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Evaluating soil salinity and water management in Chaco Canyon, New Mexico

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ABSTRACT

Previous studies in Chaco Canyon, New Mexico suggested that water management systems constructed during periods of increased aridity resulted in elevated salinity levels to the point that soils were no longer viable for growing cultigens. Salinity, pH, powder X-ray diffraction, and inductively coupled plasma atomic emission spectroscopy analyses of sediments and water collected from Chaco Canyon between the years 2013 and 2015 demonstrate conclusively that soils were suitable for the cultivation of maize by Ancestral Puebloans. Our findings clearly indicate that the salts are non-deleterious sulfate minerals. All of the cations and anions needed to form these minerals occur in the water of Chaco Canyon. Thus, increased soil salinity was not a critical factor in the abandonment of Chaco Canyon by Ancestral Puebloans. Sulfate and volcanogenic minerals increased soil fertility that allowed for the development and maintenance of an agricultural urban center in this dryland environment. Water management of sulfate and volcanic mineral rich soils created an environ ideal for maize agriculture. The occurrence of non-local Ancestral Puebloan maize in Chaco Canyon can be explained in terms of kinship mobility, the distance that goods and services move between extended families.

1. Introduction

Puebloans live in the four corners area of the United States and include speakers of the Hopi, Keresan (Acoma, Cochiti, Laguna, San Felipe, Santa Ana, Santo Domingo, Zia), Tewa (Hano, Nambe, Ohkay Owingeh, Pojoaque, San Ildefonso, Santa Clara, Tesuque), Towa (Jemez), Tiwa (Isleta, Picuris, Sandia, Taos), and Zuni languages. Between 800 and 1250 CE (Pueblo I, II, and III), Ancestral Puebloans built an expansive, hierarchical society in the drylands of Chaco Canyon in New Mexico (Fig. 1, Table 1). Chaco Canyon is located in the central San Juan Basin of northwest New Mexico, a region of aridity and water scarcity even in the best of times. In this dryland setting, Ancestral Puebloans constructed massive, complex, multistory stone buildings called pueblos, which served as housing, food and water storage, and ceremonial centers. Pueblos were built even during periods of severe droughts, which occurred between 1140 and 1190 CE, in the late 1300s CE and at about 1450 CE, although the total area inhabited by Ancestral Puebloans dropped substantially over that time period (Vivian, 1990; Lekson, 2006; Plog, 2012).

Previous archaeological research at Chaco Canyon suggests that water management systems, e.g., canals, furrows and reservoirs, constructed during periods of climate change and increased aridity, elevated soil salinity levels to the point that agricultural fields were no longer viable for growing cultigens such as maize (Judd 1964; English, 2001; Benson et al., 2006, 2009; Benson, 2010; Worman and Mattson, 2010). These investigations further suggest that levels of salt pollution rose until storable cultigens had to be imported and eventually led to the depopulation of Chaco Canyon by most Ancestral Puebloan occupants by the mid-1100s CE. Stable strontium isotope analysis of maize cobs

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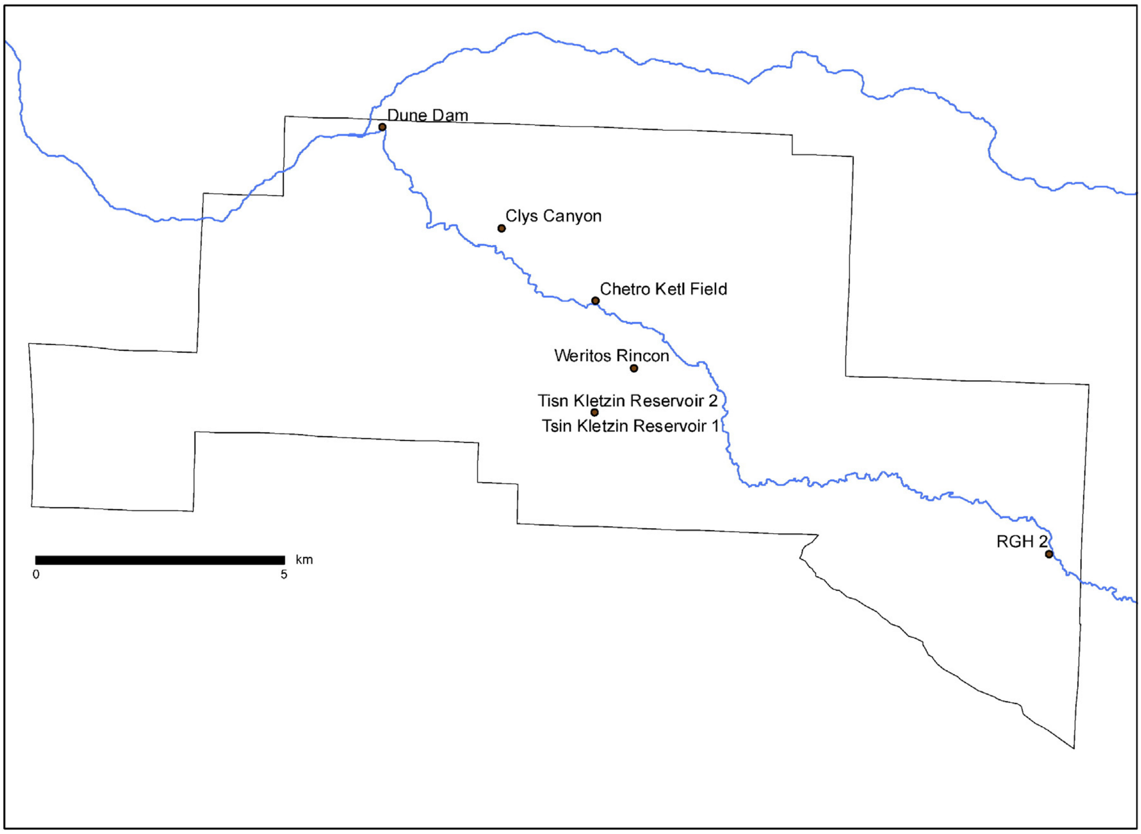

Fig. 1. Geographic location of Chaco Canyon soil sample sites.

recovered from archaeological contexts suggests some were grown upwards of 90 km from Chaco Canyon (Cordell et al., 2008; Benson et al., 2009; Drake et al., 2014), lending support to the over salinization theory for the depopulation of the area.

Previous studies assume that the term salt is synonymous with the mineral halite (NaCl) and other chloride minerals such as bischofite ($MgCl_2$) and sylvite (KCl) (Judd 1964; English, 2001; Benson et al., 2006, 2009; Benson, 2010; Worman and Mattson, 2010). High levels of chloride minerals can indeed be deleterious to cultigens such as maize, for example, reducing plant growth and producing smaller, thicker, and scorched leaves (Munns, 2002). However, not all salts are chlorides and not all salts are harmful to plants (Sawyer and Barker, 2003).

Chemically, a salt is a solid ionic compound, which forms from the neutralization of an acid and a base, a metal and an acid, a metal and a nonmetal, a base and an acid anhydride, or an acid and a base anhydride (Skoog et al., 2004). A salt is a nonvolatile and odorless compound composed of both metallic and nonmetallic elements. Salts may be inorganic or organic and is basic as forms hydroxides with the addition of water, or acidic as forms hydronium with the addition of water (Skoog et al., 2004). Salts may form from the cations ammonium (NH_4^+), calcium (Ca^{2+}), iron (Fe^{2+} [under anoxic conditions] and Fe^{3+} [under oxic conditions]), magnesium (Mg^{2+}), potassium (K^+), pyridinium ($C_5H_5NH^+$), or sodium (Na^+) and the anion acetate (CH_3COO^-), carbonate (CO_3^{2-}), chloride (Cl^-), citrate ($HOC(COO^-)(CH_2COO^-)_2$), cyanide ($C{\equiv}N^-$), fluoride (F^-), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-}) (Skoog et al., 2004).

Geologically, salts result from the evaporation of water and chemical precipitation, super-saturation and crystallization, of mineral sediment. Salts may be marine or terrestrial in origin and occur as bedded sedimentary rocks or as a massive crust or crystalline efflorescence in bedrock vugs, caves, and unconsolidated sediments. In drylands, such as Chaco Canyon, salts occur when saline-rich meteoric water reaches the surface or openings and cavities in unconsolidated sediments through capillary action and then evaporates (Boggs, 2006).

While the presence of salt in the soils of Chaco Canyon is well documented (Benson et al., 2006, 2009; Benson, 2010, 2011), there is a paucity of data concerning the chemical composition and mineralogical nature of these salts or the pH of the soil. Alkalinity is another soil factor that can compromise agriculture in drylands. Similarly, there is no basis of comparison between the salinity and pH of soils used by Ancestral Puebloans in Chaco Canyon and the salinity of soils that have been successfully irrigated and farmed by historic and modern Puebloans.

The dispersal of maize agriculture from Mesoamerica to the American Southwest occurred as a result of group-to-group diffusion ~2100 BCE. (Merrill et al., 2009). Since that time, maize agriculture has been the economic foundation and an essential aspect of traditional Puebloan culture. Maize agriculture led to the Puebloan theocratic sociopolitical system of water management, land use, and complex ceremonies designed to ensure a bountiful harvest of maize (Vlasich, 2005). Today, Puebloans practice the same irrigational agricultural techniques, as did their prehistoric and historic ancestors (Vlasich, 2005).

Soil samples were obtained from solid sediment cores extracted and profile excavations in Chaco Canyon to resolve the issues of salinity, pH,

Table 1
Geographic location of the sample sites.

Sample Site	Site Code	Easting[a]	Northing[a]
Cheto Ketl Field	29SJ1680	234,200	3,994,150
Clys Canyon	29SJ1714	232,310	3,995,612
Dune Dam	29SJ1761	229,914	3,997,646
Roberts Great House (RGH2)	29SJ2384	243,319	3,989,050
Tsin Kletzin Reservoir 1	29SJ686	234,178	3,991,896
Tsin Kletzin Reservoir 2	29SJ686	234,178	3,991,896
Weritos Rincon	29SJ301	234,970	3,992,797

[a] The coordinates are UTM zone 13 N and NAD27 datum.

and maize agriculture. The study areas included Chetro Ketl Field, Cly's Canyon, Dune Dam, and Robert's Great House, and the Tsin Kletsin and Werito's reservoirs examined during the summers of 2013, 2014, and 2015 (Fig. 1, Table 1). Water samples were collected from the Chaco and Escavada washes as well as two small-secluded rim-rock drainages or sandstone alcoves (Rincons 1 and 2) that are tributary to Chaco Wash near to Chaco Wash where it confluences with Escavada Wash. Comparative sediment samples were also collected from the agricultural fields of historic San Lazaro Pueblo and irrigated agricultural fields located on three Keresean speaking Puebloans—Santa Ana, Kewa Pueblo, and San Felipe—and one Tiwa speaking Puebloan peoples, Sandia (Fig. 2) (see Table 2).

2. Methods

2.1. Salinity

A conductivity cell was used to calculate the salinity of sediment samples extracted from solid sediment cores and excavated profiles. Soil salinity was calculated as ppm to compare with water salinity. Salinity was determined as the total dissolved solids (TDS) and electrical conductivity (EC) of the sediment samples in solution. Salinity was expressed as a conductivity unit, deci-Siemens per meter (dS m^{-1}), which is the product of the measured conductance (reciprocal of resistance) and the conductivity cell constant. Salinity measurements were obtained on water extracts. A saturated soil paste with pure water was used because this is a standard procedure to mimic the field condition of most soils. Plant tolerance to salinity was expressed based on EC values of a saturation paste extract (Rhoades et al., 1999; Wang et al., 2007).

2.2. pH

A standard pH meter was used to measure pH. A finely ground soil paste saturated with pure water at room temperature was created by placing 20 g of soil in a 100 ml beaker and stirred with a magnetic stirrer. The electrode was cleaned with pure water between sample measurements and blotted dry. Test strips of pH paper were used as an independent method of measurement.

2.3. XRD

Powder X-ray diffraction (XRD) analysis was used to determine the mineral and chemical composition of the salts, which effloresce in the soils of Chaco Canyon. Samples were prepared for analysis following the procedures described by Tankersley and Balantyne (2010) and Tankersley et al. (2011, 2015). Glass slides of mineral sediments were prepared by an air-dried smear method and scanned on a Siemens D-500 X-ray diffractometer using a Cu-Kα radiation source. Minerals were identified on the basis of peak position and peak intensity.

2.4. ICP-OE

Inductively coupled plasma optical emission spectrometry (ICP-OES), also known as inductively coupled plasma atomic emission spectroscopy, was used to determine the quantity (ppm) of trace metals and sulfate in water samples (5 ml) collected from Chaco Wash, Escavada Wash, Rincon 1, and Rincon 2 to ascertain the source of salt in the Chaco Canyon sediment samples. A bench-top, dual-view PerkinElmer Optima 8300 ICP-OES with two solid-state SCD detectors was used to obtain detection limits and simultaneous measurements in an argon flame.

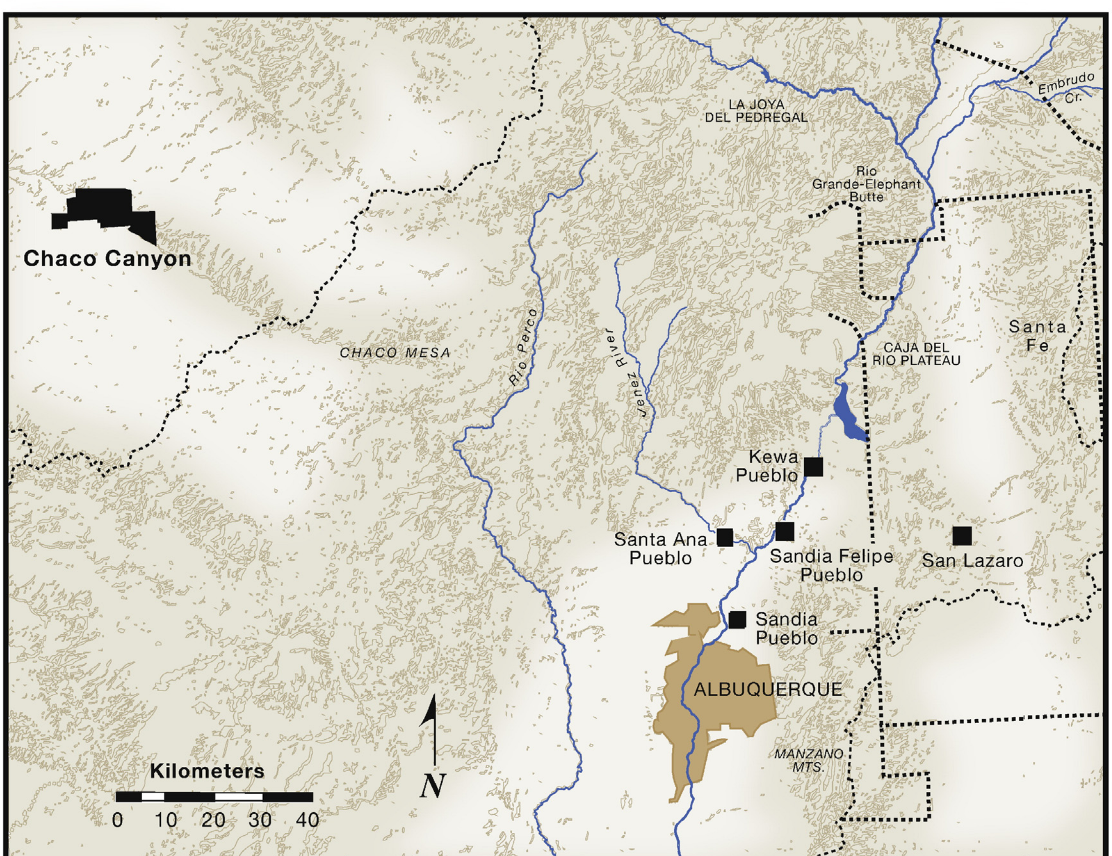

Fig. 2. Geographic location of Historic and Modern Pueblos.

Table 2
Radiocarbon ages for Robert's Great House.

Site complex	Depth (cm)	Sample	Lab number (UCIAMS)	^{14}C Age (1 σ)	Calibrated Age (2 σ)	Cultural Stage
Roberts Great House	93–103	Unidentified Wood Charcoal	135120	1260 ± 15	729 ± 28 CE	Pueblo I
Roberts Great House	118–198	Unidentified Wood Charcoal	135121	1235 ± 15	758 ± 40 CE	Pueblo I
Roberts Great House	130–157	Uncarbonized Twig	150903	1120 ± 20	928 ± 29 CE	Pueblo II
Roberts Great House	157–250	Unidentified Wood Charcoal	150904	1095 ± 20	939 ± 34 CE	Pueblo II

3. Chaco Canyon and Pueblo study sites

Soil was collected from several key archaeological sites, and historic and modern Pueblos to evaluate the chemical composition and mineralogical nature of salts in the sediments of Chaco Canyon to help remedy the ambiguity mentioned in the published literature (Judd 1964; English, 2001; Benson et al., 2006, 2009; Benson, 2010; Worman and Mattson, 2010). Basic descriptions of the sediments from the Chaco Canyon cores collected in 2013 are presented in Tables 3 and 4. Water samples were also collected to determine the quantity of saline cations and anions.

3.1. Chetro Ketl field

Chetro Ketl is also known as rain town, shining pueblo, broad house, scaled rock, and the house in the corner (Linford, 2000; Vivian and Hilbert, 2012), and is the largest Great House in Chaco Canyon by area and second largest by room count with about 400 rooms and 12 kivas constructed over a D-shaped area of >1 ha (Vivian, 1990). Chetro Kelt was constructed and later remodeled by Ancestral Puebloans primarily between ~1040 CE and the early 1000s CE. Chetro Ketl is located 0.6 km east of Pueblo Bonito and directly across from Chaco Canyon's South Gap (Fig. 1; Lekson, 2006). In addition to the Great House, Chetro Ketl includes a refuse mound >60 m long, almost 40 m wide, and ~6 m high. Chetro Ketl field is a well-defined gridded rectangular area covering >8 ha and is thought by Vivian (1990) to be an agricultural field complex (see Loose and Lyons 1976; Strum, 2016).

3.2. Cly's Canyon

West of Chetro Ketl, water management features were constructed at ~1000 CE (Pueblo II) in a side canyon on the north side of Chaco Wash, approximately half way between Pueblo Bonito and Peñasco Blanco (Fig. 1). Ancestral Puebloans constructed a dam to capture and channel rim-rock runoff water in Cly's Canyon to agricultural fields (Vivian et al., 2006).

3.3. Dune Dam

The Dune Dam area is located in the extreme western end of Chaco Canyon at the confluence of the Chaco and Escavada washes (Fig. 1) (Lekson, 2006). The area is named for a large complex of sand dunes, which extend almost completely across the width of Chaco Canyon that Force et al. (2002) and proposed dammed Chaco Wash during Pueblo II occupation (~900–1150 CE) of Chaco Canyon, forming a small lake. Between 900 and 1000 CE (Pueblo II), Anestral Puebloans may have used mortar and rock to close the gap between the bedrock canyon wall and the dune complex, creating a shallow reservoir for agricultural use presumably by the nearby Peñasco Blanco Great House community (Force et al., 2002; contra Hall 2010, Love et al., 2011). Today, the area immediately upstream of the Dune Dam is relatively flat and contains stratified clay-rich sediments and paleosols. These sediments suggest the presence of an ephemeral shallow lake or playa, an environment in which evaporite minerals would naturally concentrate.

3.4. Robert's Great House

Robert's Great House, also known as site 29SJ2384, is located southeast of Wijiji Pueblo near the eastern end of the Great House

Table 3
Soil sample descriptions.

Chetro Ketl East Field Core
0–15 cm: modern A horizon; dark grayish brown (10YR4/2) silty sand; large soft crumbs;
15–132 cm: banded grayish brown (10YR5/2) and light grayish brown (10YR6/2) compact but granular silty sand;
132–152 cm: light yellowish brown (2.5Y6/3) compact sand; weakly laminated; faint lighter mottles;
152–170 cm: grayish brown (2.5Y5/2) granular sandy loam; probable paleosol.
Cly's Canyon
0–38 cm: light yellowish brown (10YR6/4) granular sand; grades gradually into stratum below;
38–107 cm: yellowish brown (10YR5/4) granular sand; visible particulate carbon;
107–142 cm: stratified very pale brown (10YR7/3) and yellowish brown (10YR5/4) granular sand in bands; bands vary from 1 to 2 cm in thickness;
142–157 cm: yellowish brown (10YR5/4) granular sand.
Dune Dam 2013 Core
0–5 cm: pale brown (10YR6/3) granular sand;
5–12 cm: grayish brown (10YR5/2) granular sand;
12–44 cm: pale brown (10YR6/3) granular sand, wide, weakly expressed bands;
44–72 cm: dark grayish brown (2.5Y4/2) sandy clay; weakly banded with thin sand lenses;
72–104 cm: light olive brown (2.5Y5/3) dense sand;
104–118 cm: grayish brown (2.5Y5/2) sandy clay; weakly banded with thin sand lenses;
118–124 cm: light olive brown (2.5Y5/4) dense sand;
124–128 cm: dark grayish brown (2.5Y4/2) sandy clay; weakly banded;
128–166 cm: light olive brown (2.5Y5/4) dense sand;
166–183 cm: light brownish gray (2.5Y6/2) granular sand;
183–190 cm: dark grayish brown (2.5Y4/2) sandy clay; weakly banded;
190–215 cm: light olive brown (2.5Y5/3) dense sand;
215–221 cm: grayish brown (2.5Y5/2) sandy silt, weakly banded;
221–237 cm: light olive brown (2.5Y5/3) and light brownish gray (2.5Y6/2) strongly banded sand;
237–243 cm: grayish brown (2.5Y5/2) silty sand with small white calcium concretions and small black carbon flecks.
Tsin Kletzin Reservoir Core #2
0–4 cm: yellowish brown (10YR5/6) granular sand;
4–26 cm: dark yellowish brown (10YR4/6) granular sand; particulate carbon flecks; grades gradually into stratum below;
26–90 cm: light yellowish brown (10YR6/4) granular sand;
90–118 cm: stratified very pale brown (10YR7/3) and yellowish brown (10YR5/4) granular sand in bands; bands vary from 1 to 4 cm in thickness;
118–143 cm: dark yellowish brown (10YR4/6) granular sand.
Werito's Rincon Core
0–13 cm: very pale brown (10YR7/3) granular loamy sand;
13–22 cm: pale brown (10YR6/3) loam, small subangular blocks;
22–44 cm: brown (10YR5/3) loam; platy structure;
44–58 cm: dark grayish brown (104/2) loam; large crumbs; probable ponded reservoir sediments or paleosol;
58–76 cm: stratified light grayish brown (10YR6/2) and very pale brown (10YR8/2) loamy sand; platy to massive; pale calcium carbonate or gypsum mottles;
76–97 cm: dark grayish brown (10YR4/2) loam with small light and dark, and some red (2.5YR6/4) mottles; a few bits of subangular gravel; blocky; probable ponded reservoir sediments or paleosol;
97–132 cm: light yellowish brown (10YR6/4); sand; granular; faintly laminated;
132–147 cm: brown (10YR5/3) loam; massive.

Table 4
Profile sample descriptions.

Robert's Great House Op. 100 profile soil units
0–5 cm: brown (7.5YR 4/4) granular fine sand and silty sand; small amounts of fibric organic matter; abundant rootlets.
5–10 cm: strong brown (7.5YR 5/6) thinly stratified fine sand and silt; compact and granular structure.
10–15 cm: dark brown (7.5YR 3/2) organic sandy silt; fine crumb to granular structure; abundant rootlets.
15–19 cm: brown (7.5YR 5/3) sandy silt; very fine crumbs; scarce rootlets.
19–22 cm: light brown (7.5YR 6/3) dense silt (fluvial mud).
22–30 cm: brown (7.5YR 5/3) finely stratified silt and fine to medium sand lenses; compact granular structure; widely scattered charcoal fragments.
30–46 cm: light brown (7.5YR 6/4) lightly stratified, indurated and massive, but friable silty fine sand; widely scattered calcium carbonate concretions.
46–50 cm: brown (7.5YR 5/3) finely stratified silty sand; widely scattered charcoal flecks.
50–63 cm: light brown (7.5YR 6/3) dense silt (fluvial mud); includes intrusive channel filled with water-laid sediments (see 07–109 cm).
63–75 cm: brown (7.5YR 5/3) lightly stratified large hard crumb to massive, but friable sandy silt; widely scattered charcoal fragments and secondary pot sherds; the base of this unit is formed by apparent field furrows.
75–85 cm: light brown (7.5YR 6/3) lightly stratified massive, but friable sandy silt.
85–92 cm: brown (7.5YR 5/3) weakly stratified sandy silt; widely scattered pot sherds; sandstone ball.
92–109 cm: pinkish gray (7.5YR 6/2) massive silt loam; abundant charcoal fragments and secondary pot sherds; includes intrusive channel filled with water-laid sediments (see 13 A).
07–109 cm: light gray (7.5YR 7/1) strongly stratified, water-laid silt filling channel; the base of this unit is formed by apparent field furrows. Embedded within Units 13 and 9.
110–115 cm: Pinkish gray (7.5YR 6/2) blocky clay (likely created from channel seepage).
109–123 cm: brown (7.5YR 5/2) hard crumb to massive silt loam.
123–133 cm: brown (7.5YR 5/4) massive, but friable fine sandy loam; widely scattered charcoal fragments.
133–148 cm: pink (7.5YR 7/4) indurated massive silt loam; widely scattered charcoal fragments.
148–228 cm: pithouse fill. Non-uniform. Strongly stratified brown and light brown medium to fine sand and silt; includes zone of oxidized sediments between 152 and 162 cm; increasing charcoal with depth.
228–279 cm: pithouse interior fill. Strongly stratified brown and light brown medium to fine sand and silt; abundant charcoal fragments and pot sherds.
228–338 cm: light brown (7.5YR 6/3) weakly stratified massive, but friable, silt loam.
278–295 cm: embedded within Unit 19; Dark gray (7.5 4/1) massive, but friable silt loam; abundant coal fragments.
338–349 cm: Ab (buried topsoil horizon); very dark gray (7.5YR 3/1) blocky to massive silt loam; infilled root channels within ped structures.
349–357 cm: brown (7.5YR 5/3) massive fine sandy loam.
357 + cm: light brown (7.5YR 6/3) massive loamy silt (apparently top of thick horizon).
Chaco Canyon Pit House Core RGH4
0–2 cm: modern A horizon; dark grayish brown (10YR4/2) granular sand with folic organic matter;
2–16 cm: pale brown (10YR6/3) granular sand;
16–31 cm: brown (10YR5/3) granular sand;
31–51 cm: pale brown (10YR6/3) granular sand;
51–52 cm: diffuse, wavy band of light gray (10YR7/2) loamy sand;
52–64 cm: pale brown (10YR6/3) granular sand;
64–66 cm: grayish brown (10YR5/2) granular sand with one prominent red (10R5/6) mottle;
66–66.5 cm: diffuse, wavy band of light gray (10YR7/2) loamy sand;
66.5–99 cm: dark grayish brown (10YR4/2) compact loamy sand, with increasing carbon flecks with depth;
99–117 cm: light yellowish brown (10YR6/4) compact loamy sand with abundant carbon flecks, scattered white calcium inclusions, and diffuse yellow and orange mottles;
117–139 cm: light gray (10YR7/2) granular sand;
139–153 cm: light brownish gray (10YR6/2) compact sand, widely scattered carbon flecks;
153–163 cm: yellowish brown (10YR5/4) compact sand; carbon flecks increasing with depth;
163–164 cm: diffuse band; white (10YR8/1) sand; massive; likely Ca concretion;
164–183 cm: grayish brown (10YR5/2) compact loamy sand; abundant carbon flecks; diffuse white Ca concretions;
183–205 cm: pale brown (10YR6/3) compact sand with scattered carbon flecks.

concentration in Chaco Canyon (Fig. 1) (Lekson, 2006; Lister and Lister, 1981). Occupation spanned Basketmaker III to Pueblo III (~500 to 1200 CE) as evidenced by the coexistence of multiple pit houses in close proximity to the great house. Robert's Great House itself includes ~40 rooms and two kivas constructed at ~1100 CE (Pueblo III; Lister and Lister, 1981).

Four AMS radiocarbon ages obtained from excavated contexts and a solid sediment core in the immediate vicinity of the Great House range from 729 ± 28 CE to 939 ± 34 (Pueblo I to Pueblo II; Table 3). Radiocarbon ages 729 ± 28 CE (UCIMAS 135120) and 758 ± 40 CE (UCIAMS 135121) were obtained from a collapsed Pueblo I pithouse. Radiocarbon ages 928 ± 29 CE (UCIAMS 150903) and 939 ± 34 CE (UCIAMS 150904) were obtained from a solid sediment core extracted near Robert's Great House. Architectural and ceramic evidence for the Ancient Pueblo itself suggest an early 1000s CE construction for the site layout, although the rooms were never occupied or completed (Bishop et al., 2014, 2015).

In 2013, five solid sediment cores were extracted from within and near Robert's Great House (Fig. 3). In 2014, ten more cores were extracted from across the landscape adjacent to the great house and two deep profiles created by ongoing arroyo dissection were cleaned and sampled. One of these profiles included a collapsed and buried pit house (Fig. 3). Descriptions of the "Pithouse Profile" and of Core 4 are included in Table 4. The Pithouse Profile represents the most culturally complex stratigraphic sequence examined in our investigations including the collapsed and abandoned Basketmaker III pithouse buried under aggrading sediments which were subsequently channelized with irrigation ditches most likely roughly contemporaneous with the construction of Robert's Great House. On the other hand, Core 4 is typical of much of the area's landscape: the convergence of two drainages and the complex sequence of aggrading sediments, punctuated by episodes of channel cutting.

3.5. Tsin Kletsin Reservoir

Tsin Kletsin is a two-story Great House located on top of South Mesa ~3 km from Pueblo Bonito (Fig. 1; Lekson, 2006). Approximately 80 rooms and 3 kivas were constructed by Ancestral Puebloans at ~1100 CE (Pueblo II; Vivian, 1990). Runoff water was captured in a reservoir behind Werito's Dam, providing water for agriculture <1000 m northeast of Tsin Kletsin (Lagasse et al., 1984; Vivian, 1990).

3.6. Werito's Rincon

Several small multicomponent Ancestral Puebloan habitations or hamlets are located in Werito's Rincon area, east of the Tsin Kletsin Great House (Fig. 1; Lekson, 2006). The hamlets contain small blocks of rooms and pit features, which date between ~750 and 900 CE (Pueblo I; Vivian, 1990). In addition to the habitation sites, there is a multicomponent reservoir, which may contain historic, Navajo, and Ancestral Puebloan sediments, though the present depression is a likely consequence of the Civilian Conservation Corps (CCC) of the 1930s. Solid sediment cores were extracted from the Werito's Rincon reservoir during the summer of 2013.

3.7. Chaco Wash, Escavada Wash, and Rincons 1 and 2

Chaco Wash is an intermittent stream or arroyo, which has cut through Cretaceous sandstone, siltstone, shale, and coal to form Chaco Canyon (Fig. 1). Escavada Wash intersects with Chaco Wash at the western end of Chaco Canyon to form the Chaco River, near an Ancestral Puebloan Great House, Peñasco Blanco (Fig. 1; Vivian, 1990; Lekson, 2006).

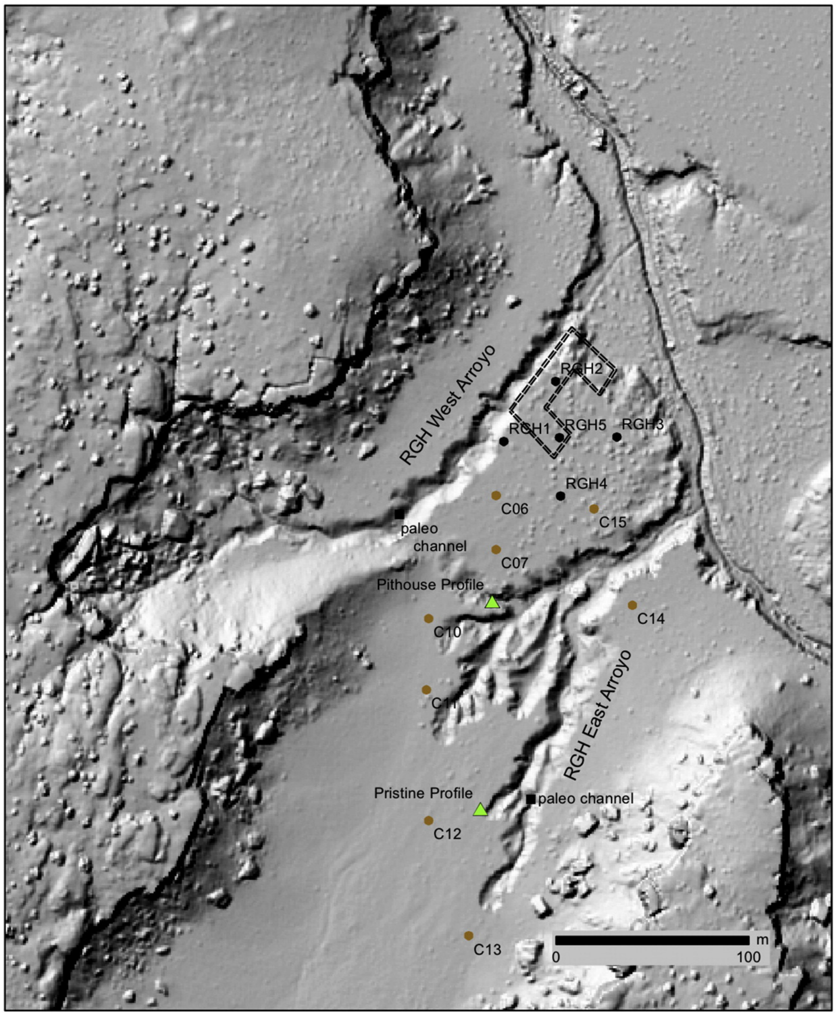

Fig. 3. Location of Robert's Great House sample sites.

3.8. San Lazaro Pueblo

San Lazaro is the largest historic Pueblo in the Galisteo Basin of northern New Mexico and is located on the Arroyo del Chorro, a tributary of Galisteo Creek and the Rio Grande River (Fig. 2). The Tano built the Pueblo at ~1300 CE and it was occupied until 1696 CE (Pueblo III, IV, V). During that time, between 1941 and 5000 rooms, kivas, kilns, shrines, agricultural fields, canals, and reservoirs covered an area of ~176 ha (Nelson, 1914; Tankersley, 2002).

3.9. Modern Rio Grande Pueblo Reserves

Several Eastern modern Puebloan reserves are located within the Rio Grande basin, which extends from south-central New Mexico to central Colorado (Fig. 2). Volcanic-rich soils extend from the edges to the center of the Rio Grande basin. A complex system of modern canals, dams, and ditches are used to irrigate the soil for agriculture on the Santa Ana, Kewa, San Felipe, and Sandia Pueblos.

4. Results

4.1. Salinity analysis

The average salinity of the Chaco Canyon soil samples was 251 ppm (Table 5), taken from individual coring efforts that descended 1–3 m from the surface with laboratory soil sampling units consisting of 10 cm increments. The greatest variability and the highest levels of salinity in Chaco Canyon were found in the Dune Dam soil samples, which ranged between 11 and 3060 ppm with an average of 1247 $\pm$ 955 ppm (the uncertainty is expressed as 1 σ). This area resembles a playa so a concentration of evaporite mineral salts is not surprising. However, all of the other Chaco Canyon locations sampled had relatively low salinity levels at between 26 and 177 ppm.

The salinity of soil samples from historic and modern Puebloan agricultural fields ranged from 16 to 58 ppm with an average of 30 ppm (Table 4). The average salinity of soil samples from the historic agricultural fields of San Lazaro Pueblo was 26 $\pm$ 14.3 ppm. The salinity of soil samples from the modern agricultural fields of the Kewa Pueblo average 21 $\pm$ 2 ppm; Sandia Pueblo average 39 $\pm$ 5 ppm; Santa Ana Pueblo average 39 $\pm$ 5 ppm; and a single soil sample from a modern agricultural field on the San Filipe Pueblo was 24 ppm.

4.2. pH

With the exception of the Robert's Great House area, all of the soils sampled in Chaco Canyon had pH values that fall within the ideal pH range of 5.5–7.5 for *Zea mays* cultivation (Table 6; Espinoza and Ross, 2001). The greatest variability in soil pH and the most alkaline soils were found in the lower levels (120 and 220 cm) of a single core (Core 7) extracted near Robert's Great House, which are in the alkaline range (pH > 8; Table 6). The high alkaline levels were not unexpected because the core penetrated calcareous regolith on a spur of bedrock now mostly buried under alluvium.

Table 5
Chaco Canyon salinity data.

Depth (cm)	Cheto Ketl Field (ppm)	Clys Canyon (ppm)	Dune Dam (ppm)	Roberts Great House (ppm)[a]	Tsin Kletzin Reservoir 1 (ppm)	Tsin Kletzin Reservoir 2 (ppm)	Weritos Rincon (ppm)
0–10	100	24	11	79	23	20	126
10–20	100	22	13	47	24	22	173
20–30	193	28	185	44	23	20	137
30–40	372	30	335	43	26	26	103
40–50	202	30	1320	45	27	25	153
50–60	264	38	2290	52	32	26	262
60–70	300	49	2590	53	29	27	161
70–80	213	25	2390	43	23	23	121
80–90	163	28	31	53	24	21	213
90–100	153	34	839	56	23	42	176
100–110	163	89	995	70	26	51	56
110–120	141	38	1520	76	27	58	54
120–130	123	37	1790	94	32	84	56
130–140	138	38	1550	112	29	20	198
140–150	120	67	1200	119		22	139
150–160	93	100	2280	75		20	126
160–170			3060	60		26	173
170–180			21	126		25	137
180–190			11	126			103
190–200			21	141			153
200–210			2040	147			262
210–220			2310	174			161
220–230			1670	206			
230–240			1270	96			
240–250			477	132			
250–260			2190	108			
Range (ppm)	93–372	22–100	11–3060	43–206	23–32	20–84	54–262
Mean (ppm)	177	42	1247	91	26	31	147
Standard deviation	75.7	22.5	954.6	43.8	3.1	16.7	55.2

[a] Averages based on 307 samples (12 cores and 2 profiles).

4.3. XRD

The mineral salts anhydrite, blodite, celestie, felsobanyaite, gypsum, lonecreekite, sepiolite, and sulfoborite in addition to smectite and quartz were identified in the powder X-ray diffractometry of soils from Chaco Canyon (Fig. 4, Table 7). Anhydrite occurs at Chaco Canyon as a sulfate evaporite-mineral salt in the soil as a dehydrated form of gypsum. Blodite, celestite, felsobanyaite, gypsum, lonecreekite, sepieolite, and sulfoborite are sulfate evaporite-mineral salts, which occur as groundwater precipitates in oxidizing and acidic conditions,

Table 6
Chaco Canyon pH data.

Depth (cm)	Cheto Ketl Field (pH)	Clys Canyon (pH)	Dune Dam (pH)	Roberts Great House (pH)[a]	Tsin Kletzin Reservoir 1 (pH)	Tsin Kletzin Reservoir 2 (pH)	Weritos Rincon (pH)
0–10	7	7	7	7–7.3	7	7	7
10–20	7	7	7	7–7.6	7	7	7
20–30	7	7	7	7–7.6	7	7	7
30–40	7	7	7	7–7.6	7	7	7
40–50	7	7	6.7	7–7.4	7	7	7
50–60	7	7	6.4	7–7.3	7	7	7
60–70	7	7	6.6	7	7	7	7
70–80	7	7	7	7–7.3	7	7	7
80–90	7	7	7	7	7	7	7
90–100	7	7	7	7	7	7	7
100–110	7	7	6.7	7–7.5	7	7	7
110–120	7	7	7	7–7.5	7	7	7
120–130	7	7	7	7–7.9	7	7	7
130–140	7	7	7	7–8.5	7	7	7
140–150	7	7	7	7–8.7		7	7
150–160	7	7	7	7		7	7
160–170			7	7–7.8		7	7
170–180			7	7–8.2		7	7
180–190			7	7–8.8			7
190–200			7	7–9.3			7
200–210			7	7–9.3			7
210–220			7	7–9.3			7
220–230			7	7–7.4			
230–240			7	7–7.4			
240–250			7	7–7-4			
250–260			7	7			
Range (pH)[b]	7 (neutral)	7 (neutral)	6.4–7 (acidic to neutral)	7–9.3 (neutral to basic)	7 (neutral)	7 (neutral)	7 (neutral)

[a] Ranges are based on 307 samples (12 cores and 2 profiles).
[b] Maize pH tolerance is 5.5 to 7.5.

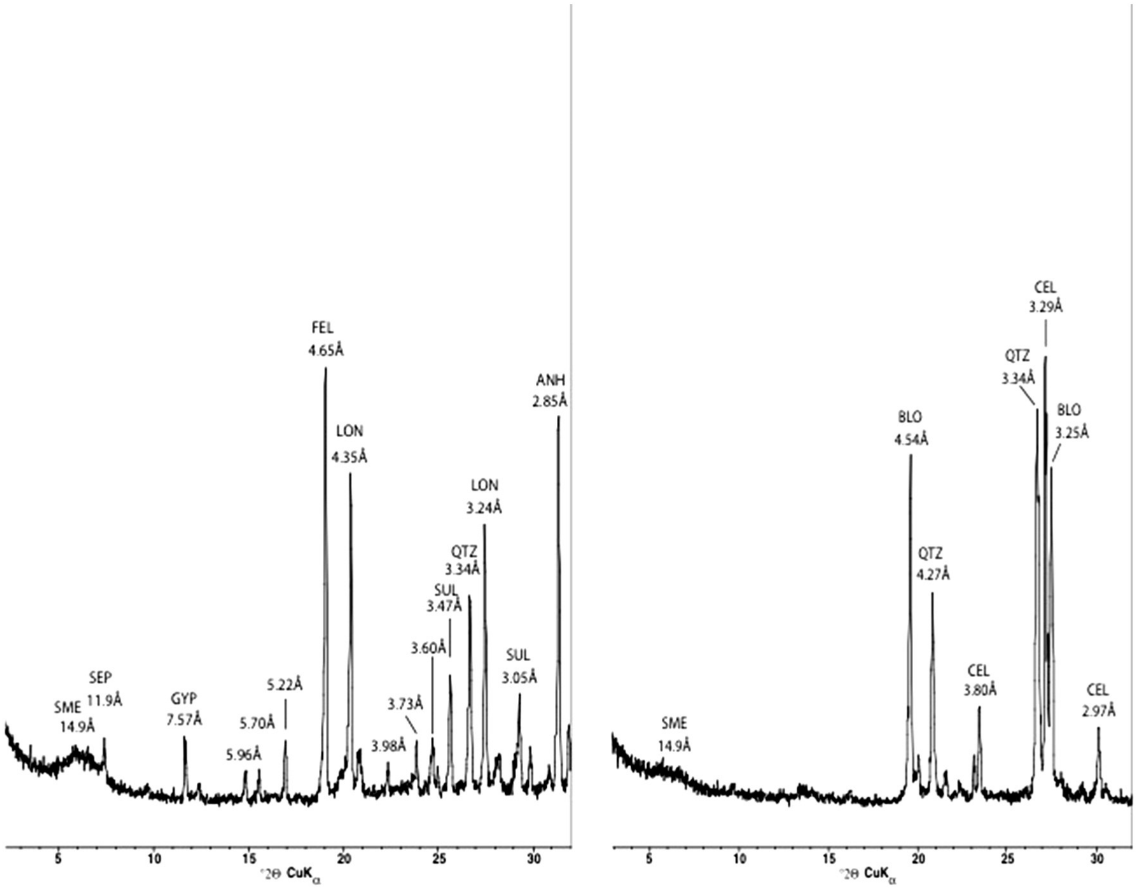

Fig. 4. XRD of Chaco Canyon mineral salts.

efflorescing in near-surface soils. Smectite is volcanogenic clay, which originates from the degradation of eruptive igneous rocks such as tuff and volcanic ash. At Chaco Canyon, it co-occurs with trace amounts of heavy volcanogenic minerals such as apatite, biotite, clinopyroxene, and zircon, which are not present in the Cretaceous age bedrock (Haussner et al., 2015). Quartz is ubiquitous in the soils of Chaco Canyon. While quartz can be volcanic in origin, it is abundant in the Cretaceous age sandstones and siltstones, which line the valley walls and account for its presence in the soils tested.

4.4. ICP-OES

All of the cations (Al, B, Ca, Fe, Mg, Na, Sr) and anions (S, SO_4) needed to form the mineral salts in the soils of Chaco Canyon occur in the water samples from the washes and adjacent rincons (Table 8). The Chaco and Escavada Washes are particularly enriched in calcium and sodium cations and the sulfate anion, but they also occur in the rincons. The abundant silicon cation likely originates from both the Cretaceous bedrock and volcanogenic clays.

5. Discussion

According to the *Soil Survey of San Juan County New Mexico, Eastern Part* (Soil Conservation Service, 1980), the floor of the entirety of Chaco Canyon is mantled in soils of the Blancot-Notal Association. Blancot Series is a clay loam desert soil that has been classified as a Haplargids (Aridisol). Notal Series is a clayey desert soil that has been classified as a Camborthids (Aridisol). Both the Blancot and Notal Series are mature soils and are notably saline (1200 to 5100 ppm) and are rated as having "poor" potential for grain and seed crops. However, the Blancot-Notal Association also includes several other soil series, notably Turley (an immature clay loam desert soil classified as a Torriorthents) and Fruitland (an immature sandy loam desert soil classified as a Torriorthents), both of

Table 7
XRD of Chaco Canyon mineral salts.

Mineral	Chemical Composition	Angstrom
Anhydrite (ANH)	$CaSO_4$	2.85
Blodite (BLO)	$Na_2Mg(SO_4)_2 \cdot 4(H_2O)$	4.54, 3.25
Celestite (CEL)	$SrSO_4$	3.80, 3.29, 2.97
Felsobanyaite (FEL)	$Al_4(SO_4)(OH)10 \cdot 5(H_2O)$	4.65
Gypsum (GYP)	$CaSO_4 \cdot 2(H_2O)$	7.50
Lonecreekite (LON)	$(NH_4)(Fe{+}{+}{+},Al)(SO_4)2 \cdot 12(H_2O)$	4.35, 3.24
Sepiolite (SEP)	$Mg_4Si_6O_{15}(OH)2 \cdot 6(H_2O)$	11.9
Smectite (SME)	$(Na,Ca)0,3(Al,Mg)2Si_4O_{10}(OH)2 \cdot n(H_2O)$	14.90
Sulfoborite (SUL)	$Mg_3B_2(SO_4)(OH)8(OH,F)_2$	3.47, 3.05
Quartz (QTZ)	SiO_2	4.27, 3.34

Table 8
ICP AES analysis of Chaco Canyon water samples.

Cations and anions	Chaco wash (ppm)	Escavada wash (ppm)	Rincon 1 (ppm)	Rincon 2 (ppm)
Sulfur (S)	47.17	28.56	4.25	3.76
Sulfate (SO_4)	120.00	84.00	11.30	9.30
Sodium (Na)	118.63	165.24	21.72	31.30
Calcium (Ca)	11.49	6.68	27.17	11.93
Magnesium (Mg)	1.06	0.59	2.35	1.26
Strontium (Sr)	0.31	0.19	0.21	0.16
Aluminum (Al)	0.03	0.09	BD[a]	0.02
Iron (Fe)	0.04	0.12	BD[a]	BD[1]
Boron (B)	1.65	1.39	1.37	1.45
Silicon (Si)	19.60	31.30	11.10	6.70

[a] BD = Below detection.

which have generally low salinity and rated as having “good” grain and seed crop potential. Both of these Entisols have typically developed in a combination of geologically young fluvial and Aeolian sediments such as characterize the floor of Chaco Canyon.

Mapping at the soil association is notably coarse, relying on extrapolation away from a very limited number of field sample points; it is unknown if any samples were actually collected within Chaco Canyon during the survey. Notably, a cursory look at the county soil survey could lead one to conclude that the soils within Chaco Canyon are largely saline and unsuitable for agriculture. However, detailed sampling of portions of the canyon floor such as we conducted reveals a highly complex soilscape, much of it well suited to irrigation agriculture.

The salinity level of soils in Chaco Canyon varies geographically and stratigraphically. Soil salinity levels between 2000 and 4000 ppm will stress maize and reduce the plant's growth potential by one half (Hussein et al., 2007). While deleteriously high salinity levels (>2000 ppm) were found in the Dune Dam area, all of the other locations sampled were below the range that would stress cultigens such as maize (Hussein et al., 2007). Additionally, many of the soils sampled in Chaco Canyon are well within the salinity range found on productive historic and modern Puebloan agricultural fields.

Previous studies of soil salinity in Chaco Canyon have confused or obfuscated NaCl with the natural and anthropogenic abundance of sulfate mineral salts (Benson, 2010, 2011; Benson et al., 2006, 2009). Salts in the soils of Chaco Canyon are mineral sulfates, i.e., anhydrite, blodite, celestite, felsobanyaite, gypsum, lonecreekite, sepieolite, sulfoborite. Water from the Chaco and Excavada washes and adjacent rincons shows that all of the cations and anions needed to precipitate these mineral salts in the unconsolidated soils of Chaco Canyon are present.

Mineral salts, such as calcium and sodium sulfate in soil concentrations of 25% or less are not deleterious for maize agriculture (Van Alphen and de los Rios Romero, 1971; Western Plant Health Association, 2002). Indeed, they not only decrease the toxic effects of NaCl, but sulfates also are significant fertilizers. Calcium and sodium sulfate can be used to aid seed emergence, break up compacted clay soils, decrease the bulk density of soil, help plants absorb plant nutrients, improve soil development, stabilize organics, and reduce acidity, erosion, runoff, and water logging (Western Plant Health Association, 2002).

Sulfate mineral salts are among the most important and sacred raw materials of past and present Puebloan cultures. The occurrence of sulfate mineral salts even influenced the selection of Pueblo sites. For example, the location of Santa Domingo Pueblo, today known as Kewa Pueblo, was selected because of its close proximity to a deposit of calcium sulfate, i.e., gypsum (Chapman, 1936). Given this known preference in historic Puebloan settlements, we should expect to find a high level of sulfate mineral salts on Ancestral Puebloan habitation sites.

Linguistically, Puebloan people call sulfate mineral salts, which occur in the soils of Chaco Canyon, *jaspe* and *yeso*. Modern Puebloan people grind sulfate mineral salts and mix them with water to create a whitewash to paint the inside and outside of their homes. Sulfate mineral salts are also ground and mixed with other mineral pigments to make different colored paints. Traditionally, Pueblo windows were made from selenite, the crystalline form of gypsum ($CaSO_4$) called *isinglass*, which was split along cleavage planes until it was thin and translucent (Stevenson, 1904; Parsons, 1939).

Ceremonially, modern Puebloan people place sulfate mineral salts on altars during certain ceremonies as sun symbols. Sulfate salts are also swallowed to produce supernatural sight to divine witches and determine the causes of illnesses, and knives made from selenite are carried in fetish bags. Given their softness (two on the Mohs qualitative ordinal scale of mineral hardness), these knives can only be used in ceremonial cutting. Similar to their use on houses, ground sulfate mineral salts are used to paint kiva walls and *katsina* ceremonial masks and to create the color white in sand painting healing ceremonies. Additionally, tribal leaders gift pieces of sulfate minerals to gamesters (Munson et al., 1989; Stevenson, 1904; Fewkes, 1920; Jeancon, 1923; White, 1928). In other words, we should expect to find a high concentration of anthropogenic sulfates on Ancestral Pueblo archaeological sites, which are not directly related to water management activities.

Both anthropogenic and natural and processes have a relative impact on the abundance of sulfate mineral salts on Ancestral Puebloan sites. As masonry structures fell into ruin, fragments of selenite windows, internal and external sulfate-based paints, and artifacts manufactured from sulfate minerals would have been deposited the soils of the immediate vicinity. Additionally, evaporation of sulfate-rich water in Ancestral Puebloan reservoirs and irrigation canals would have increased sulfate minerals concentrations in the soil.

Chaco Canyon is formed in the Cretaceous Cliffhouse Sandstone and Menefee formations. The Menefee Formation includes gypsum-rich sub-bitumenous coal (Miller, 1984). Dissolution of gypsum occurs as groundwater percolates through coal seams in the Menefee Formation. The dissolution of calcium sulfate from coal and redeposition in porous Quaternary sediments would account for a natural increase concentration in soil sulfates.

Given that natural and anthropogenic sulfates are derived from the local Cretaceous bedrock, it is geochemically impossible to determine their origin. Archaeologically context, however, can be used to infer anthropogenic sulfates. For example, the salinity levels in a solid sediment core extracted from the center of Robert's Great House is higher than those from the surrounding area suggesting an anthropogenic rather than natural occurrence of sulfates (Fig. 5).

Another soil condition that can compromise many crops including *Zea mays* in arid regions is excessive alkalinity. Our pH tests of soils from throughout Chaco Canyon indicate that levels were firmly within the typical tolerance range (pH 5.5–7.5) in all but one isolated sample further supporting the idea that the canyon environment was suitable for maize-based agriculture so long as sufficient water could be delivered to the crop.

The movement of maize into Chaco Canyon from significant distances has been questioned (Cordell et al., 2008; Drake et al., 2014). Any movement that did occur can easily be explained in terms of “kinship mobility,” that is, the distance goods and services, ceremonial or economic, move between extended families. At historic contact such distances were considerable (Ford, 1972; Geib and Heitman, 2015). Puebloans practiced kinship mobility over a distance of >300 km (Espinosa, 1988; Preucel, 2002; Tankersley, 2002; Wilcox, 2009). Additionally, a recent analysis of Chaco Canyon pollen samples found unusually high concentrations of maize pollen, supporting local agricultural production during the occupation of the Great Houses (Geib and Heitman, 2015).

Rather than viewing Chaco Canyon as an arid environmental wasteland, Ancestral Puebloan innovations in water management created an agricultural oasis (Vivian, 1990). In addition to the fertilizing sulfate mineral salts, Chaco Canyon was blanketed by felsic volcanic ash falls, which further enriched its soils (Haussner et al., 2015). Hydrologic modeling, based on multiple parameters including slope, soil permeability, soil depth, vegetation, and aridity further suggests that previous studies have underestimated the agricultural potential of Chaco Canyon (Dorshow, 2012; Vivian and Watson, 2015; Wills and Dorshow, 2012).

The construction of water management systems in arid environments to cope with rapid and profound climatic fluctuations is of more than a little anthropological interest (Scarborough, 2003). While the focus of this paper is on Chaco Canyon, these findings are germane to modern urban centers built in arid environments anywhere and anytime in the world. While the cost of building water management systems in drylands may be measured in terms of salt pollution, it is important to determine whether or not the salts are deleterious to agriculture and toxic to drinking water.

6. Conclusions

The theory that Ancestral Puebloan water management systems built in the dryland environment of Chaco Canyon, New Mexico led to

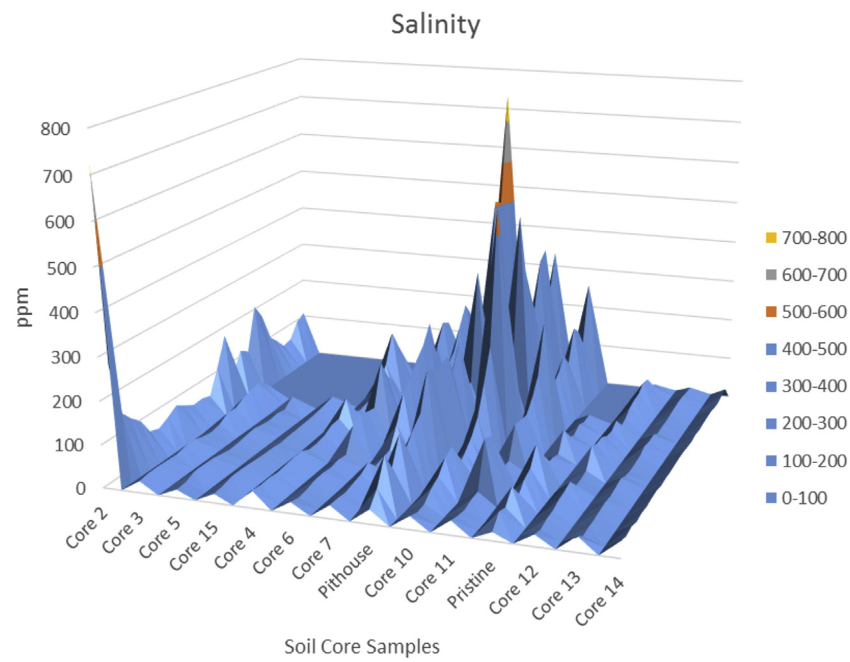

Fig. 5. Salinity of Robert's Great house soil samples.

catastrophic salt pollution and ultimately the abandonment of the area can no longer be supported. While numerous evaporite mineral salts are present in the soils of Chaco Canyon, NaCl and other potentially toxic salts are generally scarce. Furthermore, the salinization theory is ethnocentrically biased because it (1) ignores the use of sulfate mineral salts by Puebloan peoples and (2) assumes that the importation of maize was required for survival in Chaco Canyon.

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