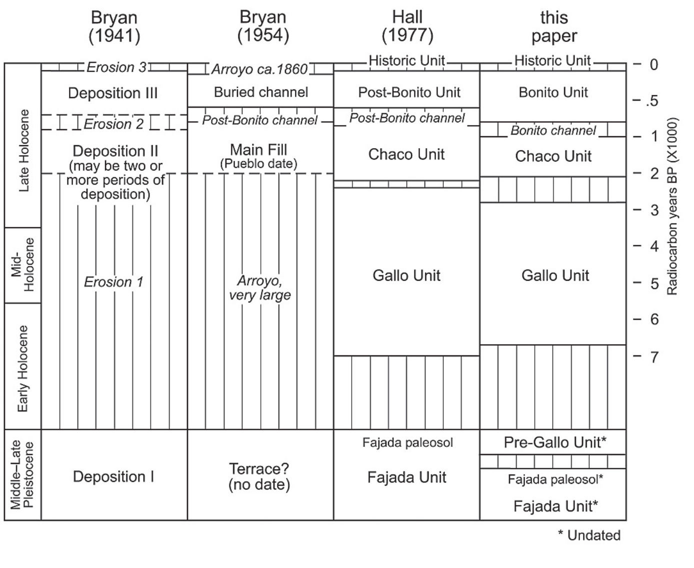

FIGURE 2. Correlation chart of alluvial fill at Chaco Canyon, New Mexico. The Southwestern alluvial sequences summarized by Bryan (1941) include Chaco Canyon.

(10YR 7/3), thin-bedded, silty fine sand that rests directly on the red Fajada paleosol (Hall, 1977, p. 1609, fig. 9, Gallo Wash II pollen section). The bed structures are 2-4 cm thick and are continuous across the exposure. The thin-bedded sand was found only at this one locality in the canyon where it is exposed with a thickness of about 1.3 meters and rests directly on the Fajada paleosol (this is the only exposure of the Fajada paleosol buried in the canyon fill). These sediments and pine zone were initially shown at the base of the Gallo unit and associated with the earliest radiocarbon dates from the Gallo (Hall, 1977, p. 1616). In a re-assessment, the thin-bedded sand is distinct from the massive sand of the Gallo unit, and the pollen content diverges strongly from all other alluvial records at Chaco Canyon. Based on the above, I re-interpret the small exposure as a separate unit, provisionally called Pre-Gallo. The outcrop is an isolated erosional remnant. It is overlain unconformably by massive sand of the Gallo unit. Based on the high percentages of *Pinus* pollen and stratigraphic position between the Fajada paleosol and the Gallo unit, it is likely late Pleistocene in age, although an early Holocene age cannot be ruled out. The pollen record indicates an abundance of pine trees in the region, both pinyon and ponderosa pine, compared to later in the Holocene. Further investigations of the Pre-Gallo unit will fill a gap in the alluvial record at Chaco.

Gallo unit, 6700 to 2800 years BP

The Gallo unit is best exposed along Gallo Wash between the Visitor Center and the junction of Gallo Wash with Chaco Wash. Its preserved thickness is 4.5 meters. It is composed of yellowish brown to brown (10YR 5/3-4), very fine-to-fine quartz sand. It is massive, well sorted, and the quartz grains are subangular. Some beds are silty. The yellowish brown sand that makes up the unit is derived from local Cretaceous sandstone. Beds in the unit can be traced up gradient along small tributaries to the canyon escarpment. The massive sand along Gallo Wash includes rare beds of hard, grayish brown silty clay that represent overbank deposits (Fig. 3). The base of the Gallo unit is not exposed except at the isolated outcrop of Pre-Gallo unit. Although Bryan (1954) reported measured sections from alluvium that was subsequently differentiated as the Gallo unit by Hall (1977), he regarded it as part of his main valley fill.

The chronology of the Gallo unit is based on eight radiocarbon dates on charcoal from in place, fire-reddened sediment, ca. 6700 to 2800 ^{14}C years BP. Two of the dated horizons may have been prehistoric hearths, but artifacts were not associated with the features and whether they are cultural is uncertain. Two alluvial sequences from the Rio Puerco drainage basin, Sandoval County, have radiocarbon ages on charcoal from natural burns that indicate a correlation with the Gallo unit period of deposition beginning ca. 6800 years BP (French et al., 2009).

Chaco unit, 2100 to 1000 years BP

The Chaco unit is the main alluvial fill exposed in Chaco Canyon. It is also the main valley-fill alluvium discussed extensively by Bryan (1954) (Fig. 4). It is pale brown to grayish brown (10YR 5/2-6/3) silty clay. Sand is a minor component of the alluvium except for the lower part of the unit that is characterized by

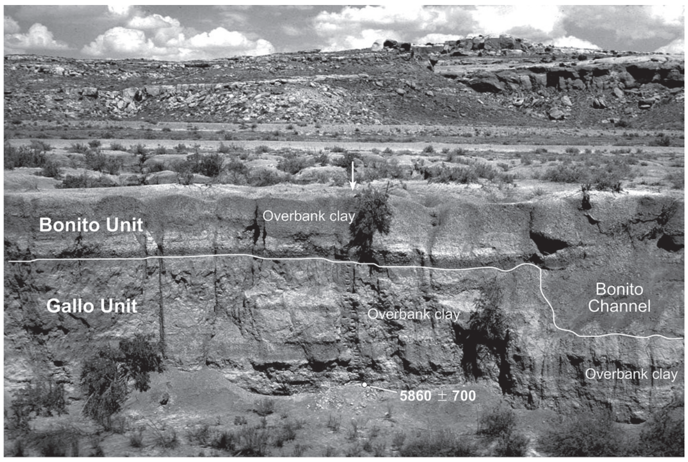

FIGURE 3. Gallo and Bonito units on north bank of Gallo Wash. Note inset Bonito channel on right that contains reworked potsherds. Gallo Wash I pollen section shown by arrow in center; 5860 ± 700-year age is from radiocarbon site 12, Table 1; measured section is 6.5 meters thick. Grayish brown, silty clay overbank alluvium occurs at 480–535 cm (labeled) and 365–375 cm (labeled) depth in the Gallo unit and in the upper 150 cm (labeled) of the Bonito unit. Site corresponds with photography station D (Fig. 1); photograph taken in 1972.

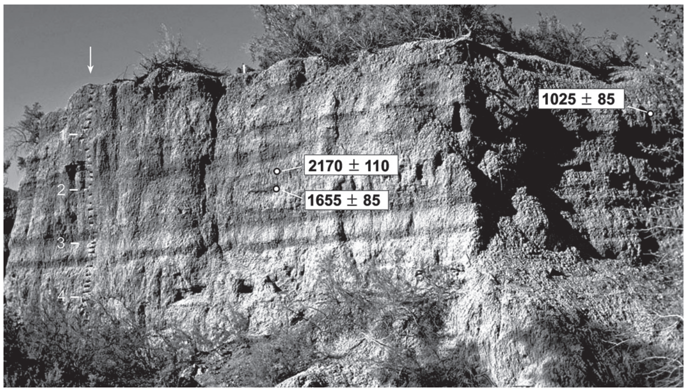

FIGURE 4. Radiocarbon-dated Chaco unit from mid-canyon; Chaco Wash IV pollen section with 1-meter increments, shown by arrow. The dark- and light-colored beds represent clay-silt from upstream and sandier beds of local origin, respectively. Site corresponds with photography station C, Fig. 1; photograph taken in 1972.

channel-fill deposits composed of very fine-to-fine-grained quartz sand. The upper part of the unit is a massive, grayish brown silty clay with low-relief, wide, shallow channel fills of dark and light colored beds of silty clay. The sedimentology of the various shallow channel forms and associated features are described in detail by Love (1980, 1983a, 1983b). Most of the Chaco unit is characterized by overbank deposits, the clay sediments derived from upstream sources in the Chaco drainage basin. Uncommon thin beds of yellowish brown, fine-grained sand, derived from local sandstone, are also present in the Chaco unit (Fig. 4)

The age of the Chaco unit is based on nine radiocarbon dates, all from charcoal samples collected from prehistoric hearths or archaeological features buried in the alluvium. The ages range from ca. 2100 to 1000 ^{14}C years BP. The Chaco unit is the main alluvium in the central axis of the canyon. It occupies a large paleovalley in the canyon fill left by the downcutting and erosion of the Gallo alluvium between 2800 and 2100 years BP (Fig. 5). Upstream, the Chaco unit directly overlies the Gallo unit (Fig. 6).

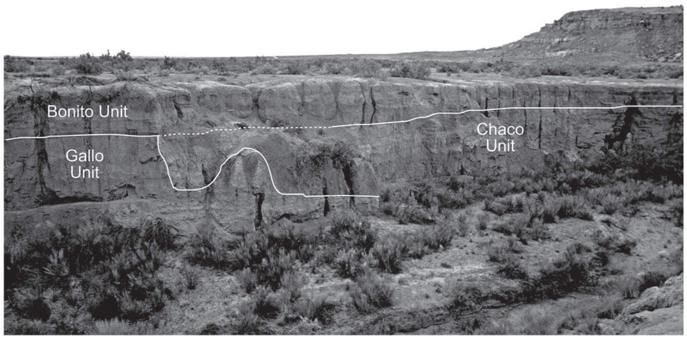

FIGURE 5. Rare exposure of cut-and-fill relationship of the Gallo and Chaco units, south bank of Gallo Wash. Four radiocarbon dating sites (9, 11, 12, 14) in Gallo alluvium are located within less than 0.8 km from this cut-and-fill exposure; three radiocarbon dating sites (4, 5, 7) in the Chaco alluvium are located 1.0 to 1.2 km from this exposure. The Gallo and Chaco units are overlain by Bonito unit. Site corresponds with photography station A, Fig. 1; photograph taken in 1972.

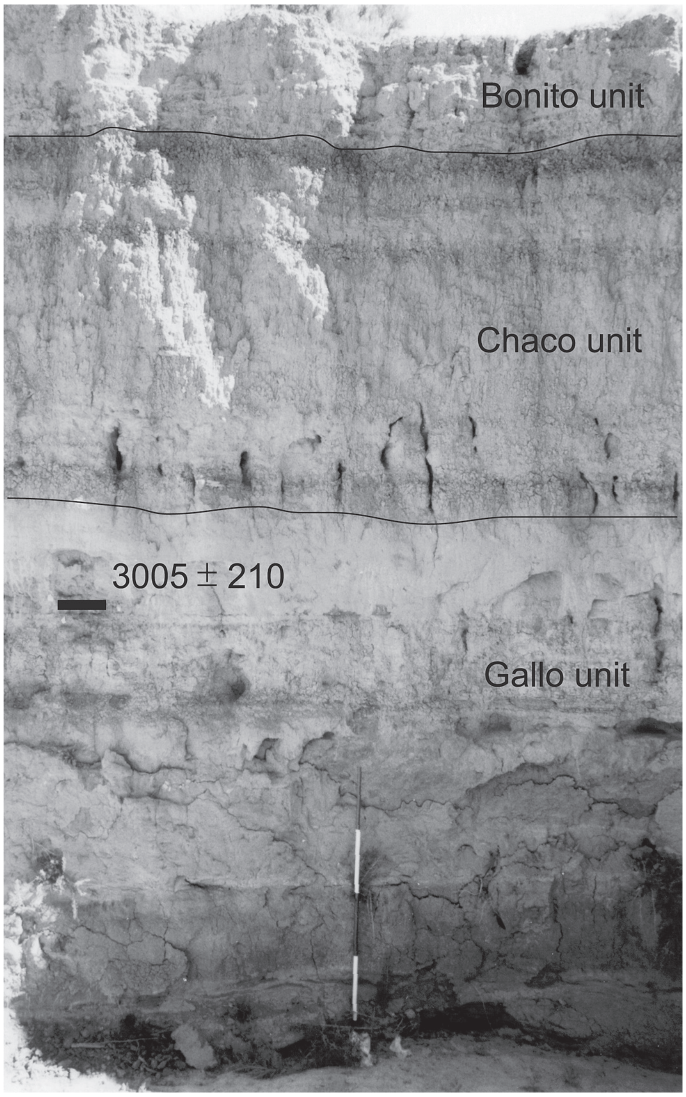

FIGURE 6. Stratigraphic relationship of Gallo, Chaco, and Bonito units; located 0.51 km upstream from eastern park boundary, north bank of Chaco Wash arroyo. A weak A horizon soil occurs at the top of the Chaco unit alluvium. Buried A horizon soils are uncommon in the valley fill; most dark-colored beds are thin alluvial deposits of silty clay. The 2-m scale at the base of the section is divided into 0.5-m increments; photograph taken in 1973.

A plot of radiocarbon age versus depth in the valley fill shows a clear separation of the Chaco and Gallo units (Fig. 7). Initially, I extended the age of the Chaco unit to 850 years BP in deference to discussions of buried Puebloan architecture by Senter (1937) and Bryan (1954). In retrospect, cultural activity invariably disrupts and confuses the natural stratigraphy. Accordingly, I am redefining the end of deposition of the Chaco unit at 1000 ^{14}C years BP based on the youngest radiocarbon ages from the upper part of the unit (Fig. 2; Table 1).

Snails in the Chaco unit

Shells of two freshwater and six terrestrial species of snails occur in the Chaco unit alluvium (Hall, 1980). The shells are

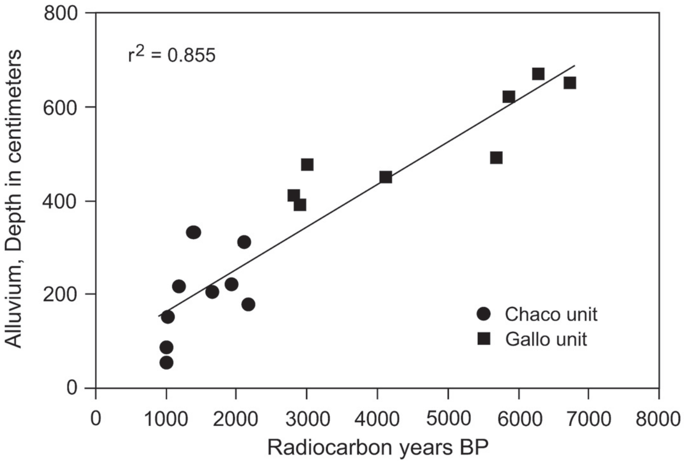

FIGURE 7. Age-depth relationship of 17 radiocarbon-dated horizons in the Gallo and Chaco units; data from Table 1.

sparsely scattered throughout exposures of the alluvium and are not concentrated in zones or shell beds. The more abundant aquatic form, *Stagnicola cockerelli*, can be found across the region in small pools, ephemeral-to-intermittent ponds, and ditches where, although in small numbers, it seems to persist from season to season. It has a strong tolerance for dry conditions (Leonard, 1959, p. 50; Bequaert and Miller, 1973, p. 196). The presence of *S. cockerelli* is compatible with the deposition of the Chaco unit in a seasonally-wet floodplain environment. Other species in the Chaco alluvium are *Gyraulus* sp., *Gastrocopta pellucida hordeacella*, *Hawaiia minuscula*, *Pupilla hebes*, *Pupoides hordaceus*, *Succinea* sp., and *Vallonia gracilicosta*. The terrestrial snail *H. minuscula* occurs commonly in late Holocene overbank alluvium elsewhere in New Mexico.

Bonito unit, ca. 1200 AD to 1880 AD

The Bonito unit fills a paleochannel and occurs as overbank, fine-textured alluvium overlying the Gallo and Chaco units across

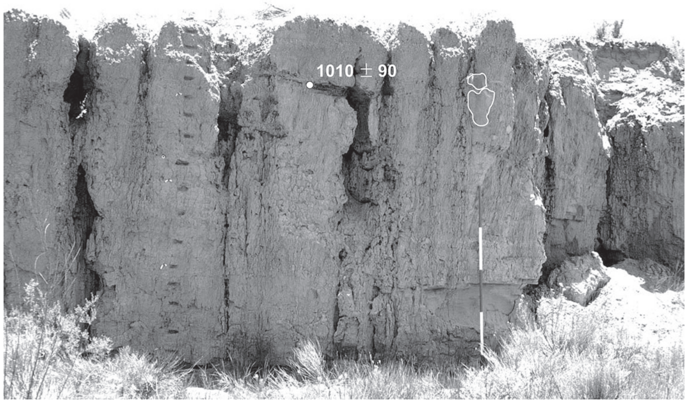

FIGURE 8. Chaco unit with Chaco II pollen section that can be seen as small notches in the alluvium. Vertical stone slabs are outlined above the 2-meter scale. The section of the arroyo wall with these stone slabs was photographed in 1924 by O. C. Havens and illustrated in Bryan (1954, pl. 3, right) but has since collapsed. Site corresponds with radiocarbon site 2 and photography station B, Fig. 1; photograph taken in 1972.

the canyon floor (Hall, 1977). The unit was initially named Post-Bonito for the sediment that fills Kirk Bryan's post-Bonito channel (Bryan, 1954, p. 32) (Fig. 2). The unit name is simplified to Bonito and Bryan's prehistoric post-Bonito channel is simplified to Bonito channel. The Bonito channel is technically a paleochannel because it is filled and buried by younger alluvium. The sediment is pale brown to grayish brown (10YR 6/3-5/2), very fine-to-fine grain quartz sand in the lower half and silty clay in the upper levels. The sand in the lower part of the channel fill can have cross-beds. The silty clay in the upper part is both massive and has thin discontinuous clay beds. The Bonito alluvium accumulated as low-energy overbank deposits on the canyon floor and is 2.1 m thick in the area of Gallo Wash (Fig. 3). Based on the small number of snail shells, the local floodplain environment may have been less moist than the conditions represented by the Chaco unit. Once the Bonito channel was largely filled, overbank deposition and aggradation on the canyon floor continued until it was terminated by the incision of the present-day channel during the late nineteenth century.

Ceramic age of the Bonito unit

The Bonito unit is not directly dated. However, Bryan noted the presence of late Pueblo Bonito pottery types in the basal sand and gravel of the channel, hence the origin of the term post-Bonito channel (Bryan, 1954, p. 34). During fieldwork in 1972-73, I collected a large number of potsherds from three exposures of the Bonito channel, including Bryan's channel localities 4 and 16; the potsherds were identified by Alden C. Hayes. Collectively, the ceramics are Basketmaker II through Pueblo III. The youngest type is Sosi Black-on-white with a dendro-calendar chronology of AD 1075 to 1200 (Hall, 1977, p. 1602). Based on this ceramic evidence, the filling of the Bonito channel began sometime after AD 1075. The downcutting of the Bonito channel ended the period of deposition of the Chaco unit ca. 1000 ^{14}C years BP (ca. 925 cal. BP, cal. AD 1025). Based on other alluvial sequences in the Southwest and Plains, the amount of time it takes for an arroyo channel to downcut and back-fill may be no more than 200 years (Hall, 1986; 1990a). The above evidence and numbers are consistent with the erosion and initial filling of the Bonito channel sometime between ca. AD 1000 and 1200.

Another large collection of reworked potsherds has been recovered from Bonito channel deposits by Force et al. (2002). Using a dating method called "earliest possible age of latest sherd" (EPALS), the age of the Bonito channel fill was concluded to be between ca. AD 1025 and 1090 (Force et al., 2002, p. 13, 25). Based on the ceramic assemblage containing Sosi Black-on-white discussed above, with a chronology of AD 1075 to 1200, the EPALS age of the Bonito channel fill would be AD 1075. However, I argue that using only the time of appearance of a ceramic type and ignoring the full time range of its manufacture and use is not justified as a basis for a chronology. Also, reworked potsherds only provide a "later-than" age for sherd-containing sediments and are unsuitable as a basis for high-resolution alluvial chronology, such as proposed for the Bonito alluvium by Force et al. (2002) (Hall and Ferguson, 1994).

Historic unit, twentieth century

Deposition of the Bonito unit ended with the incision of the modern arroyo channel. Channel downcutting may have begun in the late nineteenth century; channel widening continued into the early twentieth century. The modern arroyo is wider and deeper than Bryan's Bonito channel in most places, although erosion of the modern arroyo is not as great as the degree of canyon erosion that occurred between 2800 and 2100 years BP. In 1935, to halt widening of the arroyo and to protect prehistoric ruins close to the channel, 94,000 seedlings of willow, tamarisk, wild plum, and cotton were planted in Chaco Wash. Additional erosion-control efforts have been applied in the wash, and, perhaps as a consequence, more than two meters of sediment have accumulated in the arroyo. Additional details and aspects of the geomorphology and sedimentology of Chaco Wash are thoroughly discussed by Love (1977, 1979, 1980, 1983a, 1983b) and will not be reviewed here.

DISCUSSION OF THE ALLUVIAL RECORD

Origin of Gallo and Chaco alluvium

The alluvial fill at Chaco Canyon has duel origins: local and upstream. Alluvium of local origin is yellowish brown, very fine sand derived from weathered Cretaceous sandstones and transported by way of small tributaries and reentrants into the canyon escarpments. Alluvium from upstream sources is grayish brown, silty clay derived from Cretaceous and Paleocene shale in the upper part of the Chaco drainage basin. The Gallo unit is composed primarily of sandy alluvium of local origin. The Chaco unit is composed largely of clayey sediment from upstream sources. The alluvium can also incorporate a mix of sediment from the two different sources. Inspection of the Gallo unit shows the presence of at least two clay beds from upstream sources (Fig. 3). Likewise, the Chaco unit contains thin beds of local yellowish sand (Fig. 4). The origin of the alluvium could be a variable affecting the pollen content, the local and upstream areas having slightly different vegetation. However, pollen analysis of both sand and clay in the Gallo unit produced the same results (Hall, 1977, Gallo Wash I pollen diagram). Thus, even though the alluvium in Chaco Canyon is derived from two different geographic areas, the pollen record in this case does not seem to reflect those differences.

Overbank alluvium

The present-day geomorphology of the canyon floor at Chaco Canyon contrasts sharply with conditions in the past. Today, runoff from the drainage basin is funneled into a broad arroyo and inner channel, and deposition occurs only in the wash. In the past, runoff flowed in comparatively small, shallow channels. Muddy water would top the banks of the shallow channels and spread out over the canyon floor. As flow dissipated, the fines settled out. Shrink-swell processes result in turbation of the new clay with previously deposited clay, resulting eventually in a homogenous deposit of massive clay on the valley floor. These massive, fine-textured sediments are referred to in this paper as overbank alluvium. Thin-bedded silty clay also accumulates in shallow channels and swales where the laminar beds become buried and preserved in paleochannels. Both the Chaco and Bonito units are characterized by overbank alluvium that likely accumulated in a scenario such as briefly described above.

Thick, massive clay beds in alluvial sequences in the Southwest are sometimes called cienega deposits (Eddy and Cooley. 1983). Cienegas are spring-fed watercourses in the desert, and sediment buildup in cienega valleys occurs by slow overbank aggradation. However, thick, massive clay beds are also called cumulic soils (French et al., 2009). Cumulic soils are common in alluvial sequences in the Great Plains where they are regarded as over-thickened A horizons (Hall, 1990a). They form by slow aggradation of fine-textured sediment on valley floors and may be one or more meters thick, representing a thousand years or more of accumulation. Both cienega deposits and cumulic soils form by slow overbank alluvial sedimentation. The environmental circumstances leading to cienega deposits and cumulic soils are also similar: both develop during periods of locally wet conditions on valley floors.

Environmental conditions in Chaco Canyon during the deposition of the overbank alluvium of the Chaco unit were not especially wet. The principal freshwater snail that occurs in the Chaco unit is tolerant of ephemeral wet habitats that are seasonally dry. Pollen grains representing wet-ground plants, such as sedges (Cyperaceae), are absent. Pollen analysis instead indicates that the canyon floor was a shrub grassland with greasewood, not a wet-meadow plant community. Overall, however, the evidence indicates that conditions leading to the deposition of the Chaco unit may have been only slightly moister than today. The deposition of the Bonito unit likely occurred under circumstances that were even less moist.

The paleoecological evidence points to an absence of permanent wet conditions in the canyon during the late Holocene. It is suggested that the overbank alluvium accumulated on the canyon floor during seasonal runoff events, perhaps related to late-summer monsoon rainfall. A regional wetter climate may have promoted more frequent runoff events with increased stream flow than seen in the canyon today. The existence of a cienega or cumulic soil depositional environment, however, is ruled out.

"Lake Chaco"

One of the more unusual suggestions concerning the late Quaternary geology of the region is a prehistoric saline lake at Chaco Canyon. It was been speculated that a sand dune at the mouth of Chaco Wash at the junction with Escavada Wash dammed Chaco Wash, forming a lake of unspecified depth but extending 1-2 km upstream in Chaco Canyon (Force et al., 2002, p. 4, 34). The timing of the formation of the lake is not determined. However, it has been hypothesized that the lake was present until about AD 900-1025 and drained when the eolian dam failed, resulting in a lowered base level and downcutting of the Bonito channel (Force et al., 2002, p. 27, 35). During my 1972-73 fieldwork, I found no evidence of ponded sediments exposed in any of the arroyo cutbanks at Chaco. Subsequent fieldwork, including inspection of the localities mentioned by Force et al. (2002) where ponded deposits supposedly occur, also revealed no lacustrine sediments.

Lacustrine beds have clear sedimentary structures and properties that are widely recognized and documented (e.g., Allen and Anderson, 2000; Allen et al., 2009; Lucas and Hawley, 2002; Hall, 2001). One type of sedimentary feature found in lacustrine deposits is thin-bedded laminar structures. The sediments at Chaco that have been interpreted as lake deposits were described by Force et al. (2002, p. 4, 5): "The laminated deposits consist of sandy mud layers commonly with mud-crack structures, containing fine gypsum and 1-2 mm gypsum crystals...interlayered with fine to medium-grained sand, locally with standing-ripple laminae" Two photographs in the Force et al. report (p. 5) show the laminated sediments that purportedly represent pond deposits. However, the sediments described and illustrated by Force et al. as lacustrine in origin are instead channel-fill alluvium that occurs throughout the canyon. The deposits are thin clay beds that accumulated in shallow channels in low-energy environments, such as documented in the Chaco unit (Figs. 9, 10). The dark- and light-colored laminae in the paleochannel of the Chaco unit are silty clay with the light bands containing more very fine-grained sand (Table 2). The clayey laminae are commonly disrupted by desiccation cracks and insect burrows and show evidence of micro-deformation, typical of mud and clay-drape deposition in ephemeral channels. Sand-size gypsum crystals and crystal aggregates occur throughout the Chaco unit in the canyon and their presence is related to drying following sediment deposition, not to saline lacustrine environments. The interpretation of a lake at Chaco Canyon is mistaken.

Mapping the alluvial fill

The geologic mapping of Chaco Canyon by the U.S. Geological Survey has completely ignored previous studies of the alluvial fill by Bryan (1941, 1954), Hall (1977), and Love (1977). Weide et al. (1979) mapped the entire canyon floor as Naha alluvium, a term used by Hack (1941) for late Holocene alluvium in northeastern Arizona. While the Naha alluvium may correspond in part to the Deposition III and buried channel alluvium of Bryan (1941,

FIGURE 9. Laminar silty clay fill of shallow paleochannel in overbank deposits in the Chaco unit. Close-up of laminar beds shown in Figure 10. Site corresponds with photography station E; 1-meter scale; photograph taken in 2009.

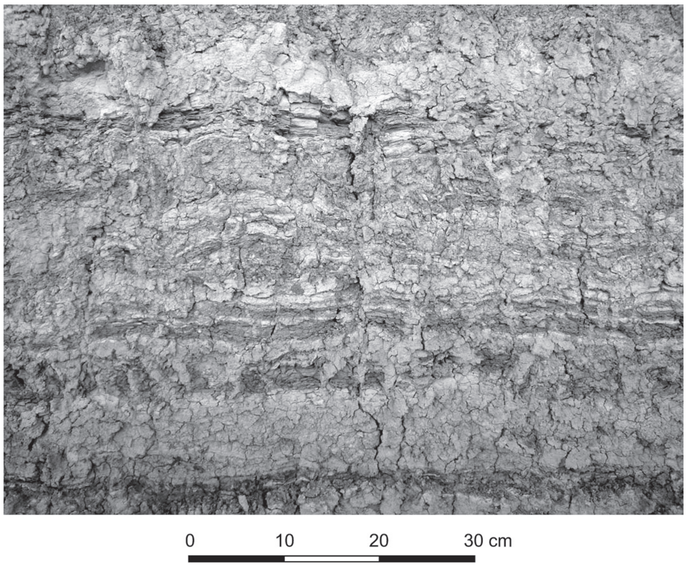

FIGURE 10. Close-up of silty clay laminar beds in paleochannel fill in the Chaco unit shown in Figure 9. Color of dark and light bands may be related to clay and sand content: dark bands with more clay and less very fine sand, light bands with less clay and more very fine sand (see Table 2). Laminar beds in shallow paleochannels such as these may have been confused with lacustrine deposits by Force et al. (2002).

1954) and the Post-Bonito unit of Hall (1977) (Bonito unit of this paper), an equivalency was never established. In addition, the alluvial fill deposits exposed at the surface of the canyon floor are not uniformly the same, as indicated by the presence of archaeological sites of different ages. The archaeological survey of Chaco Canyon reported in Hayes et al. (1981) documented the presence of 265 Puebloan sites and 18 Archaic and Basketmaker sites located on the alluvial valley floor. Therefore, the alluvium exposed at any one place on the canyon floor may be Gallo, Chaco, or Bonito units. Not only is it inappropriate to apply the name Naha alluvium to Chaco Canyon, but the implication that all of the alluvium at the surface of the canyon floor is Bonito or equivalent is incorrect. The mistaken mapping of the surficial geology of the canyon floor is perpetuated in later maps by Scott et al. (1984) and Mytton and Schneider (1987).

PALYNOLOGY OF ALLUVIUM

One of the goals of the 1972-73 investigation was to establish a pollen biostratigraphy of the radiocarbon-dated alluvium and to determine a history of past vegetation and paleoecology for the Chaco area. Pollen analysis at Chaco Canyon has been conducted on alluvium from the Pre-Gallo, Gallo, Chaco, Bonito, and Historic units as well as surface materials, Wetherill's reservoir, and woodrat middens (Hall, 1977, 1988). Pollen analyses applied to ethnobotanical investigations of various archaeological sites at Chaco Canyon are not reviewed here. All of the studied materials contained abundant, well-preserved pollen. Pollen concentration varies with sediment texture, with clay containing high amounts and sand containing low amounts of pollen. It was found that pollen concentration averages between 5000 and 10,000 but can be as high as 200,000 grains per gram. The main reason for such favorable pollen content in the alluvium at Chaco is its overall fine texture. Pollen grains, composed of organic material, have settling properties similar to silt and clay. Thus, silty and clayey alluvial sediment contains large amounts of pollen, transported as part of the suspended load and deposited in low-energy floodplain and flood-terrace environments. On the other hand, pedogenesis and weathering can degrade and destroy pollen grains, significantly reducing the amount of pollen and altering the percentages of the pollen taxa in the weathered sediment. The general absence of secondary weathering of the alluvial units at Chaco as well as the fine texture of the alluvium has resulted in copious, well-preserved pollen assemblages that are well suited for paleo-vegetation reconstruction. This is in contrast to many other palynologic studies in the Southwest, where pollen grains exhibit poor preservation and pollen assemblages have been altered by differential degradation and corrosion (Hall, 1995).

Reworked Cretaceous palynomorphs

An unusual aspect of the Chaco alluvial pollen record is the presence of many recycled Cretaceous spores and pollen grains, probably from the coal beds of the Menefee Formation (Upper Cretaceous) that outcrop along the canyon escarpment. Recycled Cretaceous spores, pollen grains, and a rare megaspore and dinoflagellate occur in all of the alluvial pollen assemblages. The concentration of the Cretaceous palynomorphs in the Holocene alluvium ranges from 100 to 12,000 per gram or 0.3 to 95 % of the total Cretaceous-Quaternary palynomorph content. Recycled pre-Quaternary spores and pollen grains may be more common in alluvium than generally recognized (Scott and Srivastava, 1984). The pollen analyst must be alert to possible reworked pollen taxa. The recycled Cretaceous spores and pollen grains are generally recognizable owing to their distinct morphology. In this study, in order to count pollen from the alluvium, it was necessary to learn the various types of Cretaceous palynomorphs. Confusion of pre-Quaternary with Quaternary taxa will lead to erroneous pollen counts. Recycled palynomorphs also contaminate radiocarbon dates on bulk sediment, resulting in ages that are too old.

POLLEN ANALYSIS OF WOODRAT MIDDENS

Fossilized woodrat (*Neotoma* spp.) nests occur in abundance along sandstone escarpments at Chaco Canyon. The nests are made up largely of collections of plant materials selected for bedding, construction, and food, the whole mass cemented by dried urine (Finley, 1958; Wells and Jorgensen, 1964). Where protected in crevices from rainfall, cemented nests or middens can be preserved for many thousands of years. A series of woodrat middens from Chaco Canyon yielded needles of pinyon pine and twigs of juniper, leading to the interpretation of a pinyon-juniper woodland (Betancourt and Van Devender, 1981). Twigs from the woodrat middens were radiocarbon dated 10,600 to 9460 and 5550 to 460 ^{14}C years BP, with a gap in the record between ca. 9500 and 5500 years BP. Pollen analysis of pieces of matrix from the same middens showed that the vegetation at Chaco was a shrub grassland and that pinyons and junipers were present only in small, isolated numbers on sandstone escarpments throughout the Holocene, similar to today (Hall, 1988). It is ironic that earlier assertions of Puebloan deforestation of the Chaco Canyon area were centered on the mistaken view that a forest was present.

Floristics of plant macrofossils

The Chaco case study has been a turning point in Southwestern paleo-vegetation research during the past 20 years, demonstrating that plant macrofossils from woodrat middens are presence-only floristic records and cannot be used for literal interpretation of plant communities (Hall, 1997). A good corroboration of this is illustrated by the Stephen's woodrat (*N. stephensi*) with a modern range that includes Chaco Canyon (Findley et al., 1975, p. 246). A Stephen's woodrat specifically selects a nesting site near a living juniper tree that will ultimately provide 90% of the individual's annual diet (Vaughan, 1980, 1982). The resulting midden contains many juniper twigs, but all from only one tree. A literal interpretation of a juniper woodland from a juniper-bearing fossil midden can be clearly mistaken. The presence of at least one juniper is sure, but whether the tree is an isolated individual or part of a forest cannot be determined from plant macrofossils alone. The same argument can be made for other plant macrofossil taxa as well. Because of these uncertainties, it is widely acknowledged that pollen analysis is the only reliable method for vegetation reconstruction. While floristics from plant macrofossils add valuable information on the presence of some species, the abundance of those species in plant communities can only be determined by pollen analysis.

Radiocarbon ages from woodrat middens

The standard laboratory methodology of woodrat midden analysis involves (a) disaggregation of the midden mass in water and (b) wet sieving to recover the macro-remains; the pollen grains and other fine debris are washed away. A radiocarbon age of a midden is generally obtained from a collection of twigs that have been picked from the sieved material, the age often determined on macros from one species. In the case with the Chaco middens, a small piece of each midden was set aside for pollen analysis. The age of the pollen assemblages were assumed to be the radiocarbon age on twigs from the middens (Hall, 1988). It is now recognized that the radiocarbon age of pollen-bearing detritus from a midden is not the same age as the macrofossils. AMS radiocarbon ages of pollen-bearing detritus can differ by 2000 to 3000 years from the radiocarbon age of twigs from the same midden (Hall and Riskind, 2010). This relationship calls into question the age of the midden pollen record reported by Hall (1988) and by others. The pollen counts and vegetation reconstruction are true, but the reported age of the pollen samples may be off by hundreds if not thousands of years. Clearly, a new pollen study of the Chaco woodrat midden material with AMS ages from each pollen residue is warranted.

VEGETATION HISTORY

Modern vegetation

The present-day vegetation of Chaco Canyon is desert-shrub grassland with isolated juniper (*Juniperus monosperma*) and pinyon pine (*Pinus edulis*) along sandstone escarpments. The dominant shrub is fourwing saltbush (*Atriplex canescens*) and rabbitbrush (*Chrysothamnus* spp.), and the dominant grasses are galleta (*Hilaria jamesii*), blue grama (*Bouteloua gracilis*), alkali sacaton (*Sporobolus airoides*), sand dropseed (*S. cryptandrus*), and Indian ricegrass (*Oryzopsis hymenoides*). The canyon floor is dominated by greasewood (*Sarcobatus vermiculatus*) and fourwing saltbush shrub with grasses. Juniper and pinyon pine are more abundant on the north side of Chacra Mesa (south of Chaco Wash) and an isolated stand of ponderosa pine (*P. ponderosa*) occurs at the eastern end of the mesa in the upper Chaco drainage basin near the Continental Divide. Directly north of Chaco, the vegetation is Indian ricegrass-big sagebrush (*Artemisia tridentata*) association, and northeast of Chaco, at slightly higher elevation, the vegetation is dominated by big sagebrush with western wheatgrass (*Agropyron smithii*), galleta, alkali sacaton, blue grama, and sand dropseed along with scattered clumps of juniper and pinyon pine. The treeless area south of Chaco is an alkali sacaton-fourwing saltbush association with western wheatgrass, blue grama, and rabbitbrush (Donart et al., 1978).

Paleo-Vegetation

The vegetation history of Chaco Canyon is well documented by pollen analysis of alluvium and fossil woodrat middens along with floristics from plant macrofossils. The Chaco Canyon pollen records indicate the dominance of desert-shrub grassland vegetation throughout the past 10,000 years. The record also shows that minor shifts in numbers of shrubs and trees have occurred in the area. Within the context of desert-shrub grassland, the following sequence of plant community and floristic change is arranged by time and stratigraphy, using the original data reported by Hall (1977, 1988) and Betancourt and Van Devender (1981).

Mean percentages of *Pinus* spp., Cheno-Am (Chenopodioideae-*Amaranthus*), and *P. edulis* pollen, the three most abundant pollen taxa in the Chaco material, may serve as a general index to the similarities and differences in the data (Figs. 11, 12, 13). Plots of the mean percentage values also illustrate a high degree of variability of the different pollen profiles. The data from the Pre-Gallo unit and Atlatl Cave also fall outside the general population of the Gallo-Chaco-Bonito profiles, suggesting that they represent different plant communities. [In traditional Southwest pollen analysis, Cheno-Am is a pollen taxon of the Chenopodiaceae family and the genus *Amaranthus*, pollen grains of which are indistinguishable during routine pollen counting. Recently, the Chenopodiaceae family has been re-classified as the subfamily Chenopodioideae in the Amaranthaceae family (APG, 1998; APG II, 2003). However, the term Cheno-Am, representing pollen grains of the Chenopodioideae subfamily and *Amaranthus*, retains validity in pollen analysis and is applied in this paper.]

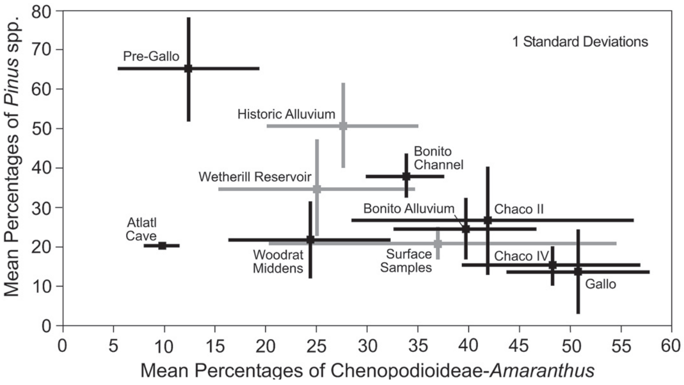

FIGURE 11. Diagram of mean percentage values of *Pinus* spp. versus Chenopodioideae-*Amaranthus* (Cheno-Am) pollen for different pollen profiles at Chaco Canyon. Twentieth century pollen data are shown in gray (from Table 3).

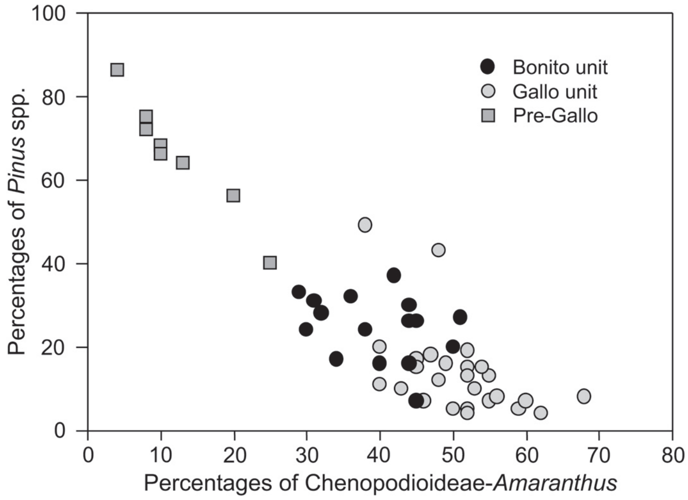

FIGURE 12. Plot of *Pinus* spp. versus Chenopodioideae-*Amaranthus* (Cheno-Am) percentage values from individual pollen samples from the Pre-Gallo, Gallo, and Bonito units. Percentage values from the Chaco unit fall in the middle of the Gallo and Bonito scatter but are not shown here. The plot of individual percentage values illustrates great variability in the pollen data. Figure constructed from Gallo Wash I and Gallo Wash II pollen diagrams (Hall, 1977).

Late Pleistocene, 10,600 to 9500 years BP

Two woodrat middens provide a glimpse into the late Pleistocene-early Holocene transition, revealing a relict stand of trees along the escarpment microhabitat at Atlatl Cave. Spruce (*Picea* sp.), limber pine (*P. flexilis*), Rocky Mountain juniper (*J. scopulorum*), Douglas fir (*Pseudotsuga menziesii*), and possibly ponderosa pine are all present. While these are components of a mixed conifer forest, the macrofossil record also includes species from arid grasslands: Indian ricegrass, fourwing saltbush, big sagebrush, plains prickly pear (*Opuntia polyacantha*), and yucca (*Yucca angustissima*). The pollen record from the middens is clear that the trees represent a relict stand and not local forest vegetation. Instead, the vegetation was desert shrub grassland, the shrubs including fourwing saltbush and big sagebrush. The late Pleistocene vegetation may have been similar to the modern plant community in the San Juan Basin mapped as Indian ricegrass-big sagebrush series (Donart et al., 1978). However, a plot of the Cheno-Am and pinyon pine pollen data from the two Atlatl Cave samples falls far outside the range of variability of all of the other material from Chaco Canyon, including twentieth century records (Figs. 11, 13). The late Pleistocene vegetation represented by these data may have no modern analogue.

Late Pleistocene-Early Holocene (?)

The Pre-Gallo unit alluvial sediments incorporating the "pine pollen zone" are interpretated as late Pleistocene or possibly early Holocene, pre-dating the Gallo unit. The pollen assemblages have 66% pine and 12% Cheno-Am that are the highest amount of pine and the lowest amount of chenopod in the Chaco Canyon records

Table 3. Mean pollen percentage data from Chaco Canyon, New Mexico.

Pollen Profile	***Pinus* spp. %**			**Chenopodioideae-*Amaranthus* %**		
(No. of samples)	Mean ± 1 SD	Min.*	Max.*	Mean ± 1 SD	Min.*	Max.*
Surface samples (7)	21.0 ± 4.1	15	26	37.0 ± 17.1	22	70
Historic alluvium (20)	50.7 ± 10.7	34	67	27.7 ± 7.5	14	39
Wetherill Reservoir (11)	34.6 ± 12.3	14	56	25.1 ± 9.7	10	48
Bonito alluvium (16)	24.6 ± 7.8	7	37	39.7 ± 7.0	29	51
Bonito channel (11)	37.9 ± 5.6	27	45	33.9 ± 3.9	30	42
Chaco alluvium II (13)	26.8 ± 13.7	7	57	41.9 ± 13.9	25	67
Chaco alluvium IV (18)	15.6 ± 5.0	7	28	48.3 ± 8.8	31	63
Gallo alluvium (26)	13.7 ± 10.7	4	49	50.8 ± 7.0	38	68
Pre-Gallo (8)	65.9 ± 13.6	40	86	12.3 ± 6.9	4	25
Woodrat Middens						
Holocene (17)	21.5 ± 9.7	10	39	24.4 ± 8.0	15	37
Atlatl Cave (2)	20.5 ± 0.7	20	21	9.5 ± 3.5	7	12

* Percentage values rounded to whole numbers

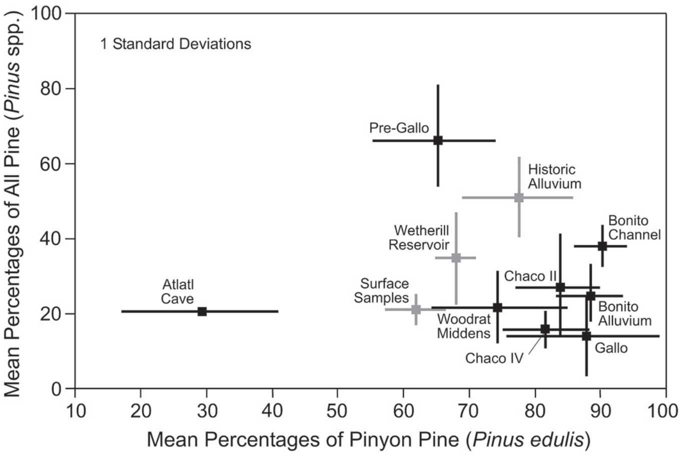

FIGURE 13. Mean percentages of pinyon pine (*Pinus edulis*) pollen versus mean percentages of all pine *(Pinus* spp.) pollen. Twentieth century pollen data are shown in gray. The pinyon pine percentages are based on differentiation of *Pinus* pollen to species, minimum 100 counts; data from Table 4.

(Figs. 11, 12). In addition, 65% of the pine is pinyon pine, the remainder mostly ponderosa pine with some limber pine (Fig. 13). The pollen indicates a strong presence of pine trees representing a local pinyon-juniper woodland with some oak (*Quercus* sp.) as well as desert shrub grassland elements such as chenopods, sagebrush, asters, cactus, and *Ephedra*. Overall, the vegetation represented by this undated material was a pinyon-juniper woodland with a desert-shrub grassland at lower elevations. Ponderosa pine may have been locally abundant at higher elevation, such as at the eastern end of Chacra Mesa, where small stands occur today. The woodland may have been restricted to areas of sandy soils with shrub grassland occurring on broad upland and lowland flats. The Pre-Gallo pollen differs from the late Pleistocene record from Dead Man Lake that has high percentages of *Artemisia* pollen, probably from big sagebrush, and moderate percentages of pine (Wright et al., 1973; reviewed by Hall, 2005).

TABLE 4. Mean pollen percentage data for *Pinus edulis* from Chaco Canyon, New Mexico

Pollen Profile (No. of samples)*	Mean ± 1 SD	Min.†	Max.†
Surface samples (7)	61.9 ± 4.6	56	67
Historic alluvium (20)	77.6 ± 8.4	63	92
Wetherill Reservoir (11)	68.1 ± 3.1	62	72
Bonito alluvium (16)	88.6 ± 5.1	79	97
Bonito channel (11)	90.3 ± 4.1	84	96
Chaco alluvium II (13)	83.9 ± 6.4	72	96
Chaco alluvium IV (18)	81.6 ± 6.6	68	90
Gallo alluvium (26)	87.9 ± 11.6	56	100
Pre-Gallo (8)	65.3 ± 9.3	53	81
Woodrat Middens			
Holocene (17)	74.4 ± 10.3	51	84
Atlatl Cave (2)	29.5 ± 12.0	21	38

* Localities are shown on maps in Hall (1977, 1997).
† Percentage values rounded to whole numbers; percentages based on minimum 100 counts of identifiable *Pinus* pollen grains

Mid- and early late Holocene, 7000 to 2500 years BP

Local plant communities were dramatically different during mid-Holocene time. The mean percentages of pine shifted from highest to the lowest values, and the percentages of chenopod changed from lowest to highest values of all of the Chaco Canyon profiles (Fig. 11). The pinyon-juniper woodland vanished, reduced to a few isolated shrubby trees along sandstone escarpments. Ponderosa pine stands in the San Juan Basin may have all but disappeared as well except for a few, small, relict populations. Chenopod shrubs, including salt-tolerant fourwing saltbush, increased to great abundance. Greasewood was less common, perhaps due to the sandy substrate of the Gallo alluvium on the canyon floor. The vegetation was desert shrub grassland with Indian ricegrass and New Mexico feathergrass (*Stipa neomexicana*). The widespread change in vegetation at this time is a response to the regional shift to warm-dry climatic conditions during the mid-Holocene, a period of aridity that is documented throughout the Southwest. Reduced rainfall and increased evaporation of soil moisture led to greater soil alkalinity, favoring chenopod shrubs and other salt-tolerant species. Increased abundance of chenopod shrubs during this arid period is also documented at a desert pollen site in southern New Mexico (Freeman, 1972).

Late Holocene, 2500 years BP to present

By ca. 2500 years BP, the regional climate was less arid. The increased moisture resulted in a slight shift in local plant communities. Chenopods became less abundant, although still the dominant shrub. The previously reduced pinyon-juniper and ponderosa pine populations may have recovered on a small scale but not reaching the abundance seen during the late Pleistocene-early Holocene. Overall, the local vegetation is desert-shrub grassland with a few individuals or small stands of pinyon pine and juniper along sandstone escarpments. Even though the regional climate resulted in less arid conditions, especially ca. 2500 to 1000 years BP, desert grassland vegetation persisted and thrived. Regional climate may also have shifted between somewhat drier to less dry conditions within the past 1000 years (Bradley et al., 2003), although pollen evidence indicates continued desert shrub grassland vegetation at Chaco Canyon.

SUMMARY OF NEW INTERPRETATIONS

Seldom does the opportunity arise when a field worker can re-evaluate past efforts with the advantage of new information and experience. In truth, I have never stopped reflecting on the geologic-palynologic records at Chaco Canyon, even though engaged by other studies in subsequent years. Below is a summary of the new information and interpretations presented in this paper.

1. The Pre-Gallo unit is a new, provisional alluvial unit. Although yet undated, it occurs stratigraphically above the Fajada paleosol and below the Gallo unit and may be late Pleistocene (or early Holocene) in age. The pollen assemblages from the Pre-Gallo have high percentages of pine, in contrast with the younger

alluvial pollen profiles that have lower percentages of pine.

2. The names Post-Bonito channel and Post-Bonito unit are simplified to Bonito channel and Bonito unit.

3. The ages of the Gallo, Chaco, and Bonito units are changed somewhat to reflect the actual radiocarbon dates without extrapolating or rounding the numbers, although no new radiocarbon ages from the alluvium have become available.

4. The Gallo unit is characterized by yellowish brown sand derived from local canyon sources, and the Chaco and Bonito units are dominated by grayish brown clay from clayey bedrock sources in the upper drainage basin, although each alluvial unit contains sediment from both sources.

5. It is suggested that the sandy Gallo unit accumulated in the canyon during the mid-Holocene period of aridity, related to low volume stream flow that was insufficient to transport all of the sand out of the canyon. A shift to wetter climate, increased discharge, and greater sediment transport after ca. 3 ka resulted in large-scale erosion of the Gallo alluvium.

6. The Chaco unit is reinterpreted as dominated by overbank, clayey alluvium deposited during seasonal runoff and overflow from one or more shallow channels. The channels may have been dry during certain times of the year. The clayey Bonito unit was also deposited across the canyon floor as overbank alluvium. Canyon-floor conditions were not sufficiently wet for cienega or cumulic soil development.

7. The local vegetation has been desert shrub grassland since the end of the Pleistocene. Throughout the Holocene, however, isolated stands and individuals of pinyon pine and juniper were present along canyon sandstone escarpments. Previous interpretations of a pinyon-juniper woodland at Chaco Canyon, based solely on plant macrofossils, are mistaken.

8. During mid-Holocene aridity, the combination of decreased precipitation and increased evaporation resulted in elevated soil alkalinity. Consequently, chenopod shrubs increased in abundance in local and regional plant communities.

9. Previous interpretations of the paleoclimate at Chaco were based on percentages of pine pollen. Large percentages of pine pollen were regarded as indicating large numbers of pine trees in the regional vegetation, and small percentages of pine pollen were regarded as indicating small numbers of pine trees in the regional vegetation. Because of the geography, topography, and pine-tree distribution in the San Juan Basin and surrounding mountains, it was further concluded that large numbers of pine trees in the region meant wetter-cooler climatic conditions, and small numbers of pine trees were related to a dry-warm climate. [It should be noted that, even though Chaco is virtually treeless, present-day surface samples in the canyon contain 21 % *Pinus* pollen, nearly all of it derived by long-distance transport from pine tree populations in the uplands and mountains in and around the San Juan Basin.] While the low percentages of pine correctly identified the warm-dry climate of the mid-Holocene, the late Holocene was initially interpreted as continuingly less arid up to the present, based on the increasing percentages of pine pollen. As a result, the period represented by the Chaco unit (and Puebloan habitation of the canyon) was initially interpreted as drier than during the later period represented by the Bonito unit.

The late Holocene paleoenvironmental record is reassessed. The overall pollen record indicates a desert shrub grassland but is inconclusive with regard to fine-scale differences in vegetation during the two periods 2.5–1 ka and 1–0 ka. The dominance of overbank clayey alluvium and the presence of mollusks in the Chaco unit, however, indicate slightly wetter conditions during the 2.5–1 ka period.

10. A hypothesis by others that a saline lake existed in the canyon during Puebloan times is mistaken; no lacustrine beds are present in the alluvial valley fill.

Recommendations for future research

1. The OSL geochronology of the Fajada unit, Fajada paleosol, Pre-Gallo unit, and the Bonito unit will dramatically improve our understanding of the late Quaternary geologic history of the canyon.

2. A systematic, detailed description of the sediments that make up the alluvial units at different locations throughout the canyon will provide valuable information on changing alluvial depositional environments.

3. While pollen analysis of alluvium and woodrat middens has provided solid information on paleo-vegetation, pollen analysis of new woodrat-midden material with AMS radiocarbon ages on the pollen residues is warranted in order to refine the dated sequence of vegetation and environmental history at Chaco Canyon.

CONCLUSIONS

The alluvial and paleo-vegetation records at Chaco Canyon are strongly related to regional climate (Fig. 14). Changes in climate result in accompanying shifts in local alluvial geomorphology and plant communities. Although the pollen record begins in the late Pleistocene, the alluvial geology is not well known until the mid-Holocene. During the arid climate of the mid-Holocene, alluvial sand of the Gallo unit accumulated in the canyon. Runoff from the meager rainfall evidently resulted in too little stream flow to transport the sand out of the canyon. During the late Pleistocene, the vegetation was a pinyon-juniper woodland on sandy substrates with a desert shrub grassland on broad flats. With the onset of mid-Holocene aridity, the tree population was dramatically reduced and the desert shrub grassland thrived. Reduced rainfall and greater evaporation resulted in increased alkalinity of soils, and salt-tolerant shrubs, such as fourwing saltbush, flourished. By 2500 years BP, the alluvial and pollen records are consistent with a shift in climate to less arid conditions. Increased discharge removed some of the Gallo alluvium. With more rainfall and runoff, clayey sediment was carried from upstream areas of the drainage basin and deposited as overbank alluvium in the canyon, forming the Chaco unit. Although stream flow may have been low and irregular, the canyon floor and shallow channel were suitable habitats for a fauna of freshwater and terrestrial snails. A change in the local hydrology about 1000 years BP, perhaps related in some undetermined way to regional climatic warming, resulted in the incision of the alluvial fill by the Bonito channel. The channel may have begun to aggrade by AD 1200. The Bonito

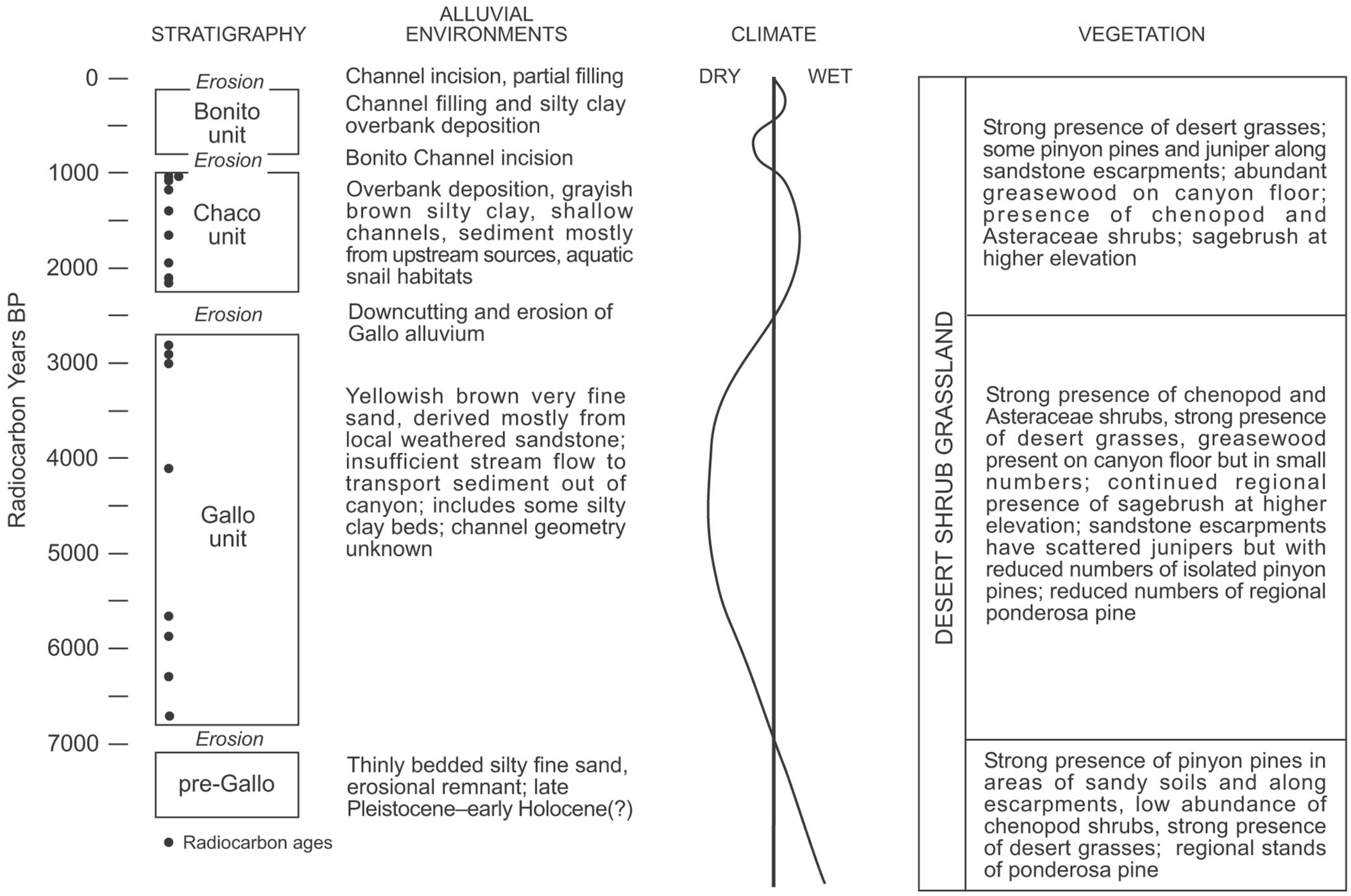

FIGURE 14. Summary diagram of Chaco Canyon alluvium, vegetation, and climate. The climate curve is summarized from various regional sources.

channel filled and overbank sedimentation continued in some areas of the canyon, forming the clayey Bonito unit. Accumulation of the Bonito alluvium was halted by late nineteenth century erosion of the present arroyo channel that is filling today. Even though minor shifts in climate in the past 2500 years have had an influence on the alluvial history, the vegetation record exhibits little variation. The present-day desert shrub grassland with a few isolated pinyon pine and juniper on sandstone escarpments may have persisted largely unchanged for the past 2500 years. The Puebloan impact on the landscape, while it has been previously argued is considerable, was nonetheless fleeting.

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