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Ancient maize from Chacoan great houses: Where was it grown?

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In this article, we compare chemical ($^{87}Sr/^{86}Sr$ and elemental) analyses of archaeological maize from dated contexts within Pueblo Bonito, Chaco Canyon, New Mexico, to potential agricultural sites on the periphery of the San Juan Basin. The oldest maize analyzed from Pueblo Bonito probably was grown in an area located 80 km to the west at the base of the Chuska Mountains. The youngest maize came from the San Juan or Animas river floodplains 90 km to the north. This article demonstrates that maize, a dietary staple of southwestern Native Americans, was transported over considerable distances in pre-Columbian times, a finding fundamental to understanding the organization of pre-Columbian southwestern societies. In addition, this article provides support for the hypothesis that major construction events in Chaco Canyon were made possible because maize was brought in to support extra-local labor forces.

Between the 9th and 12th centuries *anno Domini* (A.D.), Chaco Canyon, located near the middle of the high-desert San Juan Basin of north-central New Mexico (Fig. 1), was the focus of an unprecedented construction effort. At the height of its cultural florescence in the 11th century, Chaco culture was characterized by the construction of monumental great houses (multistory, planned structures) that required millions of pieces of dressed sandstone, tens of thousands of roof beams (1, 2), water-control systems for agriculture (3), and a network of roads that linked the Chaco Canyon with other great houses and communities spread throughout a region covering at least 60,000 km^2 (4, 5).

Archaeologists disagree about whether the Chacoan system of great houses and roads functioned in a predominantly economic, political, symbolic, or ritualistic manner (4, 6–8). Pueblo Bonito, a multistory Chaco Canyon great house of several hundred rooms "contained caches of turquoise ornaments, unusual cylindrical jars, finely crafted projectile points, wooden ceremonial objects, tropical birds from Mesoamerica, and two elaborately buried men" (ref. 4, p. 6). The size of this structure, its numerous large rooms, and the richness of its contents suggest that it was a location where imported goods were amassed.

The construction sequence at Pueblo Bonito is particularly well documented through analyses of tree rings. Major construction occurred between the mid-800s and the mid-1100s (1, 9). During the first period of construction at Pueblo Bonito, Peñasco Blanco and Una Vida great houses were built in Chaco Canyon. After the first period of construction, the early great houses underwent major expansion, and rapid construction of others, such as Kin Kletso, Pueblo del Arroyo, Chetro Ketl, Pueblo Alto, and Hungo Pavi, occurred (Fig. 2) (10).

Maize (*Zea mays* L.) was the mainstay of the Native American diet in Chaco Canyon. Understanding whether maize was imported into Chaco and among other great houses throughout the San Juan Basin is crucial to resolving questions about whether sufficient staple food was grown in the canyon to support estimated resident populations and the number of workers required for great-house construction and expansion (11–14). In addition, some scholars (7, 15, 16) view Chaco as a largely ceremonial site where pilgrims participated in ritual feasting.

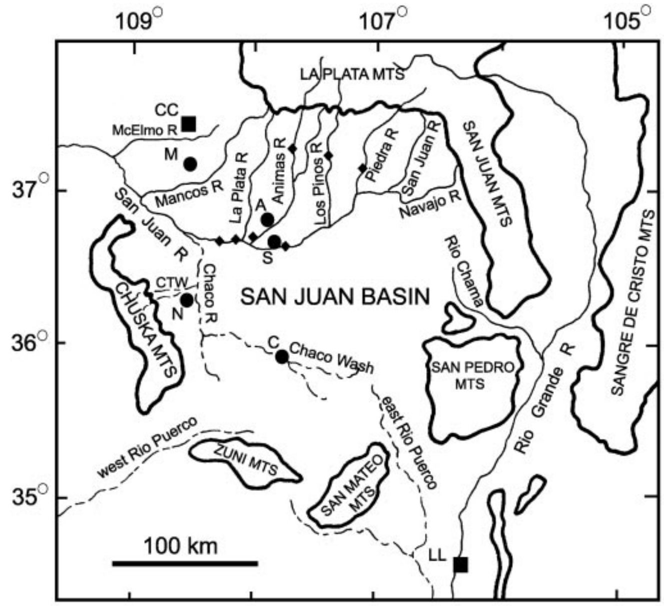

Fig. 1. Site location map for the San Juan Basin. CC, Crow Canyon; LL, Los Lunas; M, Mesa Verde; A, Aztec Ruin; S, Salmon Ruin; N, Newcomb; C, Chaco Canyon; CTW, Captain Tom Wash. ◆, Sample sites in San Juan River drainage (also see Fig. 4, which is published as supporting information on the PNAS web site, www.pnas.org). Dashed lines indicate ephemeral stream drainages.

This article demonstrates a method that can be used to tie ancient maize, the dietary foundation of southwestern Native Americans, to the locations where it was grown. Growing-season rainfall, totaling 150 mm, is considered the lower limit for maize production without irrigation (17), and maize productivity tends to be greatest where the frost-free period exceeds 120 days (18). Since 1922, May-through-September precipitation at Chaco Canyon has averaged only 119 mm, and the probability is 90% that only 93 consecutive days will be frost-free (Western Regional Climate Center, Desert Research Institute, www.wrcc.dri.edu). In addition, the Chaco River is an ephemeral stream that does not experience sustained or reliable runoff during the growing season. Today, the canyon is climatically marginal for the production of maize, and paleoclimatic reconstructions (19, 20) demonstrate that sustained production of maize at Chaco always was precarious (11).

Great-house sites other than Chaco exist at the periphery of the San Juan Basin that have superior agricultural potential,

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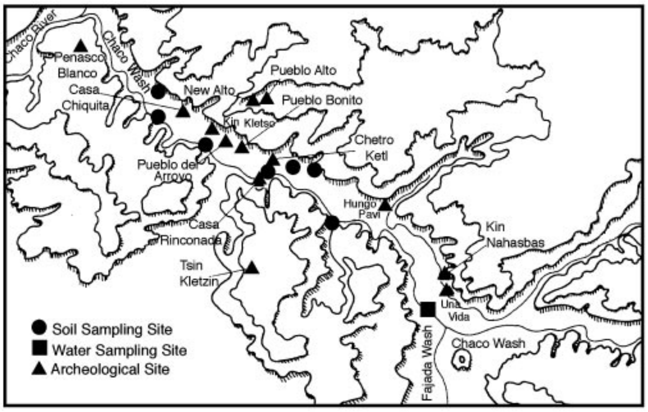

Fig. 2. Soil- and water-sampling sites in Chaco Canyon, New Mexico.

including the Newcomb/Skunk Springs (hereafter referred to as Newcomb) area on the Chuska Mountain slope, Salmon Ruin (hereafter referred to as Salmon) adjacent to the San Juan River floodplain, and Aztec Ruin (hereafter referred to as Aztec) adjacent to the Animas River floodplain (Fig. 1).

The Chuskas are the likely source area of some of Chaco's construction timber (2, 21), of high-quality chert (for flaked stone tools), and of vast quantities of Chaco's pottery (22–24). Numerous great houses at the base of the Chuska Mountains are contemporary with Pueblo Bonito and other Chaco Canyon great houses. These great houses include Newcomb, Skunk Springs, Standing Rock, Muddy Water, Kin Ya'a, and Peach Springs (25, 26).

Captain Tom Wash drains the central Chuskas (Fig. 1). Unlike Chaco Canyon, the Chuskas accumulate winter snow that melts and runs off during spring and early summer. Newcomb has a longer growing season than Chaco with a 90% probability of 136 consecutive frost-free days (Western Regional Climate Center, Desert Research Institute, www.wrcc.dri.edu).

Salmon is located adjacent to the San Juan River, the closest perennial water source to Chaco Canyon. Salmon is one of the largest Chacoan-era great houses and would have been a likely place from which residents of Chaco could have imported maize. The 398 published tree-ring dates for Salmon Ruin's Chacoan-age component, ranging from A.D. 1068 to 1116 (27), indicate that construction at Salmon was largely contemporary with the final period of Pueblo Bonito construction.

Aztec, a large Chacoan outlier (Fig. 1), contains two primary components, Aztec East and Aztec West (28). Construction of the immense Aztec West complex occurred between A.D. 1110 and 1130 with some remodeling in the 1200s. The initial construction of Aztec East postdates A.D. 1115, but the majority of tree-ring dates from Aztec East fall in the 13th century.**

The construction histories indicate that the chronologies of Pueblo Bonito, Newcomb, Aztec, and Salmon overlap, and that exchange could occur only during specific overlapping intervals. For example, exchange between Newcomb and Pueblo Bonito most likely occurred at times between A.D. $\approx$850 to $\approx$1150. Between Salmon and Pueblo Bonito, exchange most likely occurred from A.D. $\approx$1070 to $\approx$1150; and between Aztec and Pueblo Bonito, exchange could have occurred from A.D. $\approx$1115 to $\approx$1150. Because Aztec and Salmon were occupied during the late 12th and 13th centuries, exchange could have continued between these two sites.

Table 1. Element distribution coefficients in two experimental gardens

	Distribution coefficient K_d		
Garden	Ba/Sr	Mg/Sr	Y/Yb
Crow Canyon	0.29 ± 0.05	6.8 ± 0.0	15.2 ± 0.2
Los Lunas	0.31 ± 0.08	7.7 ± 0.0	17.0 ± 0.1

In this article, the provenances of pre-Columbian maize from dated contexts within the great houses of Pueblo Bonito and Aztec are established. Our thesis is that the chemistry ($^{87}Sr/^{86}Sr$ and some ratios of trace elements) of cobs should reflect the chemistry of their soil waters. The geochemistry of strontium isotopes is well understood and $^{87}Sr/^{86}Sr$ ratios have been used as environmental tracers in a variety of scientific applications (21, 29–32), and it has been shown that cobs from modern indigenous maize cultivars grown at sites in and bordering the San Juan Basin have different trace-element signatures (33).

Methods

To test the ability of $^{87}Sr/^{86}Sr$ and trace element ratios to act as provenance indicators, we used Hopi Blue corncobs and the soils they grew in from experimental gardens at the Crow Canyon Archaeological Research Center at Cortez, Colorado (34), and the New Mexico State University Agricultural Science Center at Los Lunas, New Mexico (35) (Fig. 1). Simulated soil waters were produced by leaching soils with 1% nitric acid or 1 M acetic acid, and cobs were ashed and dissolved in 3 M nitric acid (see *Supporting Methods*, which is published as supporting information on the PNAS web site). The results of the elemental analyses allowed us to define distribution coefficients (e.g., $K_{d,Ba/Sr} = [Ba/Sr]_{cob}/[Ba/Sr]_{water}$) for three elemental weight ratios (Ba/Sr, Mg/Sr, and Y/Yb) that had approximately the same values for both the Crow Canyon and Los Lunas gardens (Table 1). The $^{87}Sr/^{86}Sr$ ratios produced by both acetic and nitric acid leaches closely matched the $^{87}Sr/^{86}Sr$ ratios in the cobs grown in those soils (Fig. 3*A*), confirming this method as a provenance indicator. Because most of the Sr in the soil is present in carbonates (see *Supporting Text* and Table 4, which are published as supporting information on the PNAS web site), we elected to leach San Juan Basin soils with 1 M acetic acid for 48 h to dissolve the carbonate fraction and to replace Sr^{2+} on clay-exchange sites with H^+.

We sampled sites of potential maize cultivation, including Chaco Canyon, Newcomb, Salmon, and Aztec. Our soil-sampling strategy was guided by what is known or conjectured regarding pre-Columbian agricultural practices. In Chaco Canyon, it is possible that some fields were irrigated with runoff channeled from adjacent cliffs and from tributaries whose waters were diverted to field systems (3, 9, 36). Floodwater irrigation of crops on the Chaco Wash floodplain also may have occurred when the channel was not incised.

The Newcomb area is a site where maize was grown on floodplain deposits. When J. H. Simpson crossed the Newcomb area in A.D. 1849, he noted "very extensive and luxuriant cornfields" (37). One of three pre-Columbian Newcomb fields covered $\approx$19 km^2 with 74 km of main ditches.††

Salmon and Aztec are bordered by the floodplains of large perennial river systems (Fig. 1). Evidence exists for pre-Columbian agricultural diversion of water from the Animas River. Unfortunately, modern farming practices have obliterated

**Brown, G. M., Windes, T. C. & McKenna, P. J., 67th Annual Meeting of the Society for American Archaeology, March 20–24, 2002, Denver, CO (abstr.).

††Friedman, R. A., Stein, J. R. & Blackhorse, T., Jr., 2nd Quarterly Progress Meeting of The Southwest Native Peoples/Native Homelands Initiative, Sept. 3, 1999, Tucson, AZ (abstr.).

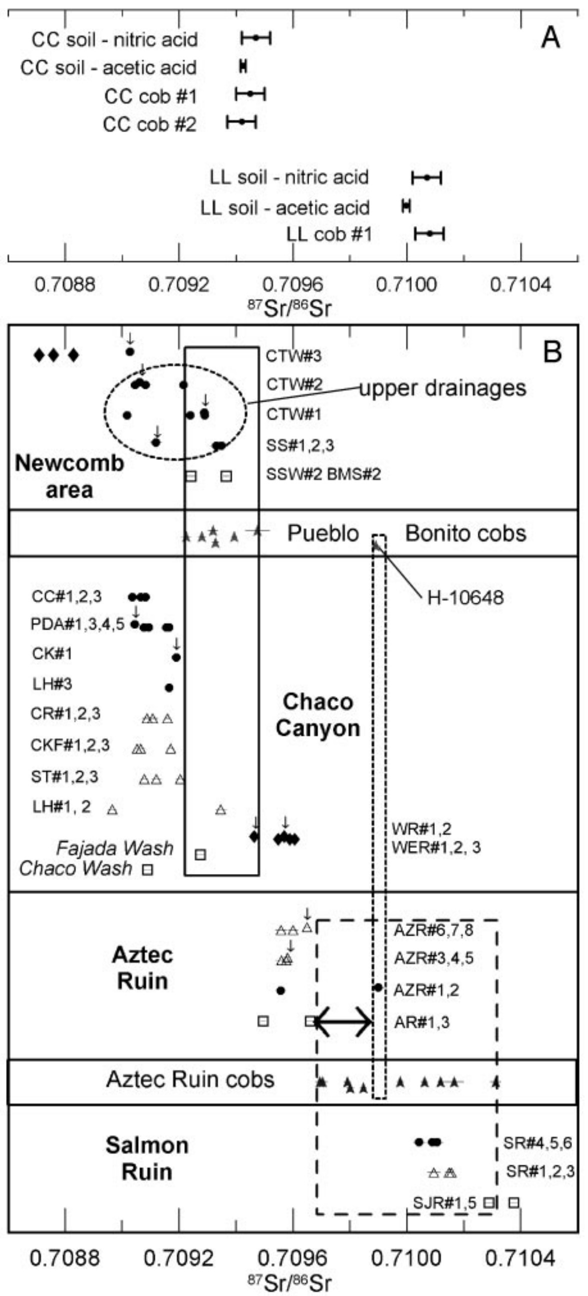

Fig. 3. (*A*) Pilot study showing that cobs and soil waters produced from Crow Canyon (CC) and Los Lunas (LL) gardens have consistent $^{87}Sr/^{86}Sr$ ratios. (*B*) $^{87}Sr/^{86}Sr$ ratios of eolian (◆), floodplain (●), and alluvial fan (△) sediments, surface waters (□), and cobs (▲) from the San Juan Basin. Small vertical arrows indicate surface-soil samples, which may not be representative of sediments deposited during the pre-Columbian occupation of the San Juan Basin. The dotted ellipse in *B Upper* encloses $^{87}Sr/^{86}Sr$ ratios from the upper drainages of Skunk Springs (SSW) and Captain Tom (CTW) washes. BMS, Basketmaker site on CTW; CC, Casa Chiquita; PDA, Pueblo del Arroyo; CK and CKF, Chetro Ketl Field area between LH and the Chetro Ketl Greathouse; LH, Lizard House Arroyo; CR, Casa Rinconada; ST, Section 10 site; WR and WER, Weritos Rincon; AZR, Aztec Ruin; AR, Animas River; SR, Salmon Ruin; and SJR, San Juan River. Doubled-headed arrow indicates possible $^{87}Sr/^{86}Sr$ range for the Animas River. The $^{87}Sr/^{86}Sr$ data displayed in this figure can be found in Table 4.

any indication of pre-Columbian irrigation along the San Juan River floodplain (P. Reed, personal communication).

Based on our knowledge of pre-Columbian agricultural strategies, soil samples were collected from alluvial fan, floodplain, and eolian deposits by augering or sampling exposures on the banks of washes and arroyos. Because we do not know the exact soil depth associated with pre-Columbian agricultural sites, samples were often taken at multiple depths. We sampled soils from a variety of locations in Chaco Canyon (Fig. 2) to compare the chemistries of Pueblo Bonito cobs with soil–water chemistries from several field locations. Water samples were collected from the San Juan River system, and from the Chaco, Captain Tom, and Skunk Springs washes. $^{87}Sr/^{86}Sr$ data for soil and surface waters (see *Supporting Text*) have been plotted together with $^{87}Sr/^{86}Sr$ ratios for archeological cobs from Pueblo Bonito and Aztec (Fig. 3*B*).

To ascertain the source of maize found in Pueblo Bonito, we analyzed seven cobs that were excavated by George Pepper between 1886 and 1899, as part of the Hyde Exploring Expedition. We also analyzed 10 cobs from Aztec. Cobs from Pueblo Bonito (excepting H-10648) were found in rooms that were built during the first phase of construction in the mid-800s. H-10648 was found in a room that was constructed between A.D. 1077 and 1082 (see *Supporting Text*). The cobs postdate construction activities and were often found associated with refuse. Thus, the oldest cobs probably date between A.D. 850 and the mid-900s, and H-10648 dates between A.D. 1080 and the end of construction at Chaco at about A.D. 1150. Six of nine cobs from Aztec have dated contexts of A.D. 1114, 1215 (two), 1240, and 1241 (two) (see *Supporting Text* and Table 5, which are published as supporting information on the PNAS web site). Rooms in Aztec West were in use a century after their construction (T. Windes, personal communication). Whereas the A.D. 1114 cob may date to the 12th century, it is possible that the rest of the cobs date to the 13th century.

Results and Discussion

Comparison of the $^{87}Sr/^{86}Sr$ ratios of the oldest Pueblo Bonito cobs with $^{87}Sr/^{86}Sr$ ratios in soil waters from Newcomb and Chaco Canyon indicates that the fields in which the maize grew were most likely located in the upper part of the Newcomb (Captain Tom Wash and Skunk Springs) drainages and/or that Sr from irrigation (wash) water was incorporated in the cobs. One water sample from the Chaco Wash, obtained when the Fajada Wash was the only contributor of water to the Chaco Wash (Figs. 2 and 3), has a $^{87}Sr/^{86}Sr$ ratio that falls within the range of Pueblo Bonito cob ratios. However, the Chaco Wash drainage area is $\approx$3 times the Fajada Wash drainage area, suggesting that Fajada Wash is usually a minor contributor of water (and Sr) to the Chaco Wash. This implies that the average $^{87}Sr/^{86}Sr$ ratio of Chaco Wash water is similar to its measured $^{87}Sr/^{86}Sr$ value and falls outside the $^{87}Sr/^{86}Sr$ range of Pueblo Bonito cobs (Fig. 3).

One surface eolian sample from Weritos Rincon (WR #1) and one alluvial fan sample from Lizard House arroyo (LH #2) have $^{87}Sr/^{86}Sr$ ratios that fall within the range of Pueblo Bonito cobs. The fields where these samples were collected are relatively small and could not have supplied much maize to people residing in the canyon (Fig. 2). In addition, other Lizard House arroyo samples have $^{87}Sr/^{86}Sr$ ratios unlike the cob ratios, suggesting that the $^{87}Sr/^{86}Sr$ of LH#2 may not be representative of material deposited in that small tributary. Cob H-10648 has a $^{87}Sr/^{86}Sr$ ratio similar to cobs found in Aztec. In addition, its $^{87}Sr/^{86}Sr$ ratio is nearly identical to the $^{87}Sr/^{86}Sr$ ratio of soil water produced from an Aztec overbank sample (AZR#2), suggesting that this cob may have grown on the Animas River floodplain. Soil waters produced from the majority of Chaco Canyon, Aztec, Salmon, and lower Newcomb field sites have $^{87}Sr/^{86}Sr$ ratios that differ markedly from the oldest Pueblo Bonito cobs (Fig. 3*B*).

To determine whether some Pueblo Bonito cobs came from maize grown on the Lizard House fan or Weritos Rincon or whether they came from maize grown in upper Newcomb

Table 2. Predicted soil–water weight ratios

Pueblo Bonito cobs	Ba/Sr	Mg/Sr	Y/Yb
H-242/242A	0.66	16.0	No data
H-242/244B	1.13	3.8	7.0
H-254/258A	0.59	3.0	11.0
H-254/258B	0.54	9.8	7.0
H-254/258C	0.84	4.5	9.0
H-7673	0.45	9.1	12.0

drainages, we compared predicted soil–water Ba/Sr, Mg/Sr, and Y/YB ratios, calculated by using measured ratios in Pueblo Bonito cobs (except H-10648) and their distribution coefficients (Tables 1, 2, and 3). The results indicate that the cobs from Pueblo Bonito most likely came from maize grown in upper Newcomb drainages.

The five highest $^{87}Sr/^{86}Sr$ ratios of Aztec cobs are similar to soil–water $^{87}Sr/^{86}Sr$ ratios from the Salmon site and to $^{87}Sr/^{86}Sr$ ratios in San Juan River water collected immediately upstream of the Salmon site (Fig. 3*B*). Sample AZR#2, a near-surface overbank deposit from the Animas River floodplain, possesses the only soil–water $^{87}Sr/^{86}Sr$ ratio that falls within the $^{87}Sr/^{86}Sr$ range of Aztec cobs. The $^{87}Sr/^{86}Sr$ ratio of Animas River water shows significant variability with the highest $^{87}Sr/^{86}Sr$ ratio having nearly the same value as two cobs from Aztec (Fig. 3*B*). We cannot rule out the Animas River floodplain as the source of some of the Aztec cobs; in fact, the Animas River may have experienced higher $^{87}Sr/^{86}Sr$ ratios, from time to time, depending on the relative flux of Sr from its tributaries. (Values ranging from 0.7095 to 0.7099 depicted by the double-headed arrow in Fig. 3*B* are plotted in Fig. 4.) In addition, the $^{87}Sr/^{86}Sr$ ratios of floodplain sediments are highly variable, ranging from 0.7096 to 0.7099 (see Fig. 4 and *Supporting Text*). However, the available data indicate that Salmon is the most likely source of cobs found at Aztec.

This article ties ancient maize to locations where it was grown. We do not know the quantity of maize brought into Chaco Canyon; however, maize found in older sections of Pueblo Bonito was most likely imported from the Newcomb area. Maize found in Aztec was grown either on the Animas River floodplain or, more likely, on the San Juan floodplain, confirming that exchange of food occurred among these areas at various times. Although a variety of preciosities have been shown to have been imported from great distances in pre-Columbian times (4), we know of no previous study demonstrating that maize, a dietary staple of southwestern Native Americans, was imported from distant agricultural sites. In addition, this article supports the hypothesis that importation of maize and labor was necessary for the construction of Chaco Canyon great houses.

Table 3. Measured soil–water weight ratios for selected potential agricultural sites

Soil site	Ba/Sr	Mg/Sr	Y/Yb
Upper Newcomb drainage			
SS #1	0.57	12	15
SS #3	0.35	13	17
CTW #1B	0.19	21	14
CTW #1C	0.11	23	16
Chaco Canyon sites			
WER #1	3.08	68	22
WER #2	2.26	79	20
WER #3	1.46	65	20
LH #2	1.46	130	24

SS, Skunk Springs; CTW, Captain Tom Wash; WER, Weritos Rincon; LH, Lizard House.

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