WATER MANAGEMENT AT PUEBLO BONITO: EVIDENCE FROM THE NATIONAL GEOGRAPHIC SOCIETY TRENCHES

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Recent archaeological investigations at Pueblo Bonito in Chaco Canyon reveal that residents constructed a large diversion channel during the eleventh century A.D. as dramatic growth resulted in the expansion of the building onto the main valley floor. Sediments in the diversion channel reflect repeated episodes of flooding, rather than slow moving water typically found in irrigation canals, and archaeobotanical data indicate deposition during late summer or early fall. Although an agricultural function is possible, the channel may have been built primarily to divert floodwaters away from Pueblo Bonito while providing a nearby water source for construction and domestic use. The diversion channel was destroyed by the entrenchment of the "Bonito paleo-channel" in the late A.D. 1000s, and then buried by a combination of cultural debris and valley flooding. Although the canyon stream system changed throughout the occupation of Pueblo Bonito, there is no evidence that the formation of a deep natural channel in the floodplain had any negative effect on the growth of the great house.

Recientes investigaciones arqueológicas en Pueblo Bonito en el Cañón del Chaco revelan que, durante el siglo XI AD, los residentes construyeron un canal de desviación de grandes dimensiones tras un crecimiento espectacular que dio lugar a la ampliación del edificio en el fondo del valle. Los sedimentos en el canal de desviación reflejan repetidos episodios de inundaciones, en lugar del movimiento lento de agua que típicamente se encuentra en los canales de riego. Adicionalmente, datos arqueobotánicos indican que la deposición de dichos sedimentos ocurrió a finales del verano o principios del otoño. Aunque es posible que haya servido una función agrícola, el canal pudo haber sido construido principalmente para desviar las aguas de inundaciones lejos de Pueblo Bonito y proporcionar una fuente cercana de agua para construcción y uso doméstico. El canal de desviación fue destruido por la trinchera del "paleo-canal de Bonito" a finales de los 1000 AD, y luego enterrado por una combinación de escombros culturales e inundaciones del valle. Aunque el sistema de flujo del cañón cambió durante la ocupación de Pueblo Bonito, no hay evidencia de que la formación de un canal natural profundo en la zona de inundación haya tenido algún efecto negativo sobre el crecimiento de la gran casa.

In order to understand why Chacoans chose to literally build the foundations of their society on shifting sands and migrating channels, and how this decision related to developing social complexity, we need to know the ways in which Chacoans worked with the opportunities and constraints presented by moving water in an arid environment. The concentration of great houses on the floor of Chaco Canyon, colloquially known as "Downtown Chaco" (Neitzel 2003:4), is unusual in the ancient Pueblo world for many reasons, but one of the most striking is the placement of large residential structures within a dynamic floodplain (Figure 1). Pueblo Bonito, Chetro Ketl, Pueblo del Arroyo, and a score of smaller but substantial buildings were constructed on surfaces

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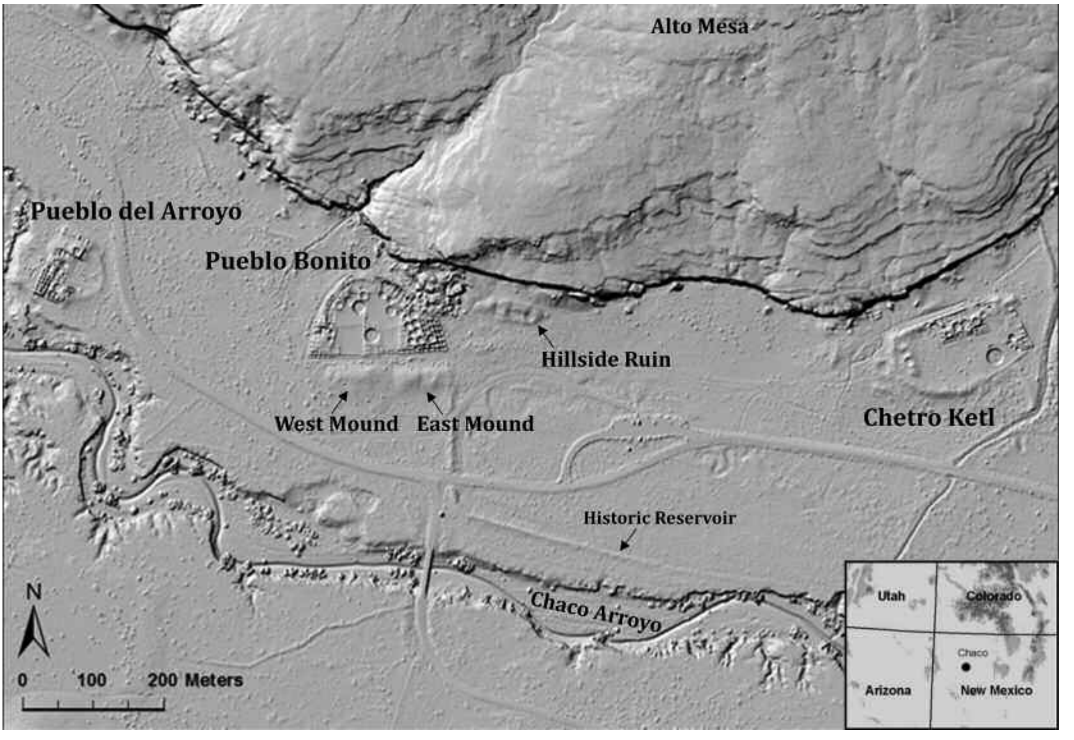

Figure 1. The "Downtown Chaco" portion of Chaco Culture National Historic Park, showing the location of great houses, the Chaco Arroyo, and Alto Mesa. The raised linear features are modern paved roads and an historic reservoir berm.

that were formed by valley flooding and expanding tributary fans. These locations were directly exposed to surface flows, some of which were immense; for example, Love (1977:295) estimated that modern peak discharge rates of 125 m^3 per second would flood the entire canyon floor in several locations when it was not incised. Although many small residential Bonito Phase (ca. A.D. 860–1140) structures in Chaco Canyon were built on ridges or rock outcrops adjacent to and just above the valley floor, the massive concentration of stone architecture most associated with the Bonito Phase was established in a seasonally active stream system confined between 60-m-high sandstone cliff walls.

In this study, we show that while the positioning of Pueblo Bonito naturally provided access to seasonally available surface water essential to the construction and growth of the great house and surrounding community, by the early eleventh century A.D., residents were also intentionally directing valley floods into at least one large, artificial channel in front of Pueblo Bonito. This diversion feature was destroyed in the late eleventh century by the incision and aggradation of a natural channel, but within a few decades valley flooding in the vicinity of the great house resumed. We know this is what happened based on new data obtained from archaeological trenches at Pueblo Bonito that were originally excavated by the National Geographic Society (NGS) in the 1920s (Figure 2, Supplemental Figure 1) and reopened by the University of New Mexico between 2005 and 2008.

In contrast to prehistoric irrigation canals in the Hohokam region of the American Southwest that were built in clearly defined farming areas (Hunt et al. 2005; Nials and Gregory 1989; Waters and Ravesloot 2001), the diversion channel in front of Pueblo Bonito was part of the great house residential complex (Figure 3). Water was directed through the midst of a dense community that experienced nearly constant construction work and landscape alteration between ca. A.D. 850 and 1200. As a result, there is a complicated history of physical relationships between alluvial geomor-

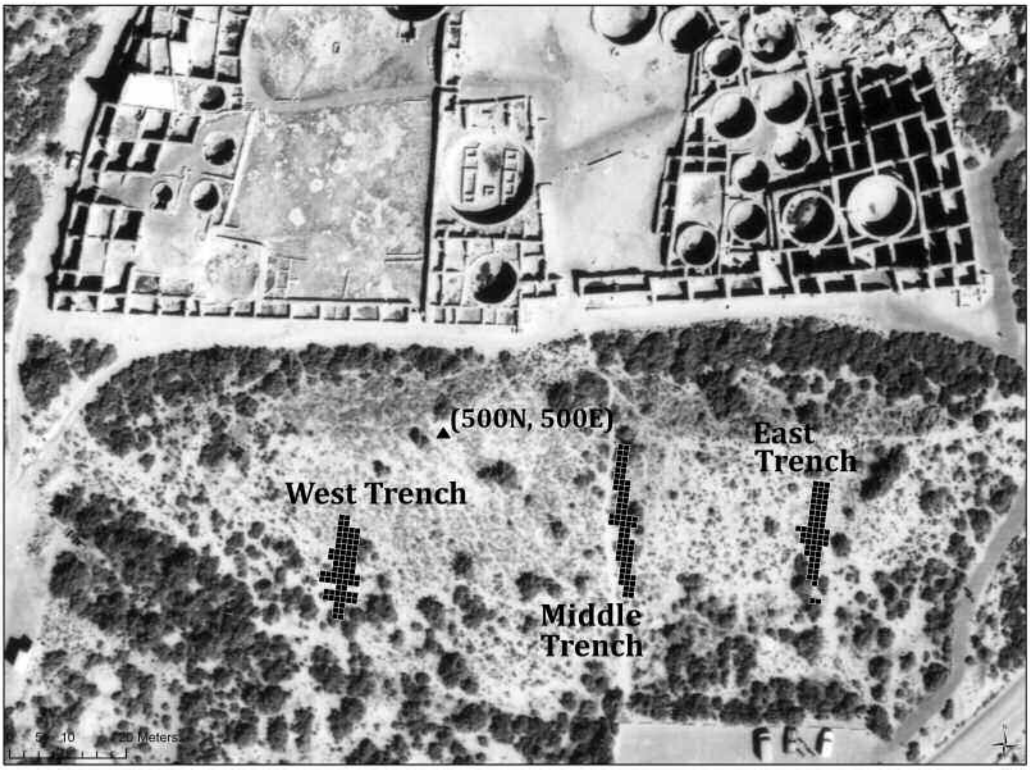

Figure 2. Location of the reopened sections of three NGS trenches south of Pueblo Bonito showing the arbitrary master datum (500N, 500E) on the West Mound and 2-x-2-m excavation units over the trenches.

phology and culture features surrounding Pueblo Bonito. In this report, we offer an interpretation of one part of this challenging empirical record for water control associated with Pueblo Bonito.

Background

The NGS trenches south of Pueblo Bonito were not excavated in order to explore the relationship between the great house and the floodplain (Supplemental Figure 1). Instead, NGS researchers hoped to find temporal ceramic sequences in the stratified deposits comprising the large earthen mounds (it would be decades before tree ring dating offered a chronometric alternative to ceramic seriation and deep tests). Famously, the Pueblo Bonito mounds proved inadequate compared to expectations derived from work in other parts of the Southwest (see Snead 2001), as researchers encountered a confusing mix of ceramic types attesting to rapid accumulation of secondary and possibly recycled deposits, including razed construction debris (Judd 1954; also Nelson 1920). After multiple tests and repeated extensions of the deep trenches over several seasons, Judd (1964:214) concluded that there was little value in the mounds for understanding Pueblo Bonito's history through ceramic seriation (Supplemental Figure 2).

However, portions of the trenches did provide surprising insights about the local environment during the Bonito Phase. In every trench and test pit excavated by NGS outside the architectural envelope of Pueblo Bonito, researchers found evidence for flowing water. Judd particularly noted very large water-worn channels under the mounds that apparently had in some places been "modified" by residents (Judd 1964:228–229). He suggested that during the early phases of occupation, precipitation runoff from behind the Chetro Ketl great house to the east flowed close to the south edge of Pueblo Bonito but was eventually "forced" away from the building onto the floodplain by piles of refuse and constraining masonry walls

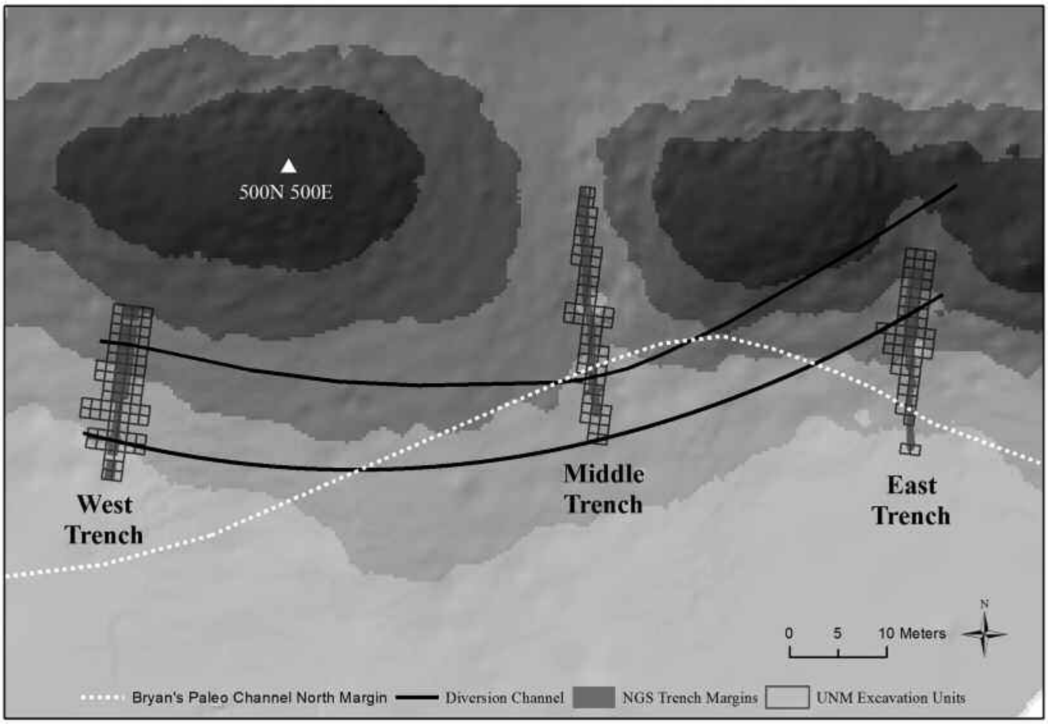

Figure 3. Projected line of prehistoric diversion channel and the edge of the Bonito paleo-channel. The reopened NGS trenches are shown as dark areas within the 2-x-2-m grid squares. The topographic surface model was derived from a total station survey at the completion of the project in 2007; shaded contour intervals ca. 70 m.

(Judd 1964:229; also Bryan 1954:45). It is important that Judd noted multiple channels, because while our report focuses on an exceptionally large artificially confined channel, it was one of at least several channels that were part of the immediate area around Pueblo Bonito.

Curiously, even though Judd was expressly concerned with the agricultural foundations of Chaco society, he was not very interested in the channels below the mounds and was generally skeptical that fields were irrigated by canals (he favored simple floodwater spreading systems). Indeed, although other channels were encountered and mapped by NGS in the Northeast Foundation Complex to the east of Pueblo Bonito, these did not warrant discussion in published reports. In the early 1970s, R. Gwinn Vivian excavated a number of small feeder ditches and head gates in several parts of the canyon (although not at Pueblo Bonito) that utilized side-canyon runoff, but these features were not associated with the large channels identified by Judd and Bryan (Vivian 1972, 1974, 1990, 1992; also Lagasse et al. 1984). Moreover, the head gates identified by Vivian were either undated or built in the twelfth century A.D. or later, following the explosive growth in great houses during the preceding eleventh century A.D. (Force et al. 2002). Thus, while Vivian's research clearly established that there were culturally modified or "engineered" water-control features near some great houses, large artificial channels were not directly connected to hypothesized field systems at Pueblo Bonito.

In contrast to their limited interest in the buried channels under the Pueblo Bonito mounds, Bryan and Judd were engaged with evidence for a deep natural channel in the southern portions of the East and West Trenches, which Bryan named the "post-Bonito channel." Bryan (1929, 1954) first identified the post-Bonito channel in the cut banks of the Chaco Arroyo and suggested that it formed late in the occupation of Pueblo Bonito based on associated ceramics. In 1924 and 1925, Judd expanded the West Trench and deepened an isolated test pit in order to provide Bryan with additional information about the position of the channel in relation to Pueblo Bonito (Bryan 1954:33). Force et al. (2002:9) renamed this channel the "Bonito Paleo-Channel Complex" and described it as a deeply entrenched, meandering stream channel 30–60 m wide, paralleled by smaller braided channels, which was incised sometime after ca. A.D. 900 and aggraded by ca. A.D. 1100. The factors that caused this channel to form are unknown (Hall 2010a; Love et al. 2011) but the existence of a deeply incised channel during the peak of great house construction in the A.D. 1000s suggests that the Bonito paleo-channel was *not* an impediment to economic growth.

The idea that a large erosional channel on the floor of Chaco Canyon might not have had negative consequences for the Bonito Phase economy is exactly the opposite interpretation offered by Bryan (1929, 1954) and Judd (1954, 1964), who thought that down-cutting signaled lower water tables and diminished farming potential (also Brand 1937; Diamond 2005). In contrast, recent geomorphological research indicates that deep channel incision in the floodplain can occur without lowered water tables (Friedman et al. 2014) and that the timing of the paleo-channel development is too ambiguous to be linked to specific economic changes or local depopulation (Force et al. 2002). Reopening the NGS trenches provided empirical data that resolve some of these issues and offer new insights about the complex physical environment in which Pueblo Bonito was built.

Methods

Chaco Canyon Alluvial Stratigraphy

The methods utilized in reexamining the Pueblo Bonito trenches were based on our assumption that previous research had revealed, however vaguely, a history of complex physical interaction between the construction and occupation of the great house and concurrent alluvial processes on the valley floor. Most of the exposed sediments in Chaco Canyon accumulated over the past 7,000 years. Hall (1975, 1977, 1983, 1988, 2010a,b) characterized this history in broad chronostratigraphic units (Figure 4). However, Love (1977, 1980, 1983) proposed that the entire canyon alluvium consists of two main sedimentary facies comprised, respectively, of headwater-derived sorted sands, silts and clays, and locally derived sediments. Main-stem deposits create discontinuous channel and overbank facies when confined in channels (predominately arroyos), whereas flood deposits spread laterally across the canyon floor when the valley alluvium is not incised. Side tributary pebbly sand fans formed throughout the Holocene and continue to extend onto the valley floor or into the arroyo inner floodplain today. At times, these alluvial fans blocked tributary-canyon re-entrants, preventing flooding from extending into tributaries, at other times floods "backed up" into small fan channels. As a result, the spatial evolution of the canyon floor is very complicated away from the valley center and toward the bounding cliffs and side drainages (Love 1977, 1983; Love et al. 2011; Wills et al. 2012; also Bryan 1929, 1954; Senter 1937).

In this study, we employ the following explicit assumptions. First, we take as given the essential role that surface water had in supporting, and perhaps catalyzing, the development of great house communities (see Vivian 1992). Second, we recognize that water also posed a significant danger with the potential to destroy field systems and inundate residential areas (e.g., consider Dorshow 2012; Huckleberry 1999; Waters and Ravesloot 2001). Third, any efforts to manage runoff and floodwaters as a critical resource, as well as to mitigate the dangers of flooding, probably had unintended consequences that may have created strong positive and negative feedbacks. Finally, the stratigraphic record of cultural occupation will be spatially complex, and therefore it is unreasonable to anticipate that a single excavation context or geological sampling location will provide a comprehensive historical understanding of water management practices.

Mapping and Excavation

A grid system (Supplemental Figure 3) was established with a master datum on the top of the West Mound with an arbitrary point of 500N, 500E, and an arbitrary elevation of 100 m (1871.451 m amsl). The grid was set so that the east-west lines would roughly correspond to the long axes of the two mounds and therefore is oriented slightly to the northeast. Pre- and post-excavation surface elevations were obtained with a total station, supplemented during and after the excavation by terres-

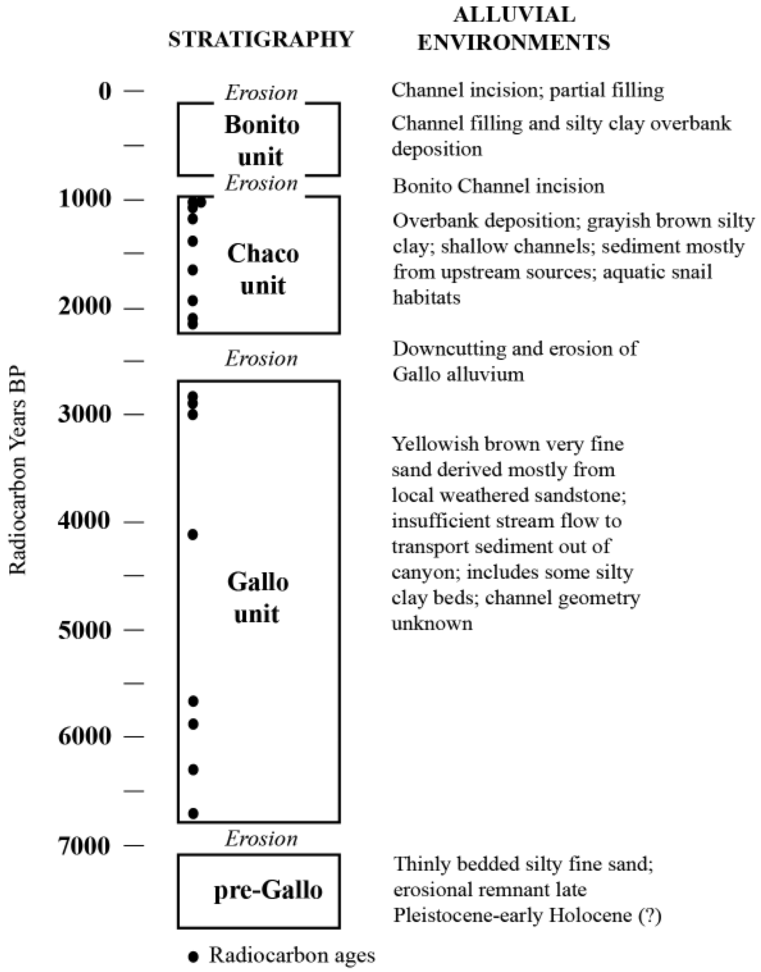

Figure 4. Summary of Chaco Canyon alluvial stratigraphy within Chaco Culture National Historic Park (adapted from Hall 2010a:244).

trial and airborne LiDAR. Grid locations and elevations were established on the trench walls using a laser level. Fill removal stopped before or at the base of the NGS excavations as required by the National Park Service, making it impossible to obtain a complete exposure of buried channel cross sections in each trench.

The grid system was superimposed on the original NGS map of trench locations (Judd 1964:Figure 23) in order to locate the edges of the excavation trenches. Initial excavation began with 20-cm levels in 2-x-2-m units and after the top edge of a trench was encountered, fill was removed in 20-cm levels within the trench. All trench fill was screened; 90 percent of each excavation level was screened through ¼-inch mesh and 10 percent through 1⁄16-inch mesh. The amount of archaeological material recovered from the trench fill (almost a quarter million objects) was unanticipated, and the time required to recover it properly reduced the volume of fill that could be excavated within the period of our research permit. All the artifacts were analyzed during a separate, National Science Foundation sponsored project initiated after completion of fieldwork (Crown 2016).

Samples

A team of paleo-environmental specialists was convened prior to excavation to design the sampling strategy for geological and biological data.

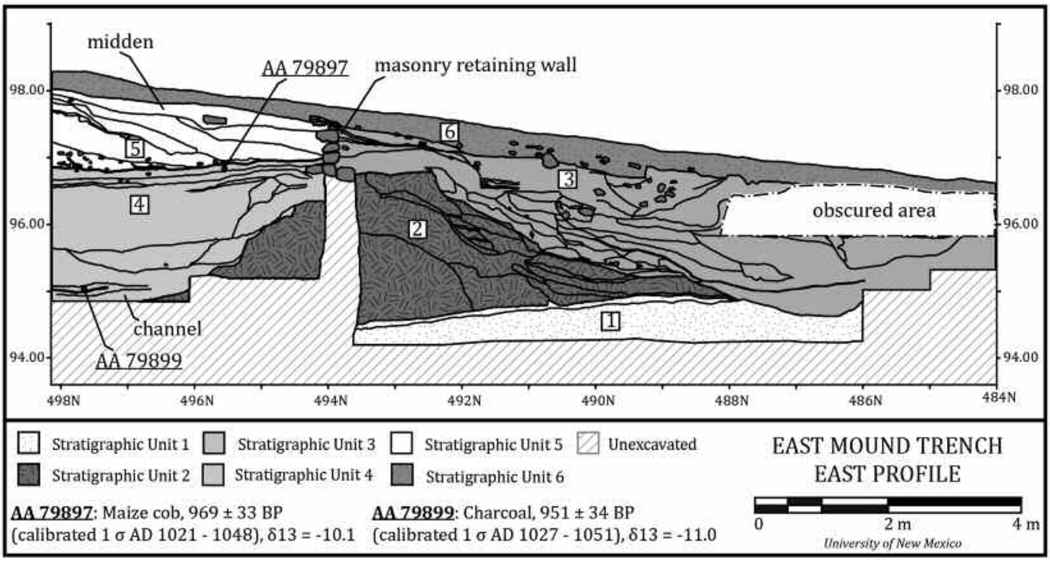

Figure 5. Stratigraphic Units identified in the East Mound Trench (details in text and Supplemental Table 1). Elevations from the site datum (500N, 500E, 100 m).

During the excavation, this same collaborative group removed and documented samples. These "integrated" samples (geology, macrobotanical, pollen, and microfauna collected simultaneously from the same location) represent a collective judgment by the team in the field about the data most relevant to understanding trench stratigraphy (Supplemental Table 1).

Initial geological field descriptions were made by David W. Love and all exposed sections were mapped, drawn, and photographed by field personnel. Individual strata were given Munsell color designations (wet and dry) during mapping and assigned to texture classes using a flow chart. Laboratory analysis of geological samples was conducted at the University of New Mexico by F. Scott Worman in the Earth and Planetary Sciences Department soil laboratory under the supervision of Professor Les McFadden. Distinctive groups of sediments evident in exposed trench sections were designated as "Stratigraphic Units," following Water's (1992:62–69) suggested guidelines for dividing lithostratigraphic sequences into recognizable and meaningful packages. Macrobotanical remains were identified by Karen Adams, pollen samples were analyzed by Susan Smith, microfaunal samples (ostracods) were analyzed by Manuel Palacios-Fest, and detailed stratigraphic interpretations in sample locations were made by David W. Love (Supplemental Figures 4–31; Supplemental Tables 2–4). Ceramic types that were collected in situ from mapped strata were identified by Hannah Mattson and Patricia L. Crown (Supplemental Table 5).

Results and Interpretations

Stratigraphy

East Trench. Six Stratigraphic Units (SU) were identified in the East Trench cross section (Figure 5; Supplemental Table 1). The lowest strata (SU 1) consisted of sandy loams that may be part of the tributary fan on which Pueblo Bonito was built. Sometime in the early to mid-A.D. 1000s, two parallel artificial banks (Figure 6; Supplemental Figures 4–6) were constructed on these sands to create a U-shaped (or "parabolic," following Purdue and Berger 2015) diversion channel (ca. 9 m wide at the top and 3 m deep) that carried a mix of main valley and tributary flows. The embankments canalized flows past the front (south side) of Pueblo Bonito and also protected the channel from overbank flooding originating on the valley floor. Channel fill consisted of thick water-lain strata left by repeated flashy floods rather than by slow moving water. Residents constructed a masonry wall (Figure 7; Supplemental

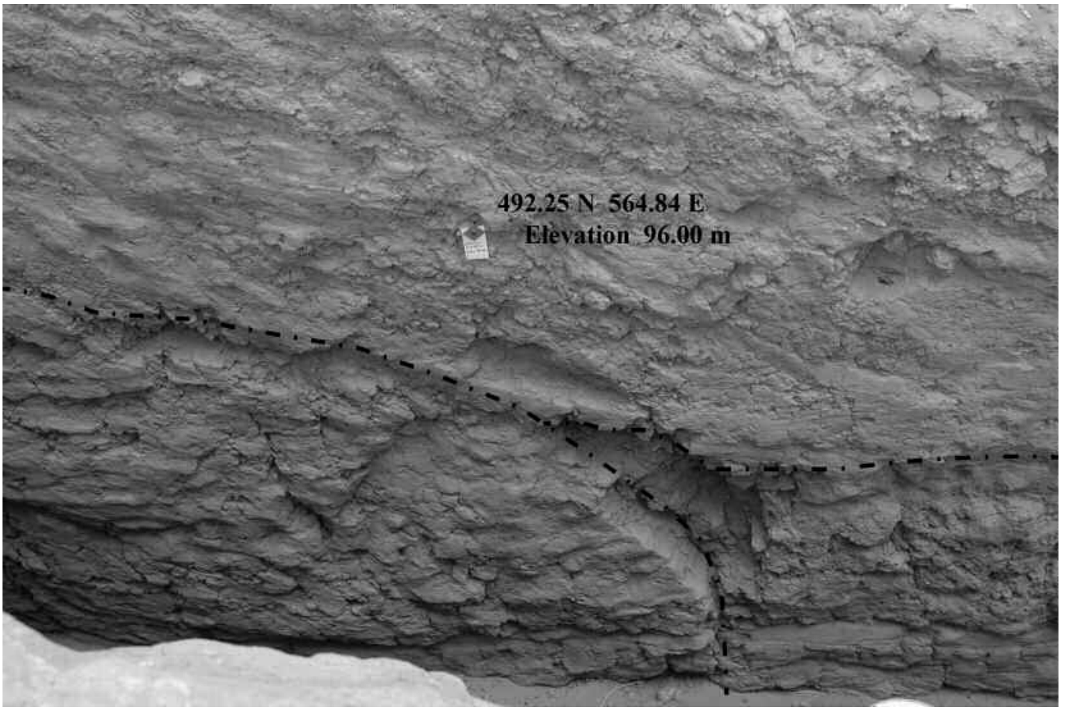

Figure 6. Detail of the artificial bank exposed in the East Trench, East Profile, SU 2, south side of masonry wall (see Figure 5).

Figure 7. Masonry wall built on top of SU 2 (artificial embankment) in the East Trench (facing south). The scale is 20 cm and the original excavation trench is visible behind the wall.

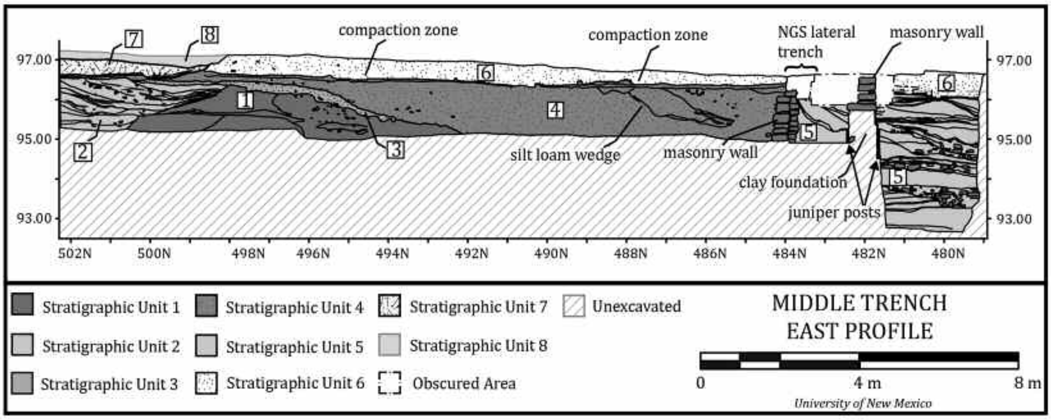

Figure 8. Stratigraphic Units identified in the Middle Trench.

Figure 2) on the south embankment as the channel filled in (we did not see evidence that the channel was cleaned out), but eventually water-lain sediments stacked up against this wall, at which point the channel and wall were buried by midden debris (SU 5) originating from the north (Supplemental Figure 7). Radiocarbon dates and ceramics are consistent with the burial of the channel in the late A.D. 1000s. At the same time that the channel was filling, overbank deposits from the floodplain were accumulating against the south side of the south embankment, reaching nearly the top of the masonry wall at elevations 50 cm higher than the last flows in the diversion channel.

Middle Trench. Eight Stratigraphic Units were defined in the Middle Trench, which was reopened along the entire length and depth of the original NGS excavation (Figure 8). The lowest exposed unit (SU 1) was a large man-made bank consisting of thick jointed layers of brown sands and clays that were intentionally piled up from floodplain overbank deposits. On the north side of this embankment were stratified anthropogenic layers that had accumulated in a shallow channel or swale with either slow-moving or standing water (Supplemental Figure 9). Stratigraphic Unit 3 was a thick layer of yellow sand that covered portions of SU 1 and 2 and contained abundant charcoal and ceramics dating to the late eleventh or early twelfth centuries A.D. (Supplemental Figure 10; Supplemental Table 5).

Stratigraphic Units 4, 5, and 6 reflect a complex interplay between floodplain dynamics and apparent cultural efforts to manage channel erosion. Briefly, the north edge of Bonito paleo-channel is evident in the far south end of the trench (SU 5) but NGS excavations did not expose the critical contact with earlier deposits, probably because excavators encountered a complicated set of masonry walls and juniper stakes at that juncture and left them in place rather than excavating below them. It is clear that a sharp, plunging boundary exists below the walls between SU 5, which are channel deposits containing large quantities of introduced rubble and SU 4, which was formed from overbank deposits prior to and following the down-cutting and aggradation of the Bonito paleo-channel (Supplemental Figure 11).

The north wall was built first and cross-bedded sand layers accumulated against it on the south (channel) side. Later, a more substantial wall was constructed ca. 1.5 m to the south inside the channel (Figure 12). This second wall was built on a foundation trench that was excavated into wet channel deposits (Supplemental Figure 13). Aggrading channel deposits continued to accumulate against the south side of the second wall until it was eventually breached, allowing valley floods to spread over both walls (SU 6) and to bury SU 4. Sometime after this flooding, a shallow channel (SU 7) formed at the north end of the trench, directly over the older channel (SU 2), indicating that water continued to flow or pond between Pueblo Bonito and the mounds.

Stratigraphic Unit 5 is notable for features that were constructed in the active edge of the Bonito paleo-channel. The geological layers in SU 5 are mainly brownish yellow cross-bedded sands fining

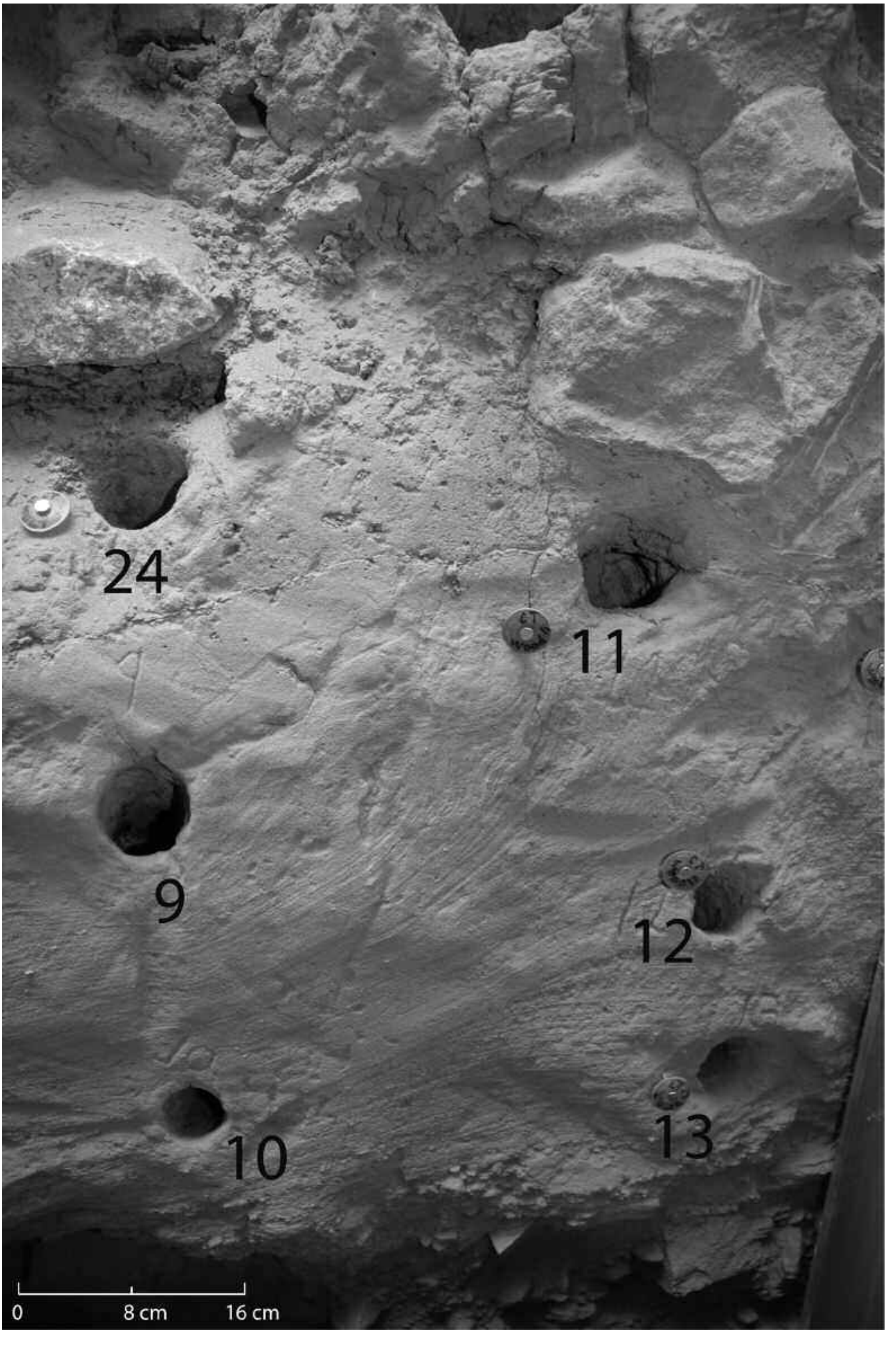

Figure 9. Middle Trench, SU 5 (Bonito paleo-channel fill) showing juniper post molds in cross-bedded sand below layer of introduced rock (numbers correspond to Supplemental Table 3).

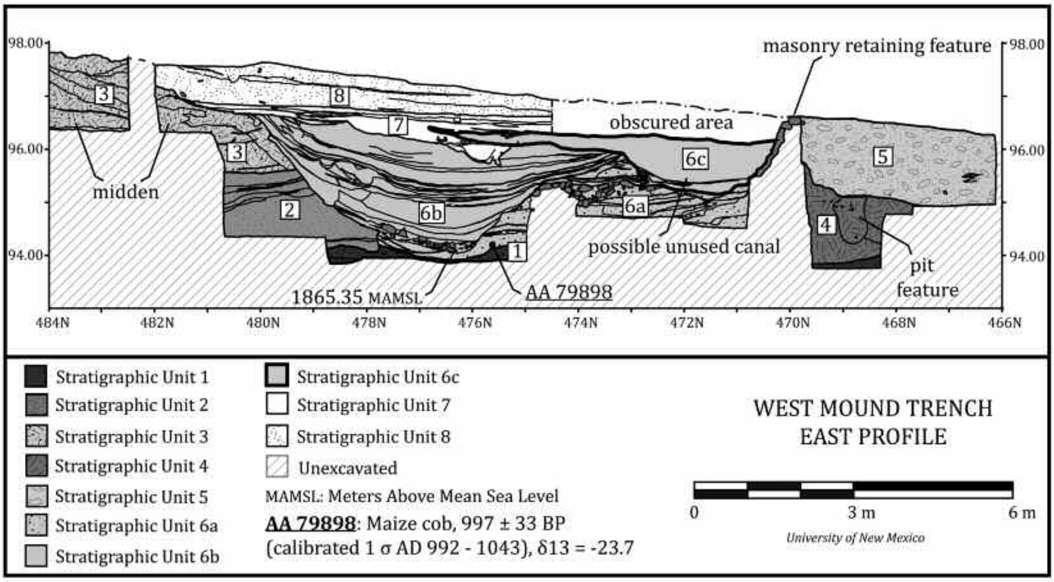

Figure 10. Stratigraphic Units identified in the West Mound Trench.

upward and capped by clay drapes (fine sediments deposited in slack water). At least four thick layers contain numerous large sandstone blocks (Supplemental Figure 11), and underlying one of these (between ca. 93.5 and 94.3 m) in cross-bedded sands were at least 25 juniper posts or stakes. Although the patterned arrangement of these juniper posts suggests a weir-like structure (Figure 9), and we are confident that these were designed as some sort of water control, we are prepared at this point only to note that they were intentionally set into the paleo-channel. Similarly, the two masonry walls along the upper edge of the paleo-channel blocked flowing water, whether as dams or revetments. Therefore, we think it is reasonable to interpret the complicated mix of cultural features and channel history as indications that residents were trying, repeatedly, to stop or reduce the advance of the paleo-channel toward Pueblo Bonito.

West Trench. There is a large channel in the West Trench (SU 6) that is similar in size (ca. 10 wide and 3 m deep) and base elevation to the diversion channel in the East Trench and is constrained on the south side by an artificial embankment (SU 4) formed by piling up sandy clay (Figure 10). The embankment has the same "muddy" appearance as the East Trench embankment and was also constructed on brownish yellow sands (SU 1). The north side of the channel does not have an artificial embankment but instead cut through thick beds of wind-reworked sands (SU 2) capped by a thick set of midden layers (SU 3). It is important to point out that the channel postdates the lower two-thirds of the midden, which consists of sandy loams containing abundant charcoal and ash, while the upper part of the exposed midden, which is characterized by dense amounts of construction debris, formed after the channel had aggraded.

We identified three distinct fill packages in the channel (SU 6a-c). Stratigraphic Unit 6a is the truncated remains of the earliest channel and is characterized by a mix of sandy layers containing abundant artifacts and charcoal. A radiocarbon date from the base of this unit indicates likely deposition in the early to middle A.D. 1000s (Figure 10). Notably, there is a dense concentration of sandstone rubble mixed with water-lain sediments in the upper part of the unit, overlain by multiple thin layers of gray clay (Supplemental Figures 15, 16). Judd (1964:219) believed that these rocks were collapsed masonry and mistakenly portrayed them as a typical Chacoan core-veneer masonry wall "erected to confine channeled floodwaters." Nevertheless, the rocks in SU 6a were introduced into an aggrading channel, much like a similar layer of rock at the base of SU 6b, as well as the rock layers in the Bonito paleo-channel fill in the

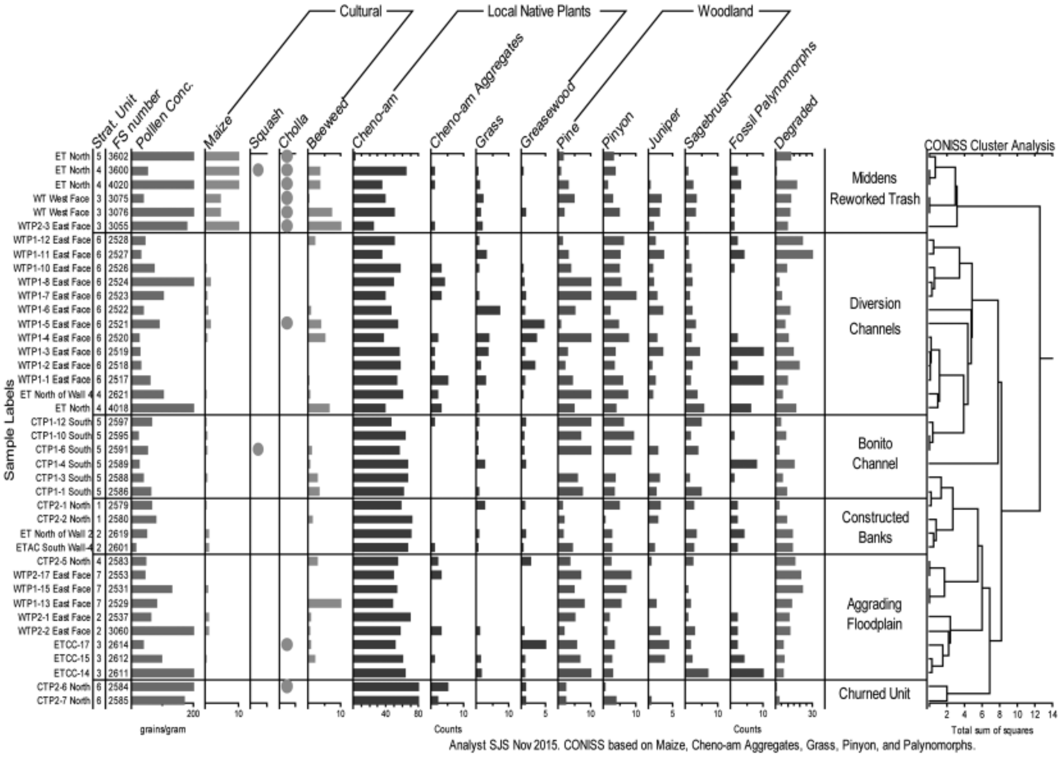

Figure 11. Summary pollen diagram showing cluster analysis dendrogram, percentages for dominant pollen types and counts of pre-Quaternary palynomorphs.

Middle Trench (SU 5). Rather than walls, these concentrations of rock appear to have been intentional efforts to line channel bottoms, possibly to reduce flow velocities in the center of the channels (see Purdue and Berger 2015:593). Unfortunately, Judd used this erroneous interpretation to project a wall along the entire south side of the West Mound (Supplemental Figure 1), which has been the basis for numerous architectural reconstructions (e.g., Stein et al. 2007).

Stratigraphic Unit 6b is the fill of a later channel that formed in the north side of the older channel. The rock layer at the base contains a number of ceramics that are stained orange, probably the result of iron oxides produced by stagnant water (see Huckleberry et al. 2012:501). A series of alternating upward fining sand and clay layers formed above the rock-lined channel bottom, mixed with thicker layers of unconsolidated clay chunks with rust coatings that are ripped-up clay beds redeposited from sources upstream (Supplemental Figures 17–21). Ceramics from SU 6b mainly date to the A.D. 1000s, but a sherd of Nava Black-on-white from the rubble at the base of the unit could indicate an early A.D. 1100s deposition (Supplemental Table 5). Discontinuous and oddly deformed localized pockets of midden occur along the north side of the channel that variously represent the slumping of eroded cultural material into the active drainage, intentional dumping of debris into the edge of the channel, or possibly excavation of clay from the channel by residents (Supplemental Figures 22, 23).

The third channel is a small parabolic canal that never carried water, constructed along the upper south edge of the original channel (Figure 10). Stratigraphic Unit 6c is the fill in this feature, comprised of massive structureless brown-gray fine sand containing large amounts of charcoal and numerous sherds. The base of the canal is a thin layer of gray clay that becomes a wedge on the south side containing large, unworked sandstone blocks, all of which was built on top of SU 4, the earlier artificial embankment (Supplemental

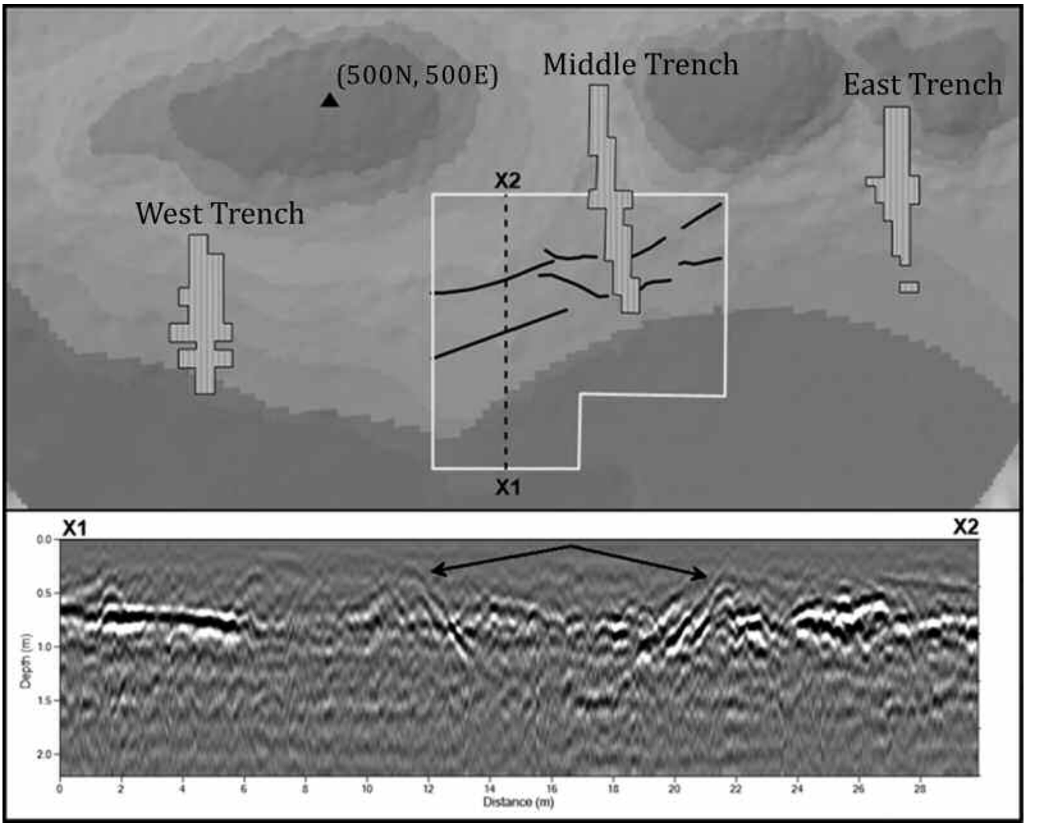

Figure 12. Projected Pueblo Bonito diversion channel west of the Middle Trench modeled from ground penetrating radar surveys. GPR reflection profile (vertical profile) showing the high amplitude, hyperbolic reflections from the edges of the channel and concave geometry of the channel body. This profile has been corrected for depth and processed to remove background noise. The channel in this location measures approximately 9 m across and reaches approximately 1.5 m in depth. Also seen nearby is the strong planar reflection from what might be possible architecture. This profile was collected using a GSSI SIR 3000 control system with 400 MHz antennas in a south to north direction, beginning at 460N 518E and ending at 490N 518E. This interpretation has not been confirmed by excavation.

Figure 24). We infer that the "wedge" was intended as a retaining wall or berm and was anchored to the underlying embankment, as Judd (1964:219) surmised. However, the top of the wedge, which is defined by a flat-lying course of rocks, does not extend laterally more than a meter either east or west, and therefore seems to have been more like a patch or reinforced section of the canal side rather than a linear feature. We know that the canal was never used to convey water because the fill (SU 6c) contained no fluvial sediments, only fine sands mixed with charcoal, ash, and ceramics.

After the small canal was built or even while it was being constructed, main valley flooding left thick, poorly sorted deposits containing ripped-up clasts of laminated fine sand, gravel lenses, and moderately large rocks against the south side of the clay wedge (SU 5). Extrapolating from Judd's (1964:Figure 24) published profiles and unpublished field notes, the Bonito paleo-channel's edge eroded into SU 5, which means the paleo-channel post-dates SU 6a-c (Supplemental Figure 32).

Stratigraphic Unit 7 is a series of water-lain deposits that formed along the top of SU 6b, attesting to a renewal of shallow flows in the channel line after a hiatus of unknown (but probably brief) duration. Stratigraphic Unit 7 is partially separated from SU 6b by a lateral finger of SU 6c, which may reflect deliberate excavation by the canal builders to extend the north side of the canal. The fact that shallow flows continued to form SU 7 *after* the unused canal was filled with sand and midden points to intentional and rapid filling of the canal; in other words, it may have been filled in so that surface water originating in main valley floods could still flow along the channel line. The uppermost part of SU 7 contains a small rivulet at the edge of the midden (SU 3) that followed a course that had been created when residents cut away part of the midden deposit (Supplemental Figures 25–27). It is not clear from where the water in this very small channel was coming (the floodplain is likely, but it is not impossible that water was directed off the sloping south side of the West Mound), but residents obviously worked to keep it open.

Stratigraphic Unit 8 caps the channel complex, extending from the edge of the midden (SU 3) to the top of the clay wedge associated with SU 6c (Figure 10). This unit consists mainly of undifferentiated aeolian fine sand with a light mix of ash, charcoal, and artifacts. Some of this material is certainly derived from the mound surface as a result of extensive disturbance during excavations and subsequent surface creep, but the absence of historical material in the profiles indicates that most of the unit is prehistoric. And because SU 8 is the last prehistoric depositional unit, the southern-most edge of the West Mound during the Bonito Phase was at the juncture of SUs 3, 7, and 8 (Figure 10, between 481 and 482 N), or ca. 8 m north of the south retaining wall drawn by Judd (Supplemental Figure 1). This revised south edge conforms to the topographic surface derived from airborne LiDAR and total station survey (Figures 1, 3).

Micro-Invertebrates. Molluscs and ostracodes are useful for understanding the quality of water and paleohydraulics in canals and reservoirs because different species are associated with particular chemical and hydrological conditions. The identification of prehistoric irrigation canals in southern Arizona has been linked to the ecological correlates of micro-invertebrates (Adams, Smith, and Palacios-Fest 2002; Bayman et al. 2004). A total of 40 samples were analyzed from the three Pueblo Bonito trenches, but none produced micro-invertebrate fossils. The absence of common gastropods found in standing water indicates that water did not remain in the channels for very long, and the absence of fragments of these organisms implies that they were also absent in the source areas for flows. Coarse grain size (Supplemental Figure 28) from SU 6b in the West Trench indicates fast, short-term discharge rather than slow-moving water.

Macrobotanicals. A total of 42 flotation samples were analyzed. The charred plant specimens in these samples (Supplemental Table 2) reflect a strong cultural signal of maize, wild economic plants, and fuel sources typically found in prehistoric sites on the Colorado Plateau. Twenty-five macrobotanical samples from the Bonito paleochannel (Middle Trench SU 5) preserved uncharred juniper (*Juniperus*) branches that were relatively straight and regular in diameter (~10 growth rings each), qualities considered important for a weir (Supplemental Table 3). This record of larger archaeological plant remains is consistent with the expected range of plants naturally occurring in the canyon in the past, as well as species recovered from previous Chaco Canyon excavations (Toll 1985). Although most of the analyzed specimens were charred, a large number of uncharred cheno-am (*Chenopodium* and/or *Amaranthus*) seeds were recovered from Unit 6b in the West Trench, above elevation 95.50 m (Figure 10), suggesting late summer or early fall flood events.

Pollen. Alluvial palynology in the Southwest is particularly challenging because of the various pathways through which pollen grains may enter sediment, including atmospheric pollen rain and redeposition via flood-churned sediment, material introduced through sheetwash, and reworked aeolian sediment (Adams, Smith, and Palacios-Fest 2002; Hall 1975). In the case of the NGS trenches, an overlay of human disturbance that included trash dumping and construction of water-control features adds another complication. The question of greatest interest for the pollen research is whether distinct signatures can be recognized and related to sedimentary units (Supplemental Table 1) and depositional processes.

Thirty-four distinct pollen types and a category of fossil palynomorphs were documented from the 58 samples collected from strata and units exposed in the reopened NGS trenches (Supplemental Table 4). One clear result from the recovered spectra is the absence of any riparian or aquatic taxa, except for single pollen grains of sedge family (*Cyperaceae*) in three samples. The relative lack of water plants complements the micro-invertebrate and sedimentary evidence that indicates that canal flows were flashy, episodic events with no perennial flow or persisting pools.

Analysis of the pollen data led to interpretation of five sensitive taxa: maize (*Zea mays*), pinyon type (*Pinus edulis*), grass (*Poaceae*), aggregates of cheno-am pollen, and fossil palynomorphs. Palynomorphs are pre-Quaternary spores and pollen derived from erosion of Cretaceous sedimentary layers visible in the cliffs bounding Chaco Canyon and its tributaries (Hall 1975). These microfossils are reworked and transported by wind and water, and redeposited in alluvial and colluvial sediment. The term *cheno-am* is an abbreviation for a generalized botanical category representing several plants, all of which produce abundant wind-blown pollen. Nearly every project sample is overwhelmed with cheno-am pollen, which is attributed to the dense saltbush (*Atriplex canescens*) community that, with greasewood (*Sarcobatus vermiculatus*), is the main vegetation bordering Chaco Wash and covering lower canyon slopes, including the Pueblo Bonito mounds (Mathien 2005:38). Aggregates (clumps) of cheno-am pollen proved a more robust variable for statistical analyses than overrepresented, single-grain cheno-am. Aggregates are interpreted to reflect on-site flowering plants, and therefore, carry a strong seasonal signal, which for cheno-am is late summer into fall.

The five sensitive pollen types were used in a statistical cluster analysis (CONISS; Grimm 1987) calculated with 40 of the project samples organized by stratigraphic units (Supplemental Table 2). Excluded were samples evaluated as sterile ($n = 4$) and from ambiguous contexts ($n = 14$), for example ripped-up clasts and locations on or straddling stratigraphic boundaries.

Samples from trash dumps and pockets of reworked midden form a unique statistical group (Figure 11), based on abundant maize and less native taxa, compared to other contexts. One of the East Trench midden samples (FS 3602, SU 5) yielded 200 maize grains out of a total count of 255 pollen grains. Midden samples with high maize also register three other economic types, squash (*Cucurbita*), cholla (*Cylindropuntia*), and beeweed. The annual beeweed thrives in disturbed ground and is an important ethnobotanical resource (Adams, Stewart, and Baldwin 2002). Beeweed is rare in the modern landscape, but a few plants were observed in 2006 growing along the main Chaco Wash arroyo (Figure 1). During the eleventh century, this weedy plant might have proliferated along canal borders, in dry channels between flows and on local soils disturbed by cultural activities. A low background expression of one to two maize grains is present in greater than a third of the samples and is interpreted to reflect reworked and redeposited midden and surface sheet-trash.

Diversion channel samples cluster within a second statistical group, defined by slightly enhanced palynomorphs, and enriched representation of grass and cheno-am aggregates, which reflect local native plants. The cheno-am aggregate imprint indicates that canals were flowing sometime between late summer and early fall, which is the season when saltbush and other common cheno-am plants flower in response to summer monsoons. Greasewood, another local floodplain element and summer-flowering species, is also notable in the diversion channel group.

Samples from stratigraphic units interpreted to represent aggrading floodplain and constructed banks, which are the berms and other features built to confine canal channels, are loosely correlated. These two contexts are characterized by low grass and generally lower piñon and absence of cheno-am aggregates. Two pollen samples were taken from SU 6 in the Middle trench, which capped exposures described as churned and compacted aeolian sediment (Supplemental Table 1). These two samples are distinct from other contexts due to almost pure cheno-am content (greater than 80 percent of counts). The most dissimilar of all samples analyzed are the six samples collected from the Bonito paleo channel (Middle Trench, SU 5). The only consistent trait within SU 5 is, with one sample exception, the absence of cheno-am aggregates.

Concordance

The NGS trenches reveal a complicated cultural interaction with an active alluvial floodplain that included multiple water channels around Pueblo Bonito whose residents clearly intended to direct surface water past the great house. We do not know for certain whether the channels evident in the East and West Trenches were sections of a single diversion feature destroyed by the Bonito paleo-channel, or whether there were originally two separate channels before the paleo-channel eroded close to Pueblo Bonito. Either alternative is plausible, and in this section we consider the likelihood of each.

Single Channel Model. The East and West trench cross sections each exhibited a channel ca. 10 m wide and 2.3 m deep containing multiple episodes of flood deposits constrained by man-made embankments of similar size, composition, and construction. Radiocarbon dates and in situ ceramics in both cross sections point to channel filling in the middle to late A.D. 1000s. We were unable to examine the entire canal cross section in the East Trench, but the *exposed* fill sequences and constituents do not match any part of the more complete exposure in the West Trench. However, it is possible that the lower portion of the East Trench fill was similar to the lowest layers in the West Trench, based on NGS profile drawings and notes indicating laminated sands overlying a concentration of rock and "construction debris" at the base of each channel cross section (Supplemental Figure 29). The lowest stratum in the West Trench channel (SU 6a) has a slightly earlier radiocarbon date than the upper fill in the East Trench channel (SU 4), which suggests that in both sections the *initial* channel use occurred in the first half of the eleventh century. Each trench channel cross section shows that dense cultural material was introduced (intentionally or by erosion) into sediments along the north side, some of which was reworked by flowing water, creating very complicated locally variable deposits.

We found no indication in the Middle Trench of a channel constrained by artificial mud embankments but ground penetrating radar showed a buried channel just west of the Middle Trench that matches a line independently projected between the East and West Trench channel cross sections based on the edges of the diversion channel exposed in the profiles (Figure 12). This buried channel is the same width and depth as the diversion channel cross sections in the East and West Trenches. The curve in the projected line might reflect an effort by builders to avoid cutting into the large West Mound midden (or an earlier, deeper midden identified by Judd [1964:Figure 7]). Apparently the Bonito paleo-channel destroyed the diversion channel in this location.

The destructive impact of the Bonito paleo-channel between the two mounds could explain the different channel stratigraphic sequences in the upper portions of the East and West profiles. If a single diversion channel was intercepted by the Bonito paleo-channel, water may still have entered the eastern portion but then spilled into the paleo-channel rather than continuing westward (which might account for distinctive layers of cultural material identified by Bryan (1954:35, 58) in the paleo-channel exposed in the Chaco Arroyo about 40 m to the southeast). The unused small ditch in the upper south portion of the West Trench cross section (Figure 10, Unit 6c) may have been built before this breach and consequently never carried any water.

Eventually the aggrading paleo-channel buried the western part of the diversion channel in overbank deposits. The Bonito paleo-channel erosion into the mound area and subsequent aggradation must have occurred in the mid to late eleventh century, or later, which is consistent with Judd's depiction of the paleo-channel edge location in the West Trench (Supplemental Figure 30), where it post-dates SUs 5 and 6 (Figure 10).

It is possible that water was diverted into the diversion channel ca. 200 m upstream, where an NGS trench revealed a similar-sized channel flanked by at least one likely embankment in the "Far East Trench" (Judd 1964:Figures 11, 24). However, the "ripped-up" layers of reworked clay in the West Trench (in SU 6b; Supplemental Figure 18) are difficult to explain as the result of long distance transport and more parsimoniously point to floodwater entering the diversion channel at a closer point.

Multiple Channels Model. An alternative to the single canal model is two separate channels that were not connected and had different sediment sources. That is, the channel cross-sections in the East Trench (SU 4) and the West Trench (SU 6) do not represent parts of the same feature. The main reasons for entertaining this alternative are the lack of correspondence between the upper sections of the two trench channel cross sections and the presence of multiple buried channels around

Pueblo Bonito. Two unconnected diversion channels imply that surface flows were captured at multiple locations and directed westward past the great house, but also that the Bonito paleo-channel cut *between* two distinct diversion features, perhaps at the intake point for the west channel.

For the moment, our view is that the probability of two separate diversion channels is very low, given the preponderance of empirical similarity between the East and West Trench channels (especially embankments, elevations of features, and GPR data) and that the differences in upper channel fill are better explained by the effect of the Bonito paleo-channel. However, this area around Pueblo Bonito experienced an extremely complicated alluvial history, and without a complete exposure of the diversion channel in the East Trench it will be impossible to dismiss a two-channel model.

Conclusions

Pueblo Bonito was built on an alluvial fan formed by tributary runoff from Alto Mesa (Figure 1) on the edge of an active floodplain, a combination that provided immediate access to water but also posed significant risks from flooding. In reopening the NGS trenches, we documented channel cross sections in the East and West Trenches that we interpret as parts of a single diversion channel that was bisected by the Bonito paleo-channel in the second half of the eleventh century A.D. The diversion channel has sedimentary features and pollen that connect it with upstream sources beyond Pueblo Bonito. Sedimentary structures composed of fine sand in the diversion channel show that the lower flow regime had time to sort the sand from silt and clay and to create and rework ripple- and plane-bed cross-laminated features and fining-upward sequences (due to relatively high flow resistance under multiple aggrading waning flows). The diversion channel was controlled initially by the construction of artificial embankments built by excavating and transporting large amounts of poorly consolidated alluvium.

The pollen analyses demonstrate correlations (Figure 11) that support the geologic interpretations and suggest additional insights into the eleventh century environment at Pueblo Bonito's front door. A strong local pollen spectra imprinted with a late summer signature from the well-defined diversion channel exposed in the West Trench (Unit 6b) is unique among all of the stratigraphic units sampled and contrasts with the Bonito paleo-channel samples (Middle Trench, Unit 5), which may signify a different catchment source for the diversion channel versus the Bonito channel and aggrading floodplain deposits.

The Bonito paleo-channel extended to the edge of the mound area in the Middle Trench, at which point it destroyed the diversion channel. The paleo-channel edge is steep in the Middle and West Trenches, consistent with Bryan's cross sections (Supplemental Figure 31), and may therefore indicate initial incision, although it is possible but less likely (given the nearly vertical edges) that the Bonito paleo-channel widened at the top during aggradation (see Friedman et al. 2014). The Bonito paleo-channel is evident in the south end of all three trenches, stratigraphically post-dating the earlier channels (also Bryan 1954:61 and Hall 2010a, b) and thus these multiple lines of evidence do not support a cutting interval of ca. A.D. 900–1025, as hypothesized by Force et al. (2002:35).

We cannot determine whether the water diverted through the diversion channel was intended for agriculture, although the soils immediately west of Pueblo Bonito are sandy loams suitable for cultivation and may have been farmed in the past. Repeated episodes of ponded water during the Bonito Phase are evident in alternating layers of sand and silty clay exposed in test pits in the Wetherill trading post area on the west side of the great house, indicating some standing water during eleventh century construction and possibly a shallow reservoir. Given the huge demand for water associated with the construction and occupation of Pueblo Bonito (ca. 40 percent of overall architecture by volume was mud, adobe, or plaster; see Vivian 1992), a nearby reservoir would have been tremendously useful and perhaps essential for construction. Indeed, because water was a critical constituent in great house construction but was seasonally variable and extremely difficult to transport, it is very likely that the size and complexity of individual great houses was a direct function of how much water could be confined near buildings (see Vivian 1992; Wills 2001).

On the basis of these observations, we favor the following scenario. First, during the early A.D. 1000s, water from valley and tributary flooding was diverted past Pueblo Bonito in one or more modified channels, which may have already existed as natural features on the floodplain. In the middle to late A.D. 1000s, the Bonito paleo-channel entrenched and intercepted a large diversion channel along the south side of the Pueblo Bonito mounds but then rapidly aggraded and was filled by the late A.D. 1000s or early 1100s. Thus residents were actively constraining water flows around Pueblo Bonito during the time when the great house was expanding most rapidly, and occupation and construction continued throughout the period when the paleo-channel incised and filled (see Lekson 1984; Love, et al. 2011).

It is understandable that Chaco researchers often equate an incised flood plain with poor conditions for agriculture as historically this has occurred throughout the American Southwest (e.g., Bryan 1954; Dean 1992:39). However, when the Chaco main valley is not incised, floodwaters spread relatively impermeable clays over local sand fans and other arable zones, and inundate local low-lying spots, thus *reducing* potential farming areas, as evident in the burial of field head gates after the Bonito paleo-channel filled (Force et al. 2002:33). Most of Pueblo Bonito and all of the other Classic Bonito Phase (A.D. 1020 to 1100) structures in Chaco were built when canyon headwaters were mainly confined to a single deeply incised channel rather than spreading laterally in shallow braided streams (see Force et al. 2002; Love 1977:300; Love et al. 2011). Therefore, the Bonito paleo-channel system might not have had the sort of negative impact on farming that is conventionally assumed and could have been generally beneficial by preventing floodwaters from reaching fields and buildings. The Pueblo Bonito diversion channel may have mitigated flood damage until it was breached; Judd (1959:172) suggested a similar role, and fate, for a masonry wall bordering the Pueblo del Arroyo great house a few hundred meters to the west of Pueblo Bonito (Figure 1). However, we are not arguing that empirical evidence shows that entrenchment of the valley floor was a *positive* factor for Chaco farmers, only that it is worth considering whether the unique geological and hydrological characteristics of the canyon offered a complex production environment that was not affected by valley erosion in the same way as other parts of the American Southwest.

In addition to the diversion channel and the edge of the channel exposed in the north end of the Middle Trench (SU 2), the NGS profiles (Judd 1964: Figures. 7, 24) suggest a number of additional buried channels at varying depths running in front of Pueblo Bonito and possibly under the southern block of rooms. Judd (1964:219) noted under the West Mound a "purposeful dump of construction debris that has been eroded, both north and south, by water action" and covered by a "puzzling" silt surface. We cannot confirm these observations, but they are consistent with the intentional placement of Pueblo Bonito in a very dynamic hydrological environment.

It is conceivable that the Pueblo Bonito diversion channel was initially designed to capture tributary runoff before it was lost to the paleo-channel. Once the Bonito paleo-channel had filled and overbank flooding resumed, the diversion channel was no longer effective and perhaps unnecessary. Shallow channels overlying the filled diversion channel and cutting into the accumulating midden deposits reflect subsequent local modest flooding regimes with shifting channels around Pueblo Bonito. As we try to make sense of this complexity, we feel that it is useful to remember that the surface of the modern floodplain in Downtown Chaco was created after the Bonito paleo-channel filled, perhaps largely after the A.D. 1200s (Hall 2010a; Love 1983) and that much, if not most, of the land surfaces used by great house residents have been buried and are not visible today except in erosional cuts or archaeological excavation units.

Unfortunately, while the three reopened trench sections provide new insights into the complexity of water management around Pueblo Bonito, the data are too limited to resolve some of the critical structural questions, especially the length of the diversion channel, likely intake points, and whether flows were simply diverted away from the great house or actively directed to catchments or fields. Still, this research shows that canyon residents were engaged in complicated landscape modification around the Downtown Chaco great houses in ways that have not been previously appreciated by archaeologists. The next step in our continuing efforts to understand how the emergence of great house communities in Chaco was connected to this more expansive picture of water management requires obtaining a comprehensive spatial and chronometric picture of such efforts within the broader scope of architectural development in the canyon core.

In the interim, it seems important that surface water was flowing through artificial and natural channels in the midst of Downtown Chaco, and that some of the architectural features evident today were built to direct or protect those channels. In other words, the landscape engineering that occurred around Pueblo Bonito, Chetro Ketl, and Pueblo del Arroyo was partly and perhaps immediately a function of the environmental potentialities associated with the intersection of mesa top runoff and floodplain hydrology. There are examples of historical Pueblos where streams run through the center of the village (Taos and Zuni) and of communities forced out of flood zones (Kewa Pueblo/Santo Domingo) but none to our knowledge where the residential building(s) was placed directly in the dynamic interface between water from large catchments spilling over cliffs immediately adjacent to the structures and then mixing with a discontinuous, shifting main valley stream system.

Emergent complex societies have a well-known connection to rivers with respect to irrigation farming, but there is a growing sensitivity among prehistorians that the complicated archaeological records for these coupled processes need to take into account more than just agricultural potential. In a pioneering example, Bar Yosef (1986) argued that the famous walls at Jericho were originally built as a barrier to flooding. Similar explorations of floodplain dynamics and socioeconomic change in developing complex societies have occurred in Africa (Macintosh 2000) and at Çatalhöyük (Boyer et al. 2006), and there is an ongoing debate about the role of seasonal inundation in the establishment of Cahokia as a regional polity (Baires et al. 2015; Munoz et al. 2015). In short, irrigation agriculture is not the only landscape modification in fluvial arid environments that is relevant to the formation of complex societies, including Chaco Canyon.

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Supplemental Materials. Supplemental materials are linked to the online version of this paper, which is accessible via the SAA member login at www.saa.org/member-login.

Supplemental Figure 1. Location of National Geographic Society trenches in the "South Refuse Mounds."

Supplemental Figure 2. Reexcavation of the East Trench in the East Mound in 2006.

Supplemental Figure 3. Grid system with arbitrary master datum at 500N, 500E, on the West Mound.

Supplemental Figure 4. East Trench, East Profile, with sample locations.

Supplemental Figure 5. East Trench, East Profile, Stratigraphic Unit 2, sample.

Supplemental Figure 6. East Trench, East Profile, sample locations in the upper portion of Stratigraphic Unit 2.

Supplemental Figure 7. East Trench, East Profile, portion of Stratigraphic Unit 5.

Supplemental Figure 8. Middle Trench, East Profile with sample locations (FS numbers).

Supplemental Figure 9. Middle Trench, East Profile.

Supplemental Figure 10. Middle Trench, East Profile.

Supplemental Figure 11. Middle Trench, West Profile, Stratigraphic Unit 5, showing sample locations and large rocks introduced to the Bonito paleo-channel.

Supplemental Figure 12. Middle Trench, North and South Masonry Walls in the fill of the Bonito paleo-channel (Stratigraphic Unit 5).

Supplemental Figure 13. Middle Trench, Stratigraphic Unit 5, North Profile Face.

Supplemental Figure 14. West Trench, East Profile face, with sample locations.

Supplemental Figure 15. West Trench, East Profile, Stratigraphic Unit 6a (facing south).

Supplemental Figure 16. West Trench, Stratigraphic Unit 6a (facing south) sample locations.

Supplemental Figure 17. West Trench, East Profile, Stratigraphic Unit 6b, sample locations.

Supplemental Figure 18. West Trench, East Profile, Stratigraphic Unit 6b.

Supplemental Figure 19. West Trench, East Profile, Stratigraphic Unit 6b, sample locations.

Supplemental Figure 20. West Trench, East Profile, Stratigraphic Unit 6b, sample locations.

Supplemental Figure 21. West Trench, East Profile, Stratigraphic Unit 6b, sample locations.

Supplemental Figure 22. West Trench, East Profile, Stratigraphic Unit 6b.

Supplemental Figure 23. West Trench, East Profile, detail of portion of Stratigraphic Unit 6b.

Supplemental Figure 24. West Trench, West Profile, Stratigraphic Unit 6c.

Supplemental Figure 25. West Trench, West Profile, Stratigraphic Unit 7.

Supplemental Figure 26. West Trench, East Profile, upper part of Stratigraphic Unit 3.

Supplemental Figure 27. West Trench, West Profile, upper part of Stratigraphic Unit 3.

Supplemental Figure 28. Grain-size distribution for Stratigraphic Unit 6b, East Face, West Trench, with sample identifications.

Supplemental Figure 29. East Mound Trench, East Profile, showing correspondence between the section mapped by the University of New Mexico and the original NGS profile map.

Supplemental Figure 30. West Mound Trench, East Profile, showing correspondence between the section mapped by the University of New Mexico and the original NGS profile map.

Supplemental Figure 31. Comparison between section of the Bonito paleo-channel described by Bryan near the Kin Kletso great house and the likely edge of the Bonito paleo-channel underneath masonry walls at the south end of the Middle Trench.

Supplemental Table 1. Stratigraphic Unit Descriptions and Interpretations.

Supplemental Table 2. Contextual details for integrated analytical samples.

Supplemental Table 3. Middle Trench, Stratigraphic Unit 5 (Bonito paleo-channel) botanical identifications.

Supplemental Table 4. Pollen Data Raw Counts.

Supplemental Table 5. Ceramic Identifications by Trench and Stratigraphic Unit.

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