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Possible sources of archaeological maize found in Chaco Canyon and Aztec Ruin, New Mexico

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ABSTRACT

Maize played a major role in Chaco's interaction with outlying communities in the southern Colorado Plateau. This paper seeks to determine where archaeological corn cobs brought to Chaco Canyon were grown. Strontium-isotope and trace-metal ratios of 180 soil-water and 18 surface-water sites in the Southern Colorado Plateau have revealed possible source areas for some of 37 archaeological corn cobs from Chaco Canyon and 10 archaeological corn cobs from Aztec Ruin, New Mexico. The most probable source areas for cobs that predate the middle-12th-century drought include several Upper Rio Chaco sites (not including Chaco Canyon). There are many potential source areas for cobs that date to the late A.D. 1100s and early 1200s, all of which lie in the eastern part of the study area. Some Athapascan-age cobs have potential source areas in the Totah, Lobo Mesa, and Dinetah regions. One Gallo Cliff Dwelling cob has a strontium-isotope ratio that exceeds all measured soil-water values. Field sites for this cob may exist in association with Paleozoic and Precambrian rocks found 80–90 km from Chaco Canyon. Potential source areas for most Aztec Ruin cobs (many of which were found in rooms dating to the first half of the 13th-century) appear to be associated with a loess deposit that blankets the Mesa Verde and McElmo Dome regions.

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1. Introduction

Chaco Canyon, New Mexico, is located in the heart of the semiarid San Juan Basin (Fig. 1). Between A.D. 850 and 1130, a dozen great houses were constructed in Chaco Canyon with major phases of construction occurring during the Late PII-Classic phase (A.D. 1040–1100) and Early PIII-Late Bonito phase (A.D. 1100–1140) (Lekson, 1984). Many Chacoan-style outlier great houses exhibiting "Bonito-style" architecture also were constructed throughout the San Juan Basin and adjacent areas during the Late Bonito phase (Fig. 1 in Van Dyke, 1999). "Bonito-style" refers to a collection of architectural features including a many-roomed, multiple-storied great house with core-and-veneer masonry, one or more great kivas, and earthworks (Marshall et al., 1982). Most of the great houses were vacated during the middle-12th-century drought with final abandonment of the remaining great houses during the late-13^{th}-century drought (Supplementary Figure 1, Benson et al., 2007).

The relation of Chaco to outlier communities has engendered a great deal of theoretical argument which Van Dyke (1999) has recently summarized. The theoretical models differ in the style and degree of control that Chaco exerted over these communities; e.g., Vivian (1989) and Wilcox (1993) have suggested that people from Chaco were directly responsible for the construction of the communities exhibiting Bonito-style architecture and Wilcox (1993) has gone so far as to suggest that Chaco was a military state with a social hierarchy in which economics and religion were centralized. In Wilcox's model, outliers functioned as military headquarters which were established to control the surrounding countryside and to obtain agriculture tribute.

Stein and Lekson (1992) have suggested a model which markedly differs from that suggested by Wilcox (1993) and have argued that the region, which encompassed 11th - and 12th-century communities with Bonito-style architecture (Supplementary Figure 1), was much too large for a coherent "state" to have existed. Instead, they suggested that Bonito-style architecture symbolically linked outlier communities that were otherwise separated by language and ethnicity. In their model, great houses, great kivas, roads, and platform mounds embodied a symbolic ritual landscape that was imitated over much of the Southern Colorado Plateau.

A range of cultural theories exist that, in terms of Chacoan control over outlying communities, lie somewhere in-between the two extremes discussed above. One of them (Judge, 1979) invokes a Chaco-outlier interaction model in which maize figured strongly. In his original theoretical construction, Chaco Canyon acted as a redistribution center for subsistence goods. Judge (1989) later

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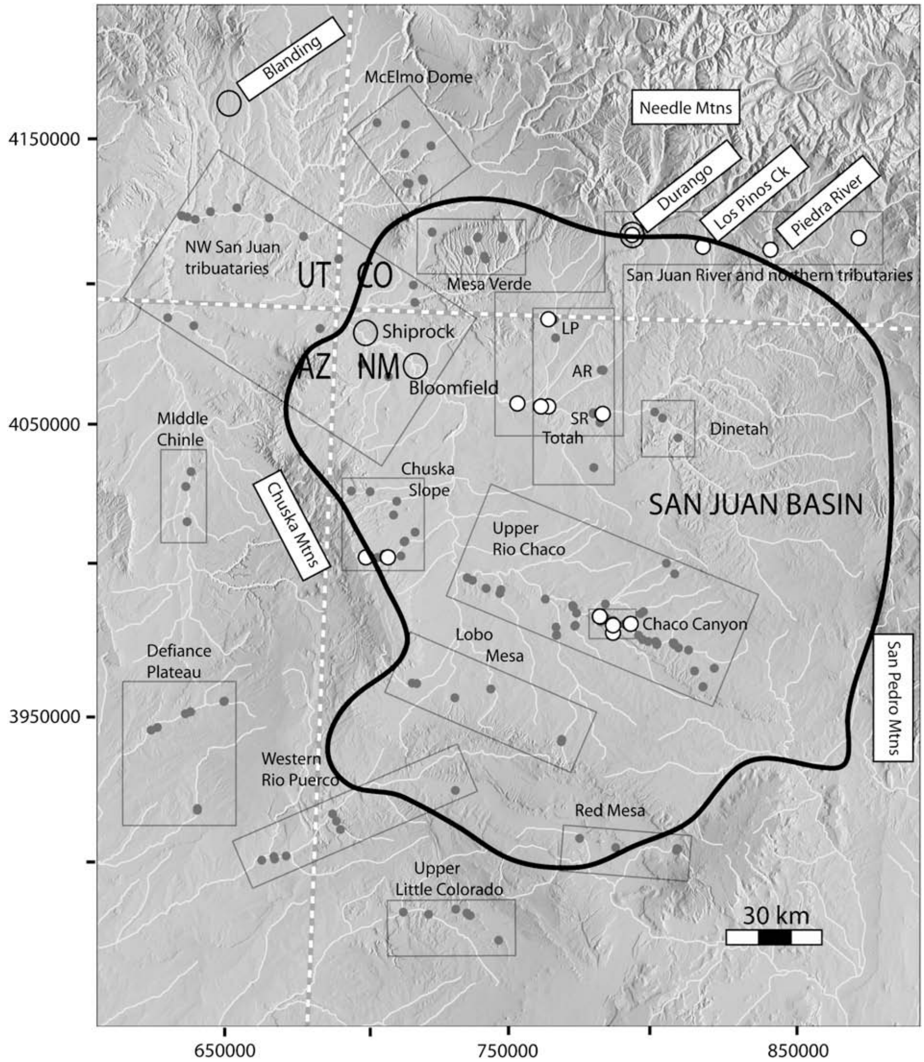

Fig. 1. Location map showing soil sample (black dots) and water sampling sites (white dots). Heavy black line forms the perimeter of the San Juan Basin. LP, AR, and SR indicate the LaPlata River, Aztec Ruin, and Salmon Ruin, respectively. Surface-water systems are shown as white lines. Rectangles bound labeled sampling regions listed in Table 2. Coordinates referenced to NAD 27 datum.

modified the redistribution model such that formal pilgrimages to Chaco developed during the Classic Bonito phase wherein "goods were transported to Chaco from outlying locations and consumed under a ritual metaphor."

We will probably never know the exact relation of Chaco to outlier great house communities. However, maize was involved in Chaco's interaction with the outliers, whether it took place under the auspices of a military state, whether Chaco acted as a benevolent redistribution center, or whether Chaco was a place of power that was visited and celebrated during "pilgrimage fairs". The importation of maize thus offers a measure of cultural exchange between Chaco and the outlying communities.

This paper represents the fourth in a series of studies (Benson et al., 2003, 2006, 2008) that seek to determine the source(s) of archaeological corn cobs (hereafter referred to as cobs) found in Chaco Canyon. In the first study, Benson et al. (2003) created synthetic soil-waters by leaching agricultural soils with acetic acid and showed that the isotope ratios ($^{87}Sr/^{86}Sr$) of strontium (Sr) in the synthetic soil-waters were identical to the $^{87}Sr/^{86}Sr$ ratios of Sr in cobs produced from those soils. They also compared the $^{87}Sr/^{86}Sr$ ratios of seven archaeological cobs from Pueblo Bonito with three candidate source areas: the Chuska slope (four soil sites), Salmon Ruin (two sites) and Aztec Ruin (three soil sites) (both located in the Totah region), and Chaco Canyon itself (10 soil sites). The data suggested that the most likely source area for six of the cobs was the Chuska slope and the most likely source of the seventh cob was the Totah region.

In the second study, Benson et al. (2006) increased the sampling density of soils in the three areas, including the Chuska slope (14 soil sites), Salmon Ruin (five soil sites), Aztec Ruin (six soil sites), and Chaco Canyon (22 soil sites). The new Totah-area samples came from the Animas and San Juan river floodplains and most of the new samples from Chaco Canyon came from side-valley tributaries. In addition, 12 new side-tributary and floodplain sites downstream from Chaco Canyon and two new upstream sites were sampled. One sample also was collected from beside the Escavada Wash north of the canyon. The $^{87}Sr/^{86}Sr$ ratios of synthetic soil-waters produced in this study showed that several downstream Rio Chaco side-tributary sites between the canyon and the Big Bend of the Rio Chaco also could have been the source(s) of six of the Pueblo Bonito cobs.

In the third study, Benson et al. (2008) sought to refine trace-metal distribution coefficients that describe the systematic partitioning of some metal pairs from soil-water into a cob. According to these authors "The use of the distribution coefficient accounts for

Table 1
Radiocarbon and $^{87}Sr/^{86}Sr$ data for archaeological cobs from Aztec Ruin and Chaco Canyon

Site no.	Site name	^{14}C Lab no.	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	^{14}C error (yr)	Cal. age midpt. (1σ AD)	Cal. age range (1σ yr)	Range prob. (fraction)	Cal. age midpt. (2σ AD)	Cal. age range (2σ yr)	Range prob. (fraction)	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$ error (2σ)
Aztec Ruin Cobs													
AZRU 533A	East Room P15											0.709848	0.000011
AZRU 533B	East Room P15											0.710119	0.000010
AZRU 1052	East Room 11											0.710166	0.000034
AZRU 1057	East Room 14											0.710312	0.000019
AZRU 3853	East Room 12											0.709801	0.000015
AZRU 3921	West Room 224											0.709791	0.000012
AZRU 9341	West Room 225											0.710062	0.000012
AZRU 9438	West Room 225											0.709705	0.000016
AZRU 9651	**West Room 225**											0.709977	0.000012
AZRU 11091	**West Room 186**											0.709694	0.000015
Pueblo Bonito Cobs													
H10648	Pueblo Bonito Room 170	Beta-188110	−8.8	1020	40	1005	974–1040	0.99	998	944–1052	0.79	0.709892	0.000016
H242/244A	Pueblo Bonito Room 3	Beta-188111	−8.9	1050	40	996	969–1023	0.90	963	892–1034	1.00	0.709319	0.000016
H242/244B	Pueblo Bonito Room 3	Beta-198921		1060	40	994	967–1020	0.83	960	893–1026	1.00	0.709475	0.000042
H254/258A	Pueblo Bonito Room 3	Beta-188112	−9.6	890	40	1181	1151–1211	0.56	1127	1035–1219	1.00	0.709394	0.000010
H254/258B	Pueblo Bonito Room 3	Beta-188113	−10.1	1080	40	972	947–998	0.64	955	889–1021	1.00	0.709225	0.000018
H254/258C	**Pueblo Bonito Room 3**	Beta-198920		1190	40	832	779–886	1.00	834	765–902	0.82	0.709280	0.000014
H7673	Pueblo Bonito Room 92	Beta-181114	−9.9	830	50	1214	1169–1258	1.00	1213	1148–1278	0.87	0.709328	0.000011
Other Chaco Canyon Cobs													
CHCU2081-1	**Una Vida**											0.709401	0.000009
CHCU2685-1	**Cliff Face**	UCIAMS#23973	−9.9	170	20	***1758***	1736–1780	0.62	***1756***	1728–1785	0.50	0.713553	0.000013
CHCU2685-2	Cliff Face	UCIAMS#23974	−10.2	360	20	***1494***	1470–1519	0.64	***1490***	1455–1524	0.54	0.710082	0.000015
CHCU32288-1	Chetro Ketl Room 92	UCIAMS#23975	−9.3	880	20	1183	1156–1210	1.00	1184	1151–1217	0.77	0.709523	0.000014
CHCU32288-2	Chetro Ketl Room 92	UCIAMS#23976	−9.1	870	20	1186	1163–1208	1.00	1186	1153–1220	0.91	0.709350	0.000009
CHCU32289-1	**Chetro Ketl Room 92**	UCIAMS#23977	−9.5	870	20	1186	1163–1208	1.00	1186	1153–1220	0.91	0.709547	0.000015
CHCU32299-1	**Kin Kletso**	UCIAMS#23978	−9.4	805	20	1238	1222–1254	1.00	1240	1209–1270	1.00	0.710747	0.000010
CHCU32999-1	**Kin Kletso**	UCIAMS#23979	−10.1	850	25	1194	1170–1218	1.00	1206	1155–1258	0.99	0.709258	0.000015
CHCU32999-2	**Kin Kletso**	UCIAMS#23980	−9.7	880	20	1183	1156–1210	1.00	1184	1151–1217	0.77	0.709280	0.000012
CHCU43684-1	Gallo Cliff Dwelling	UCIAMS#23981	−8.8	845	25	1195	1170–1220	1.00	1208	1158–1258	1.00	0.710880	0.000014
CHCU43684-2	**Gallo Cliff Dwelling**	UCIAMS#23983	−9.6	845	20	1198	1177–1219	1.00	1194	1161–1228	0.93	0.711062	0.000014
CHCU43684-3	Gallo Cliff Dwelling	UCIAMS#23984	−10.6	850	25	1194	1170–1218	1.00	1206	1155–1258	0.99	0.709638	0.000011
CHCU43684-4	**Gallo Cliff Dwelling**	UCIAMS#23985	−10.5	915	25	1070	1045–1095	0.60	1107	1032–1182	1.00	0.709770	0.000011
CHCU43684-5	Gallo Cliff Dwelling	UCIAMS#23986	−10.1	880	20	1183	1156–1210	1.00	1184	1151–1217	0.77	0.709586	0.000015
CHCU43684-6	Gallo Cliff Dwelling	UCIAMS#23987	−9.6	870	25	1186	1160–1212	1.00	1186	1149–1224	0.82	0.709412	0.000011
CHCU43684-7	**Gallo Cliff Dwelling**	UCIAMS#23989	−10.0	875	25	1184	1155–1214	1.00	1184	1148–1221	0.76	0.710244	0.000010
CHCU43684-8	Gallo Cliff Dwelling	UCIAMS#23990	−10.0	880	25	1184	1155–1212	0.90	1183	1147–1219	0.69	0.709759	0.000011
CHCU43684-9	Gallo Cliff Dwelling	UCIAMS#23991	−9.4	855	30	1190	1162–1219	1.00	1206	1152–1259	0.91	0.710010	0.000014
CHCU43684-10	Gallo Cliff Dwelling	UCIAMS#23992	−10.2	865	20	1188	1167–1209	1.00	1188	1154–1221	0.95	0.709961	0.000014
CHCU43684-11	**Gallo Cliff Dwelling**	UCIAMS#23994	−9.8	865	20	1188	1167–1209	1.00	1188	1154–1221	0.95	0.710270	0.000013
CHCU43684-12	**Gallo Cliff Dwelling**	UCIAMS#23995	−10.1	880	20	1183	1156–1210	1.00	1184	1151–1217	0.77	0.710198	0.000010
CHCU43684-13	**Gallo Cliff Dwelling**	UCIAMS#23996	−9.1	875	20	1184	1160–1208	1.00	1185	1152–1218	0.85	0.711580	0.000013
CHCU43684-14	**Gallo Cliff Dwelling**	UCIAMS#23997	−8.8	870	20	1186	1163–1208	1.00	1186	1153–1220	0.91	0.711575	0.000015
CHCU43684-15	Gallo Cliff Dwelling	UCIAMS#23998	−9.5	875	20	1184	1160–1208	1.00	1185	1152–1218	0.85	0.710143	0.000015
CHCU43684-16	Gallo Cliff Dwelling	UCIAMS#23999	−8.9	885	20	1182	1155–1208	0.86	1182	1149–1216	0.68	0.710094	0.000013
CHCU50553-1	**Cliff Face Room 29mC499**	UCIAMS#24000	−8.2	125	25	***1858***	1832–1885	0.44	***1847***	1800–1894	0.50	0.710769	0.000022
CHCU50553-2	**Cliff Face Room 29mC499**	UCIAMS#24001	−9.0	115	20	***1859***	1832–1886	0.55	***1850***	1805–1895	0.57	0.711302	0.000014
CHCU57-1	**BC 236**	UCIAMS#23972	−9.7	835	25	1201	1176–1226	0.91	1211	1164–1258	1.00	0.710165	0.000014
Site#1 Chaco E cob#1	**29SJ 176, LA 40176**	UCIAMS#24002	−8.6	155	20	***1754***	1730–1777	0.55	***1754***	1725–1782	0.43	0.710134	0.000011
Site#1 Chaco E cob#2	29SJ 176, LA 40176	UCIAMS#24003	−9.0	165	20	***1756***	1735–1778	0.61	***1756***	1727–1784	0.49	0.709839	0.000016

Bold site numbers and names indicate samples which are Sr contaminated; ^{14}C dates in italics and bold indicate Athapascan-age samples.
Pueblo Bonito cob dates taken from Cordell et al. (2008).

the bioavailability of chemical species (they are part of the soil-water solution), and the use of a metal ratio negates the effect of changes in soil-water concentration on the concentrations of individual dissolved trace-metals. However, K_D is not constant for all metal ratios. Metal pairs that contain a trace nutrient that the plant prefers to incorporate or a trace-metal that the plant prefers to exclude (e.g. lead) may exhibit widely varying K_D values. In addition to being plant-species dependent, the K_D value also depends on the set of environmental conditions under which the plant grew; e.g., moisture or nutrient stress. K_D values will tend to be relatively constant for element pairs that have similar chemical properties if those properties are neither essential nor harmful to the plant."

Using an extremely limited data set, Benson et al. (2003) had earlier suggested that three metal pairs (Ba/Sr, Mg/Sr, Y/Yb) might obey the relation

$$K_D(C_{TE1}/C_{TE2})_{Soil\ water} = (C_{TE1}/C_{TE2})_{Cob} \quad (1.1)$$

where C_{TE1}/C_{TE2} is the concentration (μg element/g dry-weight soil) ratio of trace-metals 1 and 2 and K_D indicates the distribution coefficient. If this was true, then those metal pairs could be used in the same manner as $^{87}Sr/^{86}Sr$ to further define maize source areas.

In order to refine the results of earlier studies, Benson et al. (2008) selected two cobs from each of 10 plants from each of five Native American landraces grown out at New Mexico State University's Agricultural Science Center, Farmington, New Mexico (Adams et al., 2006). Soils were obtained from both sides of the corn row at the base of each stalk at depths centered on 35 and 70 cm. After a series of pretreatments (see methods section in Benson et al., 2008), multi-trace-metal determinations were performed on the cobs and the synthetic soil-waters, using inductively coupled plasma-mass-spectrometry (ICP-MS) and ICP emission spectrometry (ICP-AES). Using all paired combinations of the 51 measured trace-metals, it was determined that four metal pairs (Ba/Sr, Ba/Mn, Ca/Sr, and K/Rb) exhibited systematic distribution coefficients (standard deviation of a metal pair K_D for a particular landrace was ≤33% of its mean value) between soil-waters and all cob types.

This paper represents a progress report with regard to our maize-sourcing research. The objective of this study was to determine the source(s) of 37 archaeological cobs found in Chaco Canyon in the hope that such data will help better decipher Chaco's interaction with other communities within the greater San Juan Basin between A.D. 850 and 1300. In the present study, we have expanded our sampling to include soils from 14 regions and 180 sites within the San Juan Basin and adjacent areas (Fig. 1); we also have analyzed 30 additional archaeological cobs. Methods employed in this study, as well as trace-metal and $^{87}Sr/^{86}Sr$ data sets resulting from this study, can be found in supplementary online material, which includes Supplementary Tables 1–5.

2. Results

2.1. Radiocarbon ages of the archaeological cobs

The ^{14}C ages of the Aztec West Ruin and Pueblo Bonito cobs that were analyzed for $^{87}Sr/^{86}Sr$ and trace-metals were not determined by Benson et al. (2003); however, Cordell et al. (2008) have recently dated seven of the Pueblo Bonito cobs and those dates have been included in Table 1. Six of the Aztec Ruin cobs (AZRU 11091, 533A, 533B, 1057, 3853 and 1052) are associated with room timber-cutting dates of, respectively, A.D. 1114, 1215, 1215, 1240, 1241, and 1241. Thus, the oldest cob was probably deposited prior to the middle-12th-century drought and the remaining cobs were deposited after the middle-12th-century drought, but prior to the late-13th-century drought.

For the present study, we were able to obtain ^{14}C dates on 29 of 30 archaeological cobs from six archaeological contexts (Cliff Face, Chetro Ketl, Kin Kletso, Gallo Cliff Dwelling, BC 236, and 29SJ 176/LA 40176; Table 1). One cob from Una Vida did not survive the acid-base treatment at the Keck Carbon Cycle AMS Facility. Most (16) of the new cobs came from a trash area in Gallo Cliff Dwelling (CHCU 43684) in which 256 cobs had been discarded.

The cobs exhibit a wide range of calibrated dates with the six youngest cobs presumably being Athapascan in origin (Fig. 2A). The Athapascan-age cobs came from three caches in and east of Downtown Chaco; e.g., the 29SJ176 samples came from a crushed "storage" room 0.5 km west of Sheep Camp Canyon. Calibrations were performed using CALIB 5.0 (Stuiver et al., 2005). The remaining 25 cobs range in age from A.D.1070 to 1240 (calibrated ages mentioned here are midpoints of 1-sigma age ranges). However, many of the cobs (21) have essentially the same age

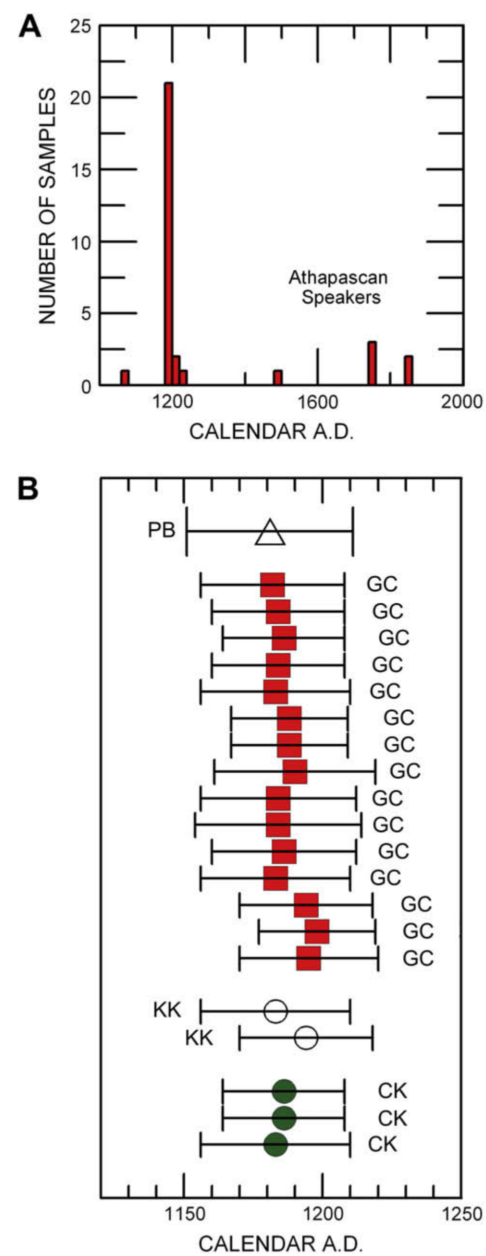

Fig. 2. (A) Calendar-age histogram of archaeological cobs discussed in this paper. (B) Twenty-one cobs from Pueblo Bonito (PB), Gallo Cliff Dwelling (GC), Kin Klizhin (KK), and Chetro Ketl (CK) that have essentially the same age.

Table 2
Site information, $^{87}Sr/^{86}Sr$, and K/Rb ratios for synthetic soil-waters from the Southern Colorado Plateau (chemical data are grouped by location)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			Pueblo Bonito		Chetro Ketl		Gallo Cliff Dwelling		Aztec Ruin	
	McElmo Dome Soils									
AP06-1	Albert Porter sage field	1	0.70966	2055	0.70966	2055	0.70966	2055	0.70966	2055
AP06-2	Albert Porter sage field	2	0.70942	1588	0.70942	1588	0.70942	1588	0.70942	1588
GPO6-1	Goodman Pt sage and rabbit brush	3	0.70937	5144	0.70937	5144	0.70937	5144	0.70937	5144
GPO6-2	Goodman Pt grass drainage	4	0.70938	2986	0.70938	2986	0.70938	2986	0.70938	2986
LR06-1	Lowry Pueblo in Pinon/Juniper	5	0.70971	877	0.70971	877	0.70971	877	0.70971	877
LR06-2	Lowry Pueblo	6	0.70945	1730	0.70945	1730	0.70945	1730	0.70945	1730
SCO6-1	Sand Canyon fallow field	7	0.70941	2306	0.70941	2306	0.70941	2306	0.70941	2306
SCO6-2	Sand Canyon in trees	8	0.70925	2352	0.70925	2352	0.70925	2352	0.70925	2352
SCO6-3	Sand Canyon fallow field	9	0.70962	1569	0.70962	1569	0.70962	1569	0.70962	1569
SPO6-1	Shields Pueblo fallow field	10	0.70962	968	0.70962	968	0.70962	968	0.70962	968
SPO6-2	Shields Pueblo fallow field	11	0.70967	1512	0.70967	1512	0.70967	1512	0.70967	1512
YJ06-1	Yellow Jacket fallow field	12	0.70967	2079	0.70967	2079	0.70967	2079	0.70967	2079
YJ06-2	Yellow Jacket fallow field	13	0.70970	2038	0.70970	2038	0.70970	2038	0.70970	2038
	Mesa Verde Soils									
CP06-1	Cliff Palace, Chapin Mesa	16	0.70999	1107	0.70999	1107	0.70999	1107	0.70999	1107
CP06-2	Cliff Palace, Chapin Mesa	17	0.70976	1094	0.70976	1094	0.70976	1094	0.70976	1094
CV06-1	Coyote Village, Chapin Mesa	18	0.70980	3053	0.70980	3053	0.70980	3053	0.70980	3053
FV06-1	Far View, Chapin Mesa	19	0.70981	985	0.70981	985	0.70981	985	0.70981	985
FV06-2	Far View, Chapin Mesa	20	0.70974	1431	0.70974	1431	0.70974	1431	0.70974	1431
LH06-1	Long House, Weatherill Mesa	21	0.70993	1231	0.70993	1231	0.70993	1231	0.70993	1231
MC06-1	Moorfield Community Mesa Verde	22	0.70981	3838	0.70981	3838	0.70981	3838	0.70981	3838
MC06-2	Moorfield Community Mesa Verde	23	0.70998	1128	0.70998	1128	0.70998	1128	0.70998	1128
MC06-3	Moorfield Community Mesa Verde	24	0.70991	2738	0.70991	2738	0.70991	2738	0.70991	2738
MH06-1	Mug House, Weatherill Mesa	25	0.70980	1069	0.70980	1069	0.70980	1069	0.70980	1069
YH06-1	Yucca House wet draw 1	14	0.70800	1629	0.70800	1629	0.70800	1629	0.70800	1629
YH06-2	Yucca House wet draw 2	15	0.70857	2441	0.70857	2441	0.70857	2441	0.70857	2441
	Totah (Aztec Ruin) Soils									
AZR#1	Animas River Bank	26	0.70990	397	0.70990	397	0.70990	397	0.70990	397
AZR#4	Aztec Ruin alluvial fan	27	0.70956	1893	0.70956	1893	0.70956	1893	0.70956	1893
AZR#7	Aztec Ruin alluvial fan	28	0.70960	1227	0.70960	1227	0.70960	1227	0.70960	1227
AZR04-1	Aztec Ruin floodplain	29	0.70957	1271	0.70957	1271	0.70957	1271	0.70957	1271
AZR04-2	Aztec Ruin floodplain	30	0.70953	548	0.70953	548	0.70953	548	0.70953	548
AZR04-3	Aztec Ruin floodplain	31	0.70959	455	0.70959	455	0.70959	455	0.70959	455
	Totah (Salmon Ruin) Soils									
SAL#1	Salmon Ruin Floodplain	32	0.71006	1099	0.71006	1099	0.71006	1099	0.71006	1099
SAL#2	Salmon Ruin Floodplain	33	0.71001	880	0.71001	880	0.71001	880	0.71001	880
SJS#1	San Juan River Bank @ Bloomfield	34	0.71024	586	0.71024	586	0.71024	586	0.71024	586
SR#2	Salmon Ruin Orchard	35	0.71016	3037	0.71016	3037	0.71016	3037	0.71016	3037
SR#5	Salmon Ruin Floodplain	36	0.71011	202	0.71011	202	0.71011	202	0.71011	202
	Totah (LaPlata) Soils									
HG06-1	Holmes Grp. flood plain	37	0.70913	3916	0.70913	3916	0.70913	3916	0.70913	3916
HG06-2	Holmes Grp. flood plain	38	0.70891	7182	0.70891	7182	0.70891	7182	0.70891	7182
HG06-3	Holmes Grp. old flood plain	39	0.70883	7421	0.70883	7421	0.70883	7421	0.70883	7421
LP06-1	La Plata R. flood plain	40	0.70877	1863	0.70877	1863	0.70877	1863	0.70877	1863
LP06-2	La Plata R. flood plain	41	0.70884	1015	0.70884	1015	0.70884	1015	0.70884	1015
LP06-3	La Plata R. old flood plain	42	0.70865	5613	0.70865	5613	0.70865	5613	0.70865	5613

(*continued on next page*)

Table 2 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			Pueblo Bonito		Chetro Ketl		Gallo Cliff Dwelling		Aztec Ruin	
	Totah (South of San Juan River) Soils									
KC07-1	Kutz Canyon Wash	178	0.70970	841	0.70970	841	0.70970	841	0.70970	841
GCW07-1	Gallegos Canyon Wash	157	0.70944	1049	0.70944	1049	0.70944	1049	0.70944	1049
	Middle Chinle Soils									
MF06-1	Many Farms	43	0.70886	3315	0.70886	3315	0.70886	3315	0.70886	3315
MF06-2	Many Farms	44	0.70922	4340	0.70922	4340	0.70922	4340	0.70922	4340
MF06-3	Many Farms	45	0.70926	4756	0.70926	4756	0.70926	4756	0.70926	4756
	Chuska Slope Soils									
CT#1	Captain Toms Wash	46	0.70929	2192	0.70929	2192	0.70929	2192	0.70929	2192
CT#2	Captain Toms Wash	47	0.70906	2434	0.70906	2434	0.70906	2434	0.70906	2434
CT#3	Captain Toms Wash	48	0.70903	1789	0.70903	1789	0.70903	1789	0.70903	1789
CTW#1B	Captain Toms Wash	49	0.70924	1370	0.70924	1370	0.70924	1370	0.70924	1370
CTW#2B	Captain Toms Wash	50	0.70922	282	0.70922	282	0.70922	282	0.70922	282
CTW#3A	Captain Toms Wash	51	0.70883	257	0.70883	257	0.70883	257	0.70883	257
SA06-1	Sanostee	52	0.70850	2583	0.70850	2583	0.70850	2583	0.70850	2583
SA06-2	Sanostee	53	0.70874	3659	0.70874	3659	0.70874	3659	0.70874	3659
SA06-3	Sanostee	54	0.70897	3023	0.70897	3023	0.70897	3023	0.70897	3023
TO06-1	Tocito seep	55	0.70877	743	0.70877	743	0.70877	743	0.70877	743
TO06-2	Tocito Wash	56	0.70890	1028	0.70890	1028	0.70890	1028	0.70890	1028
SS#1	Skunk Springs Bank Deposit	57	0.70933	328	0.70933	328	0.70933	328	0.70933	328
TGHBM#1	Two Grey Hills Basketmaker	58	0.70904	1694	0.70904	1694	0.70904	1694	0.70904	1694
TGHBM#2	Two Grey Hills Basketmaker	59	0.70917	678	0.70917	678	0.70917	678	0.70917	678
TGHBM#3	Two Grey Hills Basketmaker	60	0.70912	1800	0.70912	1800	0.70912	1800	0.70912	1800
TGHBM#4	Two Grey Hills Basketmaker	61	0.70923	1078	0.70923	1078	0.70923	1078	0.70923	1078
TGHBM#5	Two Grey Hills Basketmaker	62	0.70920	385	0.70920	385	0.70920	385	0.70920	385
TGHBM#6	Two Grey Hills Basketmaker	63	0.70930	1259	0.70930	1259	0.70930	1259	0.70930	1259
TGHBM#7	Two Grey Hills Basketmaker	64	0.70906	642	0.70906	642	0.70906	642	0.70906	642
	Upper Rio Chaco Soils									
BTW07-1	Betonnie Tsasie Wash	159	0.70946	743	0.70946	743	0.70946	743	0.70946	743
BI06-1	Bis sa ani	65	0.70871	445	0.70871	445	0.70871	445	0.70871	445
BI06-2	Bis sa ani	66	0.70898	813	0.70898	813	0.70898	813	0.70898	813
CDR04-1	Casa del Rio	67	0.70929	938	0.70929	938	0.70929	938	0.70929	938
CDR04-2	Casa del Rio	68	0.70905	197	0.70905	197	0.70905	197	0.70905	197
CDR04-3	Casa del Rio	69	0.70935	1084	0.70935	1084	0.70935	1084	0.70935	1084
CDR04-4	Casa del Rio	70	0.70910	344	0.70910	344	0.70910	344	0.70910	344
CW371-04-1	Chaco Wash @ HWY 371	71	0.70889	444	0.70889	444	0.70889	444	0.70889	444
EC06-1	East Community	72	0.70909	349	0.70909	349	0.70909	349	0.70909	349
EC06-2	East Community	73	0.70906	488	0.70906	488	0.70906	488	0.70906	488
EC06-3	East Community	74	0.70905	1689	0.70905	1689	0.70905	1689	0.70905	1689
EC06-4	East Community	75	0.70950	1883	0.70950	1883	0.70950	1883	0.70950	1883
EC06-5	East Community	76	0.70959	1105	0.70959	1105	0.70959	1105	0.70959	1105
EC06-6	East Community, flood plain	77	0.70913	981	0.70913	981	0.70913	981	0.70913	981
ES04-1	Escalon	78	0.70964	916	0.70964	916	0.70964	916	0.70964	916
ES04-2	Escalon	79	0.70949	735	0.70949	735	0.70949	735	0.70949	735
EW04-1	Escavada Wash	80	0.70907	423	0.70907	423	0.70907	423	0.70907	423
GB04-1	Great Bend	81	0.70956	1144	0.70956	1144	0.70956	1144	0.70956	1144
GB04-2	Great Bend	82	0.70941	483	0.70941	483	0.70941	483	0.70941	483
KW07-1	Kimbeto Wash	158	0.70924	623	0.70924	623	0.70924	623	0.70924	623
KB04-1	Kin Bineola	83	0.70944	1496	0.70944	1496	0.70944	1496	0.70944	1496

Table 2 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			Pueblo Bonito		Chetro Ketl		Gallo Cliff Dwelling		Aztec Ruin	
KB04-2	Kin Bineola	84	0.70931	1729	0.70931	1729	0.70931	1729	0.70931	1729
KB04-3	Kin Bineola	85	0.70932	2048	0.70932	2048	0.70932	2048	0.70932	2048
KBV04-1	Kin Bineola Valley	86	0.70963	786	0.70963	786	0.70963	786	0.70963	786
KK04-1	Kin Klizhin	87	0.70953	826	0.70953	826	0.70953	826	0.70953	826
KK04-2	Kin Klizhin	88	0.70947	758	0.70947	758	0.70947	758	0.70947	758
PP04-1	Pueblo Pintado	89	0.70920	649	0.70920	649	0.70920	649	0.70920	649
PP04-2	Pueblo Pintado	90	0.70932	562	0.70932	562	0.70932	562	0.70932	562
PP04-3	Pueblo Pintado	91	0.70962	804	0.70962	804	0.70962	804	0.70962	804
PP04-4	Pueblo Pintado	92	0.70887	744	0.70887	744	0.70887	744	0.70887	744
PP04-5	Pueblo Pintado	93	0.70941	1107	0.70941	1107	0.70941	1107	0.70941	1107
RR06-1	Reservoir Ruin	94	0.70955	1772	0.70955	1772	0.70955	1772	0.70955	1772
RR06-2	Reservoir Ruin	95	0.70967	2713	0.70967	2713	0.70967	2713	0.70967	2713
RW06-1	Raton Well	96	0.70877	1377	0.70877	1377	0.70877	1377	0.70877	1377
RW06-2	Raton Well	97	0.70891	3159	0.70891	3159	0.70891	3159	0.70891	3159
SR06-1	Shepard Ruin	98	0.70927	2545	0.70927	2545	0.70927	2545	0.70927	2545
WC04-1	Willow Canyon	99	0.70955	615	0.70955	615	0.70955	615	0.70955	615
WC04-2	Willow Canyon	100	0.70950	864	0.70950	864	0.70950	864	0.70950	864
WF06-1	Windmill Facility	101	0.70924	4178	0.70924	4178	0.70924	4178	0.70924	4178
	Chaco Canyon (Valley and Floodplain) Soils									
CC#1	Casa Chiquita	102	0.70904	809	0.70904	809	0.70904	809	0.70904	809
CKF#1	Chetro Ketl Field	103	0.70917	1017	0.70917	1017	0.70917	1017	0.70917	1017
CR#1	Casa Rinconada	104	0.70916	614	0.70916	614	0.70916	614	0.70916	614
FB04-1	Fajada Butte	105	0.70897	344	0.70897	344	0.70897	344	0.70897	344
FB04-2	Fajada Butte	106	0.70901	605	0.70901	605	0.70901	605	0.70901	605
LH#1	Lizard House Arroyo	107	0.70897	947	0.70897	947	0.70897	947	0.70897	947
PDA#4	Pueblo del Arroyo	108	0.70909	727	0.70909	727	0.70909	727	0.70909	727
S10#1	Penasco Blanco Field	109	0.70920	1660	0.70920	1660	0.70920	1660	0.70920	1660
WER#1	Weritos Rincon	110	0.70959	1537	0.70959	1537	0.70959	1537	0.70959	1537
WR#1	Weritos Rincon	111	0.70957	4074	0.70957	4074	0.70957	4074	0.70957	4074
WR#2	Weritos Rincon	112	0.70947	1159	0.70947	1159	0.70947	1159	0.70947	1159
	Chaco Canyon (Side Valley) Soils									
CC04-1	Clys Canyon	113	0.70879	2065	0.70879	2065	0.70879	2065	0.70879	2065
GW04-1	Gallo Wash	114	0.70931	3196	0.70931	3196	0.70931	3196	0.70931	3196
GW04-2	Gallo Wash	115	0.70896	861	0.70896	861	0.70896	861	0.70896	861
GW04-3	Gallo Wash	116	0.70900	1376	0.70900	1376	0.70900	1376	0.70900	1376
MC04-1	Mockingbird Canyon	117	0.70914	2154	0.70914	2154	0.70914	2154	0.70914	2154
MC04-2	Mockingbird Canyon	118	0.70921	2360	0.70921	2360	0.70921	2360	0.70921	2360
SG04-1	South Gap	119	0.70942	1455	0.70942	1455	0.70942	1455	0.70942	1455
SG04-2	South Gap	120	0.70962	1510	0.70962	1510	0.70962	1510	0.70962	1510
SG04-3	South Gap	121	0.70971	2379	0.70971	2379	0.70971	2379	0.70971	2379
	Defiance Plateau Soils									
CR06-1	Cornfield Ruin	122	0.70949	8108	0.70949	8108	0.70949	8108	0.70949	8108
CR06-2	Cornfield Ruin	123	0.70974	5747	0.70974	5747	0.70974	5747	0.70974	5747
KLI06-1	Kin Lichee	124	0.70980	1906	0.70980	1906	0.70980	1906	0.70980	1906
KLI06-2	Kin Lichee	125	0.70941	2979	0.70941	2979	0.70941	2979	0.70941	2979
KLI06-3	Kin Lichee	126	0.70960	4178	0.70960	4178	0.70960	4178	0.70960	4178
KT06-1	Kin Tiel	127	0.70991	5083	0.70991	5083	0.70991	5083	0.70991	5083
KT06-2	Kin Tiel	128	0.70980	5652	0.70980	5652	0.70980	5652	0.70980	5652
WR06-1	Wide Reed Ruin	129	0.71036	2979	0.71036	2979	0.71036	2979	0.71036	2979
WR06-2	Wide Reed Ruin	130	0.71019	5261	0.71019	5261	0.71019	5261	0.71019	5261

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Table 2 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			Pueblo Bonito		Chetro Ketl		Gallo Cliff Dwelling		Aztec Ruin	
	Lobo Mesa Soils									
KY04-1	Kin Ya-a	131	0.70946	422	0.70946	422	0.70946	422	0.70946	422
KY04-2	Kin Ya-a	132	0.70974	1211	0.70974	1211	0.70974	1211	0.70974	1211
PS04-1	Peach Spring	133	0.70986	643	0.70986	643	0.70986	643	0.70986	643
RW04-1	Red Willow	134	0.70987	608	0.70987	608	0.70987	608	0.70987	608
RW04-2	Red Willow	135	0.71013	875	0.71013	875	0.71013	875	0.71013	875
SR04-1	Standing Rock	136	0.70985	5749	0.70985	5749	0.70985	5749	0.70985	5749
	Western Rio Puerco Soils									
AN04-1	Atsee Nitsaa	137	0.70967	1414	0.70967	1414	0.70967	1414	0.70967	1414
BHA04-1	Big House Arroyo	138	0.70895	1137	0.70895	1137	0.70895	1137	0.70895	1137
FW06-1	Fort Wingate beside service road	139	0.70951	2598	0.70951	2598	0.70951	2598	0.70951	2598
HO06-1	Houck	140	0.70936	1228	0.70936	1228	0.70936	1228	0.70936	1228
HO06-2	Houck	141	0.70938	6166	0.70938	6166	0.70938	6166	0.70938	6166
HO06-3	Houck	142	0.70981	3721	0.70981	3721	0.70981	3721	0.70981	3721
KH04-1	Kin Hochai	143	0.70843	1184	0.70843	1184	0.70843	1184	0.70843	1184
WW06-1	Whitewater arroyo	144	0.70963	3884	0.70963	3884	0.70963	3884	0.70963	3884
	Red Mesa Soils									
AC04-1	Andrews Community	145	0.70931	1650	0.70931	1650	0.70931	1650	0.70931	1650
HS04-1	Haystack	146	0.70858	1527	0.70858	1527	0.70858	1527	0.70858	1527
SM04-1	San Mateo	147	0.70919	1622	0.70919	1622	0.70919	1622	0.70919	1622
SM04-2	San Mateo	148	0.70891	588	0.70891	588	0.70891	588	0.70891	588
SM04-3	San Mateo	149	0.70904	1391	0.70904	1391	0.70904	1391	0.70904	1391
	Upper Little Colorado Soils									
AT06-1	Atsinna Great House	150	0.70934	3850	0.70934	3850	0.70934	3850	0.70934	3850
KL06-1	Kluckhohn Site	151	0.70985	4032	0.70985	4032	0.70985	4032	0.70985	4032
KL06-2	Kluckhohn Site	152	0.70948	2415	0.70948	2415	0.70948	2415	0.70948	2415
PE06-1	Pescado near modern fields	153	0.71059	3691	0.71059	3691	0.71059	3691	0.71059	3691
RA06-1	Ramah fallow field	154	0.71072	3229	0.71072	3229	0.71072	3229	0.71072	3229
TC06-1	Togeye Canyon	155	0.70944	4031	0.70944	4031	0.70944	4031	0.70944	4031
YE06-1	Yellow House near drainage bank	156	0.70945	2442	0.70945	2442	0.70945	2442	0.70945	2442
	Dinetah Soils									
LCW07-1	Largo Canyon Wash	160	0.71038	1476	0.71038	1476	0.71038	1476	0.71038	1476
LCW07-2	Largo Canyon Wash	161	0.71052	1108	0.71052	1108	0.71052	1108	0.71052	1108
LCW07-3	Largo Canyon Wash	162	0.71051	893	0.71051	893	0.71051	893	0.71051	893
	Northwestern San Juan River Tributary Soils									
MR07-1	Mancos River floodplain	163	0.70870	854	0.70870	854	0.70870	854	0.70870	854
NW07-1	Navajo Wash incised floodplain	164	0.70823	1317	0.70823	1317	0.70823	1317	0.70823	1317
MAW07-1	Marble Wash floodplain	165	0.70895	1492	0.70895	1492	0.70895	1492	0.70895	1492
McC07-1	McElmo Creek floodplain	166	0.70879	1412	0.70879	1412	0.70879	1412	0.70879	1412
MOC07-1	Montezuma Creek floodplain	167	0.70904	942	0.70904	942	0.70904	942	0.70904	942
REW07-1	Recapture Wash floodplain	168	0.70870	1151	0.70870	1151	0.70870	1151	0.70870	1151
COW07-1	Cottonwood Wash floodplain	169	0.70876	1184	0.70876	1184	0.70876	1184	0.70876	1184
CW07-1	Combs Wash floodplain	170	0.70889	1297	0.70889	1297	0.70889	1297	0.70889	1297
BW07-1	Butler Wash floodplain	171	0.70891	1295	0.70891	1295	0.70891	1295	0.70891	1295
SJR07-1	San Juan River floodplain	172	0.70897	999	0.70897	999	0.70897	999	0.70897	999
CHW07-1	Chinle Wash floodplain	173	0.70872	1429	0.70872	1429	0.70872	1429	0.70872	1429
WW07-1	Walker Wash floodplain	174	0.70853	1682	0.70853	1682	0.70853	1682	0.70853	1682
TNP07-1	Teec Nos Pos Wash floodplain	175	0.70833	2075	0.70833	2075	0.70833	2075	0.70833	2075
RW07-1	Red Wash floodplain	176	0.70823	1180	0.70823	1180	0.70823	1180	0.70823	1180
SRW07-1	Shiprock Wash floodplain	177	0.70824	1463	0.70824	1463	0.70824	1463	0.70824	1463

Grey-shaded samples indicate a match between a soil-water's $^{87}Sr/^{86}Sr$ value or its K/Rb value and the range of values in a cob data set.
Rectangle indicates a soil-water whose $^{87}Sr/^{86}Sr$ and K/Rb ratios both match values in a cob data set.
K/Rb ratios are accurate to only three significant figures.

(Fig. 2B) with the mean and standard deviation of the 1-sigma midpoint calendar ages being A.D. 1187 ± 5.

Based on their accelerator mass spectrometric (AMS) ^{14}C ages (Table 1), the 36 ^{14}C-dated Chaco cobs can be split into three groups: a pre-middle-12th-century (pre-A.D. 1130) drought group (when Chaco was in its heyday), a post-middle-12th-century (post-A.D. 1180) drought group (by this time the Chacoan system had collapsed and the canyon contained only a small residual

population), and a post late-13th-century (post-A.D. 1300) drought group (a time when Athapascan speakers occupied the canyon that had been previously abandoned by the Anasazi).

In the following, we discuss the $^{87}Sr/^{86}Sr$ and K/Rb ratios of the archaeological cobs (Table 1) in terms of their provenience (where they were found) and in terms of their calibrated ages (when they were grown and brought to Chaco Canyon/Aztec Ruin).

2.2. Trace-metal ratios of the archaeological cobs

When we began to use trace-metal distribution coefficients to calculate the trace-metal ratios for the soil-waters in which the archaeological cobs grew, we realized there was a problem. For example, when we used measured Ba/Mn ratios in cobs to calculate soil-water Ba/Mn ratios by substitution into Eq. (1.1), we found that the Ba/Mn values of cob-derived soil-waters (Ave $[Ba/Mn]_{COB-DERIVED} = 7.0 \pm 3.6$) were an order of magnitude higher than the Ba/Mn values of synthetic soil-waters produced by leaching sediment (Ave $[Ba/Mn]_{MEASURED} = 0.53 \pm 0.47$) (Supplementary Tables 2–4).

To determine if the original cobs were contaminated with soil from the sites in which they were found, we plotted several measured trace-metal concentrations versus aluminum (Al) concentrations (Fig. 3). Aluminum is a principal component of aluminosilicate minerals (e.g., feldspars), but it is not a principal chemical component of plant material; e.g., Al in the five modern Southwestern Native American landraces analyzed in Benson et al. (2008) averaged only 4.9 ± 4.4 μg/g and Al in four modern cobs ranged from 3 to 28 μg/g (unpublished data of H. E. Taylor, USGS). In the Pueblo Bonito, Aztec Ruin, and 30 new cob data sets, Al values ranged, respectively, from 50 to 1000 μg/g, from 58 to 1100 μg/g, and from 29 to 3140 μg/g (Supplementary Tables 3 and 4), which suggests that some and perhaps most of the cobs had been contaminated with soil or windblown mineral dust which contained aluminosilicate minerals.

The metal-Al plots (Fig. 3) indicate that most of the cobs contain soil or dust particles that dissolved along with the ashed cobs residues when treated with a combination of strong acids (in particular HF) that were added prior to analysis (see Methods section in supplementary online material). Cerium (Ce) (a rare-earth element [REE] common in feldspars and igneous accessory minerals such as sphene, zircon, and allanite) indicates a nearly 1:1 correlation with Al (Fig. 3). The high-degree of correlation with Al is also true for a number of other metals, including Li, Fe, V, Zr, and all the REEs (data not shown), suggesting the dissolution of differing amounts of an aluminosilicate mineral with a nearly constant composition.

Also shown in Fig. 3 are plots of each of the trace-metals (Ca, Ba, Mn, Sr, K, Rb) associated with the four trace-metal K_Ds. Barium and Mn are highly correlated with Al (Fig. 3C, D) and Sr and Ca also exhibit significant correlations with Al when it exceeds 800 μg/g (Fig. 3A, B, F, G). Only K and Rb, appear uncorrelated with Al when its concentration is less than 250 μg/g ($R^2 < 0.02$) (Fig. 3H, I, J). Given the high correlations of some of the trace-metals with Al, we decided to use only cob-derived soil-water K/Rb ratios for those 28 cobs whose Al values were <250 μg/g (Supplementary Tables 3 and 4). Note that four cobs having anomalously high Sr values (Fig. 3A) (the Una Vida and Kin Kletso cobs as well as Aztec cobs AZRU 9651 and AZRU 11091), indicating contamination with soil-derived Sr, were excluded from further consideration in this paper.

Histograms illustrating the K/Rb ratios of archaeological cobs (Supplementary Table 3) from four Chaco Canyon locations and from Aztec West Ruin are displayed in Supplementary Figure 2A–E. Pueblo Bonito, Chetro Ketl, Gallo Cliff Dwelling, and Aztec West Ruin cobs have calculated soil-water K/Rb ranges of, respectively, 511–873, 845–1000, 832–1257, and 705–1599 (except for one Aztec West Ruin cob which has a soil-water K/Rb ratio of 216) (Supplementary Tables 3 and 4; Supplementary Figure 2). Given that the percent relative standard deviation (%RSD) of the K/Rb distribution coefficient is ∼30%, we increased the calculated soil-water K/Rb ranges by ±30% to account for this variance. Thus, Pueblo Bonito, Chetro Ketl, Gallo Cliff Dwelling, and Aztec West Ruin cobs have adjusted soil-water K/Rb ranges of, respectively, 358–1135, 592–1300, 582–1634, and 916–2079.

The calculated soil-water K/Rb ratios of five pre-A.D. 1130 and 13 post-A.D. 1180 cobs range, respectively, from 511 to 613 and from 765 to 1257 (Supplementary Tables 3 and 4). Their %RSD-adjusted ratios[1] range, respectively, from 358 to 797 and from 536 to 1634. The two post-A.D. 1300 Athapascan-age samples have K/Rb values of 683 and 1984, which correspond to %RSD-adjusted ranges of 478–888 and 1389–2579.

Fig. 4 is a contour plot of synthetic soil-water K/Rb ratios for the San Juan Basin and adjacent areas. Contour intervals occupied by pre-A.D. 1130 and post-A.D. 1180 cob-based soil-waters are shown in shades of grey. For plotting purposes, the pre-A.D. 1130 and post-A.D. 1180 K/Rb ranges have been set to 360–800 and 540–1600. Much of southwestern Colorado, northeastern Arizona, the north-central San Juan Basin, and a wedge-shaped area south of the Upper Rio Chaco has soil-water ratios higher than that recorded by the cobs and, as such, are ruled out as cob source areas.

2.3. $^{87}Sr/^{86}Sr$ ratios of archaeological cobs

Histograms illustrating the $^{87}Sr/^{86}Sr$ ratios of archaeological cobs (Table 1) from four Chaco Canyon locations and from Aztec West Ruin are displayed in Fig. 5A–E. The $^{87}Sr/^{86}Sr$ ratios of cobs from Pueblo Bonito, Chetro Ketl, Gallo Cliff Dwelling, and Aztec West Ruin range, respectively, from 0.70922 to 0.70948 (with one outlier at 0.70989), from 0.70935 to 0.70955, from 0.70941 to 0.71158, and from 0.70969 to 0.71017 (with one outlier at 0.71031) (Fig. 5A–D).

The three Chaco cob age groups (pre-A.D. 1130, post-A.D. 1180, and post-A.D. 1300) (Table 1) have $^{87}Sr/^{86}Sr$ ranges of 0.70922–0.70989 (five of five pre-A.D. 1130 samples), 0.70935–0.71027 (18 of 21 post-A.D. 1180 samples), 0.71088–0.71158 (three of 21 post-A.D.

Table 3
Line-of-sight distances from Aztec Ruin and Chaco Canyon to potential maize source regions

Source area	Chaco Canyon	Aztec Ruin
	Distance (km)	
McElmo Dome	160	95
Mesa Verde	120	60
Totah	75	0
Dinetah	65	
Chuska Slope	80	
Upper Rio Chaco (W)	50	
Upper Rio Chaco (E)	35	
Lobo Mesa	45	110
Western Rio Puerco	105	
Defiance Plateau	140	180

Distances are measured from the center of each potential source region.
Upper Rio Chaco (W) refers to the far western end of the Upper Rio Chaco source region.
Upper Rio Chaco (E) refers to the far eastern end of the Upper Rio Chaco source region.

[1] In calculating the %RSD adjusted ratios the value of the standard deviation of the minimum value in the range of values was subtracted from the minimum value and the standard deviation of the maximum value in the range of values was added to the maximum value.

Table 4
Site information, $^{87}Sr/^{86}Sr$, and K/Rb ratios for synthetic soil-waters from the Southern Colorado Plateau (chemical data are grouped by time)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$ pre-A.D. 1130	K/Rb pre-A.D. 1130	$^{87}Sr/^{86}Sr$ post-A.D. 1180	K/Rb post-A.D. 1180	$^{87}Sr/^{86}Sr$ post-A.D. 1300	K/Rb post-A.D. 1300
	McElmo Dome Soils							
AP06-1	Albert Porter sage field	1	0.70966	2055	0.70966	2055	0.70966	2055
AP06-2	Albert Porter sage field	2	0.70942	1588	0.70942	1588	0.70942	1588
GPO6-1	Goodman Pt sage and rabbit brush	3	0.70937	5144	0.70937	5144	0.70937	5144
GPO6-2	Goodman Pt grass drainage	4	0.70938	2986	0.70938	2986	0.70938	2986
LR06-1	Lowry Pueblo in Pinon/Juniper	5	0.70971	877	0.70971	877	0.70971	877
LR06-2	Lowry Pueblo	6	0.70945	1730	0.70945	1730	0.70945	1730
SCO6-1	Sand Canyon fallow field	7	0.70941	2306	0.70941	2306	0.70941	2306
SCO6-2	Sand Canyon in trees	8	0.70925	2352	0.70925	2352	0.70925	2352
SCO6-3	Sand Canyon fallow field	9	0.70962	1569	0.70962	1569	0.70962	1569
SPO6-1	Shields Pueblo fallow field	10	0.70962	968	0.70962	968	0.70962	968
SPO6-2	Shields Pueblo fallow field	11	0.70967	1512	0.70967	1512	0.70967	1512
YJ06-1	Yellow Jacket fallow field	12	0.70967	2079	0.70967	2079	0.70967	2079
YJ06-2	Yellow Jacket fallow field	13	0.70970	2038	0.70970	2038	0.70970	2038
	Mesa Verde Soils							
CP06-1	Cliff Palace, Chapin Mesa	16	0.70999	1107	0.70999	1107	0.70999	1107
CP06-2	Cliff Palace, Chapin Mesa	17	0.70976	1094	0.70976	1094	0.70976	1094
CV06-1	Coyote Village, Chapin Mesa	18	0.70980	3053	0.70980	3053	0.70980	3053
FV06-1	Far View, Chapin Mesa	19	0.70981	985	0.70981	985	0.70981	985
FV06-2	Far View, Chapin Mesa	20	0.70974	1431	0.70974	1431	0.70974	1431
LH06-1	Long House, Weatherill Mesa	21	0.70993	1231	0.70993	1231	0.70993	1231
MC06-1	Moorfield Community Mesa Verde	22	0.70981	3838	0.70981	3838	0.70981	3838
MC06-2	Moorfield Community Mesa Verde	23	0.70998	1128	0.70998	1128	0.70998	1128
MC06-3	Moorfield Community Mesa Verde	24	0.70991	2738	0.70991	2738	0.70991	2738
MH06-1	Mug House, Weatherill Mesa	25	0.70980	1069	0.70980	1069	0.70980	1069
YH06-1	Yucca House wet draw 1	14	0.70800	1629	0.70800	1629	0.70800	1629
YH06-2	Yucca House wet draw 2	15	0.70857	2441	0.70857	2441	0.70857	2441
	Totah (Aztec Ruin) Soils							
AZR#1	Animas River Bank	26	0.70990	397	0.70990	397	0.70990	397
AZR#4	Aztec Ruin alluvial fan	27	0.70956	1893	0.70956	1893	0.70956	1893
AZR#7	Aztec Ruin alluvial fan	28	0.70960	1227	0.70960	1227	0.70960	1227
AZR04-1	Aztec Ruin floodplain	29	0.70957	1271	0.70957	1271	0.70957	1271
AZR04-2	Aztec Ruin floodplain	30	0.70953	548	0.70953	548	0.70953	548
AZR04-3	Aztec Ruin floodplain	31	0.70959	455	0.70959	455	0.70959	455
	Totah (Salmon Ruin) Soils							
SAL#1	Salmon Ruin Floodplain	32	0.71006	1099	0.71006	1099	0.71006	1099
SAL#2	Salmon Ruin Floodplain	33	0.71001	880	0.71001	880	0.71001	880
SJS#1	San Juan River Bank @ Bloomfield	34	0.71024	586	0.71024	586	0.71024	586
SR#2	Salmon Ruin Orchard	35	0.71016	3037	0.71016	3037	0.71016	3037
SR#5	Salmon Ruin Floodplain	36	0.71011	202	0.71011	202	0.71011	202
	Totah (LaPlata) Soils							
HG06-1	Holmes Grp. flood plain	37	0.70913	3916	0.70913	3916	0.70913	3916

Table 4 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			pre-A.D. 1130		post-A.D. 1180		post-A.D. 1300	
HG06-2	Holmes Grp. flood plain	38	0.70891	7182	0.70891	7182	0.70891	7182
HG06-3	Holmes Grp. old flood plain	39	0.70883	7421	0.70883	7421	0.70883	7421
LP06-1	La Plata R. flood plain	40	0.70877	1863	0.70877	1863	0.70877	1863
LP06-2	La Plata R. flood plain	41	0.70884	1015	0.70884	1015	0.70884	1015
LP06-3	La Plata R. old flood plain	42	0.70865	5613	0.70865	5613	0.70865	5613
	Totah (South of San Juan River) Soils							
KC07-1	Kutz Canyon Wash	178	0.70970	841	0.70970	841	0.70970	841
GCW07-1	Gallegos Canyon Wash	157	0.70944	1049	0.70944	1049	0.70944	1049
	Middle Chinle Soils							
MF06-1	Many Farms	43	0.70886	3315	0.70886	3315	0.70886	3315
MF06-2	Many Farms	44	0.70922	4340	0.70922	4340	0.70922	4340
MF06-3	Many Farms	45	0.70926	4756	0.70926	4756	0.70926	4756
	Chuska Slope Soils							
CT#1	Captain Toms Wash	46	0.70929	2192	0.70929	2192	0.70929	2192
CT#2	Captain Toms Wash	47	0.70906	2434	0.70906	2434	0.70906	2434
CT#3	Captain Toms Wash	48	0.70903	1789	0.70903	1789	0.70903	1789
CTW#1B	Captain Toms Wash	49	0.70924	1370	0.70924	1370	0.70924	1370
CTW#2B	Captain Toms Wash	50	0.70922	282	0.70922	282	0.70922	282
CTW#3A	Captain Toms Wash	51	0.70883	257	0.70883	257	0.70883	257
SA06-1	Sanostee	52	0.70850	2583	0.70850	2583	0.70850	2583
SA06-2	Sanostee	53	0.70874	3659	0.70874	3659	0.70874	3659
SA06-3	Sanostee	54	0.70897	3023	0.70897	3023	0.70897	3023
TO06-1	Tocito seep	55	0.70877	743	0.70877	743	0.70877	743
TO06-2	Tocito Wash	56	0.70890	1028	0.70890	1028	0.70890	1028
SS#1	Skunk Springs Bank Deposit	57	0.70933	328	0.70933	328	0.70933	328
TGHBM#1	Two Grey Hills Basketmaker	58	0.70904	1694	0.70904	1694	0.70904	1694
TGHBM#2	Two Grey Hills Basketmaker	59	0.70917	678	0.70917	678	0.70917	678
TGHBM#3	Two Grey Hills Basketmaker	60	0.70912	1800	0.70912	1800	0.70912	1800
TGHBM#4	Two Grey Hills Basketmaker	61	0.70923	1078	0.70923	1078	0.70923	1078
TGHBM#5	Two Grey Hills Basketmaker	62	0.70920	385	0.70920	385	0.70920	385
TGHBM#6	Two Grey Hills Basketmaker	63	0.70930	1259	0.70930	1259	0.70930	1259
TGHBM#7	Two Grey Hills Basketmaker	64	0.70906	642	0.70906	642	0.70906	642
	Upper Rio Chaco Soils							
BTW07-1	Betonnie Tsasie Wash	159	0.70946	743	0.70946	743	0.70946	743
BI06-1	Bis sa ani	65	0.70871	445	0.70871	445	0.70871	445
BI06-2	Bis sa ani	66	0.70898	813	0.70898	813	0.70898	813
CDR04-1	Casa del Rio	67	0.70929	938	0.70929	938	0.70929	938
CDR04-2	Casa del Rio	68	0.70905	197	0.70905	197	0.70905	197
CDR04-3	Casa del Rio	69	0.70935	1084	0.70935	1084	0.70935	1084
CDR04-4	Casa del Rio	70	0.70910	344	0.70910	344	0.70910	344
CW371-04-1	Chaco Wash @ HWY 371	71	0.70889	444	0.70889	444	0.70889	444
EC06-1	East Community	72	0.70909	349	0.70909	349	0.70909	349
EC06-2	East Community	73	0.70906	488	0.70906	488	0.70906	488
EC06-3	East Community	74	0.70905	1689	0.70905	1689	0.70905	1689
EC06-4	East Community	75	0.70950	1883	0.70950	1883	0.70950	1883
EC06-5	East Community	76	0.70959	1105	0.70959	1105	0.70959	1105

(*continued on next page*)

Table 4 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			pre-A.D. 1130		post-A.D. 1180		post-A.D. 1300	
EC06-6	East Community, flood plain	77	0.70913	981	0.70913	981	0.70913	981
ES04-1	Escalon	78	0.70964	916	0.70964	916	0.70964	916
ES04-2	Escalon	79	0.70949	735	0.70949	735	0.70949	735
EW04-1	Escavada Wash	80	0.70907	423	0.70907	423	0.70907	423
GB04-1	Great Bend	81	0.70956	1144	0.70956	1144	0.70956	1144
GB04-2	Great Bend	82	0.70941	483	0.70941	483	0.70941	483
KW07-1	Kimbeto Wash	158	0.70924	623	0.70924	623	0.70924	623
KB04-1	Kin Bineola	83	0.70944	1496	0.70944	1496	0.70944	1496
KB04-2	Kin Bineola	84	0.70931	1729	0.70931	1729	0.70931	1729
KB04-3	Kin Bineola	85	0.70932	2048	0.70932	2048	0.70932	2048
KBV04-1	Kin Bineola Valley	86	0.70963	786	0.70963	786	0.70963	786
KK04-1	Kin Klizhin	87	0.70953	826	0.70953	826	0.70953	826
KK04-2	Kin Klizhin	88	0.70947	758	0.70947	758	0.70947	758
PP04-1	Pueblo Pintado	89	0.70920	649	0.70920	649	0.70920	649
PP04-2	Pueblo Pintado	90	0.70932	562	0.70932	562	0.70932	562
PP04-3	Pueblo Pintado	91	0.70962	804	0.70962	804	0.70962	804
PP04-4	Pueblo Pintado	92	0.70887	744	0.70887	744	0.70887	744
PP04-5	Pueblo Pintado	93	0.70941	1107	0.70941	1107	0.70941	1107
RR06-1	Reservoir Ruin	94	0.70955	1772	0.70955	1772	0.70955	1772
RR06-2	Reservoir Ruin	95	0.70967	2713	0.70967	2713	0.70967	2713
RW06-1	Raton Well	96	0.70877	1377	0.70877	1377	0.70877	1377
RW06-2	Raton Well	97	0.70891	3159	0.70891	3159	0.70891	3159
SR06-1	Shepard Ruin	98	0.70927	2545	0.70927	2545	0.70927	2545
WC04-1	Willow Canyon	99	0.70955	615	0.70955	615	0.70955	615
WC04-2	Willow Canyon	100	0.70950	864	0.70950	864	0.70950	864
WF06-1	Windmill Facility	101	0.70924	4178	0.70924	4178	0.70924	4178
	Chaco Canyon (Valley and Floodplain) Soils							
CC#1	Casa Chiquita	102	0.70904	809	0.70904	809	0.70904	809
CKF#1	Chetro Ketl Field	103	0.70917	1017	0.70917	1017	0.70917	1017
CR#1	Casa Rinconada	104	0.70916	614	0.70916	614	0.70916	614
FB04-1	Fajada Butte	105	0.70897	344	0.70897	344	0.70897	344
FB04-2	Fajada Butte	106	0.70901	605	0.70901	605	0.70901	605
LH#1	Lizard House Arroyo	107	0.70897	947	0.70897	947	0.70897	947
PDA#4	Pueblo del Arroyo	108	0.70909	727	0.70909	727	0.70909	727
S10#1	Penasco Blanco Field	109	0.70920	1660	0.70920	1660	0.70920	1660
WER#1	Weritos Rincon	110	0.70959	1537	0.70959	1537	0.70959	1537
WR#1	Weritos Rincon	111	0.70957	4074	0.70957	4074	0.70957	4074
WR#2	Weritos Rincon	112	0.70947	1159	0.70947	1159	0.70947	1159
	Chaco Canyon (Side Valley) Soils							
CC04-1	Clys Canyon	113	0.70879	2065	0.70879	2065	0.70879	2065
GW04-1	Gallo Wash	114	0.70931	3196	0.70931	3196	0.70931	3196
GW04-2	Gallo Wash	115	0.70896	861	0.70896	861	0.70896	861
GW04-3	Gallo Wash	116	0.70900	1376	0.70900	1376	0.70900	1376
MC04-1	Mockingbird Canyon	117	0.70914	2154	0.70914	2154	0.70914	2154
MC04-2	Mockingbird Canyon	118	0.70921	2360	0.70921	2360	0.70921	2360

Table 4 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb	$^{87}Sr/^{86}Sr$	K/Rb
			pre-A.D. 1130		post-A.D. 1180		post-A.D. 1300	
SG04-1	South Gap	119	0.70942	1455	0.70942	1455	0.70942	1455
SG04-2	South Gap	120	0.70962	1510	0.70962	1510	0.70962	1510
SG04-3	South Gap	121	0.70971	2379	0.70971	2379	0.70971	2379
	Defiance Plateau Soils							
CR06-1	Cornfield Ruin	122	0.70949	8108	0.70949	8108	0.70949	8108
CR06-2	Cornfield Ruin	123	0.70974	5747	0.70974	5747	0.70974	5747
KLI06-1	Kin Lichee	124	0.70980	1906	0.70980	1906	0.70980	1906
KLI06-2	Kin Lichee	125	0.70941	2979	0.70941	2979	0.70941	2979
KLI06-3	Kin Lichee	126	0.70960	4178	0.70960	4178	0.70960	4178
KT06-1	Kin Tiel	127	0.70991	5083	0.70991	5083	0.70991	5083
KT06-2	Kin Tiel	128	0.70980	5652	0.70980	5652	0.70980	5652
WR06-1	Wide Reed Ruin	129	0.71036	2979	0.71036	2979	0.71036	2979
WR06-2	Wide Reed Ruin	130	0.71019	5261	0.71019	5261	0.71019	5261
	Lobo Mesa Soils							
KY04-1	Kin Ya-a	131	0.70946	422	0.70946	422	0.70946	422
KY04-2	Kin Ya-a	132	0.70974	1211	0.70974	1211	0.70974	1211
PS04-1	Peach Spring	133	0.70986	643	0.70986	643	0.70986	643
RW04-1	Red Willow	134	0.70987	608	0.70987	608	0.70987	608
RW04-2	Red Willow	135	0.71013	875	0.71013	875	0.71013	875
SR04-1	Standing Rock	136	0.70985	5749	0.70985	5749	0.70985	5749
	Western Rio Puerco Soils							
AN04-1	Atsee Nitsaa	137	0.70967	1414	0.70967	1414	0.70967	1414
BHA04-1	Big House Arroyo	138	0.70895	1137	0.70895	1137	0.70895	1137
FW06-1	Fort Wingate beside service road	139	0.70951	2598	0.70951	2598	0.70951	2598
HO06-1	Houck	140	0.70936	1228	0.70936	1228	0.70936	1228
HO06-2	Houck	141	0.70938	6166	0.70938	6166	0.70938	6166
HO06-3	Houck	142	0.70981	3721	0.70981	3721	0.70981	3721
KH04-1	Kin Hochai	143	0.70843	1184	0.70843	1184	0.70843	1184
WW06-1	Whitewater arroyo	144	0.70963	3884	0.70963	3884	0.70963	3884
	Red Mesa Soils							
AC04-1	Andrews Community	145	0.70931	1650	0.70931	1650	0.70931	1650
HS04-1	Haystack	146	0.70858	1527	0.70858	1527	0.70858	1527
SM04-1	San Mateo	147	0.70919	1622	0.70919	1622	0.70919	1622
SM04-2	San Mateo	148	0.70891	588	0.70891	588	0.70891	588
SM04-3	San Mateo	149	0.70904	1391	0.70904	1391	0.70904	1391
	Upper Little Colorado Soils							
AT06-1	Atsinna Great House	150	0.70934	3850	0.70934	3850	0.70934	3850
KL06-1	Kluckhohn Site	151	0.70985	4032	0.70985	4032	0.70985	4032
KL06-2	Kluckhohn Site	152	0.70948	2415	0.70948	2415	0.70948	2415
PE06-1	Pescado near modern fields	153	0.71059	3691	0.71059	3691	0.71059	3691
RA06-1	Ramah fallow field	154	0.71072	3229	0.71072	3229	0.71072	3229
TC06-1	Togeye Canyon	155	0.70944	4031	0.70944	4031	0.70944	4031
YE06-1	Yellow House near drainage bank	156	0.70945	2442	0.70945	2442	0.70945	2442
	Dinetah Soils							
LCW07-1	Largo Canyon Wash	160	0.71038	1476	0.71038	1476	0.71038	1476

(*continued on next page*)

Table 4 (*continued*)

Site No.	Site Name	Map No.	$^{87}Sr/^{86}Sr$ pre-A.D. 1130	K/Rb pre-A.D. 1130	$^{87}Sr/^{86}Sr$ post-A.D. 1180	K/Rb post-A.D. 1180	$^{87}Sr/^{86}Sr$ post-A.D. 1300	K/Rb post-A.D. 1300
LCW07-2	Largo Canyon Wash	161	0.71052	1108	0.71052	1108	0.71052	1108
LCW07-3	Largo Canyon Wash	162	0.71051	893	0.71051	893	0.71051	893
	Northwestern San Juan River Tributary Soils							
MR07-1	Mancos River floodplain	163	0.70870	854	0.70870	854	0.70870	854
NW07-1	Navajo Wash incised floodplain	164	0.70823	1317	0.70823	1317	0.70823	1317
MAW07-1	Marble Wash floodplain	165	0.70895	1492	0.70895	1492	0.70895	1492
McC07-1	McElmo Creek floodplain	166	0.70879	1412	0.70879	1412	0.70879	1412
MOC07-1	Montezuma Creek floodplain	167	0.70904	942	0.70904	942	0.70904	942
REW07-1	Recapture Wash floodplain	168	0.70870	1151	0.70870	1151	0.70870	1151
COW07-1	Cottonwood Wash floodplain	169	0.70876	1184	0.70876	1184	0.70876	1184
CW07-1	Combs Wash floodplain	170	0.70889	1297	0.70889	1297	0.70889	1297
BW07-1	Butler Wash floodplain	171	0.70891	1295	0.70891	1295	0.70891	1295
SJR07-1	San Juan River floodplain	172	0.70897	999	0.70897	999	0.70897	999
CHW07-1	Chinle Wash floodplain	173	0.70872	1429	0.70872	1429	0.70872	1429
WW07-1	Walker Wash floodplain	174	0.70853	1682	0.70853	1682	0.70853	1682
TNP07-1	Teec Nos Pos Wash floodplain	175	0.70833	2075	0.70833	2075	0.70833	2075
RW07-1	Red Wash floodplain	176	0.70823	1180	0.70823	1180	0.70823	1180
SRW07-1	Shiprock Wash floodplain	177	0.70824	1463	0.70824	1463	0.70824	1463

Grey-shaded samples indicate a match between a soil-water's $^{87}Sr/^{86}Sr$ value or its K/Rb value and the range of values in a cob data set.
Rectangle indicates a soil-water whose $^{87}Sr/^{86}Sr$ and K/Rb ratios both match values in a cob data set.
Comparison is being made between soil-water and cobs grouped by age.

1180 samples), and 0.70984–0.71130 (five of six post-A.D. 1300 samples).

However, there is a possibility that some cobs also were contaminated with excess Sr from soil or windblown dust. A detailed plot of Sr versus Al (Supplementary Figure 3) shows that the correlation of these two metals previously displayed in Fig. 3F is due mainly to cobs from Gallo Cliff Dwelling. In order to guard against Sr contamination from aluminosilicate minerals we eliminated from consideration those cobs having Al values >250 μg/g and Sr values >30 μg/g. This resulted in the elimination of 20 cobs shown in bold in Table 1 and Supplementary Tables 3 and 4.

The $^{87}Sr/^{86}Sr$ ratios of the remaining uncontaminated cobs from Pueblo Bonito, Chetro Ketl, Gallo Cliff Dwelling, and Aztec West Ruin range, respectively, from 0.70922 to 0.70948 (with one outlier at 0.70989), from 0.70935 to 0.70952, from 0.70937 to 0.71014 (with one outlier at 0.71088), and from 0.70970 to 0.71017 (with one outlier at 0.71031).

The three Chaco uncontaminated cob age groups (pre-A.D. 1130, post-A.D. 1180, and post-A.D. 1300) (Table 1) have $^{87}Sr/^{86}Sr$ ranges of 0.70922–0.70989 (five of five pre-A.D. 1130 samples), 0.70935–0.71014 (11 of 12 post-A.D. 1180 samples) with one outlier having a value of 0.71088, and 0.70984–0.71008 (two of two post-A.D. 1300 samples).

2.4. $^{87}Sr/^{86}Sr$ ratios of synthetic soil-waters

Fig. 6 is a contour map of synthetic soil-water $^{87}Sr/^{86}Sr$ ratios. The different grey-shaded contour intervals correspond to the $^{87}Sr/^{86}Sr$ ranges associated with pre-A.D. 1130 and post-A.D. 1180 cobs from Chaco Canyon. The $^{87}Sr/^{86}Sr$ contour plot indicates that a rather large area, centered on the four corners and which runs southeastward to the eastern edge of the plot and then south to the bottom of the plot, can be ruled out as a cob source area. Another non-source area (white ellipsoid) occurs near the bottom of the plot along the Arizona–New Mexico border. Map numbers associated with soil sites (small black dots in Fig. 6) are displayed in Supplementary Figure 4A, B and, in addition, are associated with site names and $^{87}Sr/^{86}Sr$ values in Table 2. None of the synthetic soil-waters has a $^{87}Sr/^{86}Sr$ ratio >0.71072 (Supplementary Table 1) which indicates that one uncontaminated Gallo Cliff Dwelling cob falls outside the $^{87}Sr/^{86}Sr$ range encompassed by our synthetic soil-water database.

2.5. Combining K/Rb and $^{87}Sr/^{86}Sr$ ratios of the archaeological cobs

To the extent that we trust the K/Rb soil-water ratios derived from the archaeological cob chemistries, we can use these data in conjunction with the $^{87}Sr/^{86}Sr$ ratios in the cobs to highlight possible source areas where maize may have been grown. A potential problem with the application of the K/Rb distribution coefficient is that it was derived from maize grown under optimal conditions (Adams et al., 2006), whereas prehistoric maize was often grown under conditions of limited moisture and nutrient content, which may have altered the partitioning of trace-metal pairs during metal transport from the soil-water into the cob. Given that the precision of the $^{87}Sr/^{86}Sr$ ratios is about two digits in the fifth decimal place, we have used this error range to adjust (broaden) the measured $^{87}Sr/^{86}Sr$ values associated with a cob's provenience or age .

In Table 2, synthetic soil-water $^{87}Sr/^{86}Sr$ and K/Rb ratios that are consistent with either cob-derived soil-water $^{87}Sr/^{86}Sr$ or K/Rb ranges are highlighted in grey for Pueblo Bonito, Chetro Ketl, Gallo Cliff Dwelling, and Aztec Ruin cob data sets. When both $^{87}Sr/^{86}Sr$ and K/Rb ratios of a synthetic soil-water fall within the calculated soil-water ranges of a cob set, the $^{87}Sr/^{86}Sr$ and K/Rb values of the synthetic soil-water have been enclosed with a rectangle. These rectangles indicate potential field sites for the archaeological cobs. The cob map numbers in Table 2 are linked to their locations in Figs. 7 and 8.

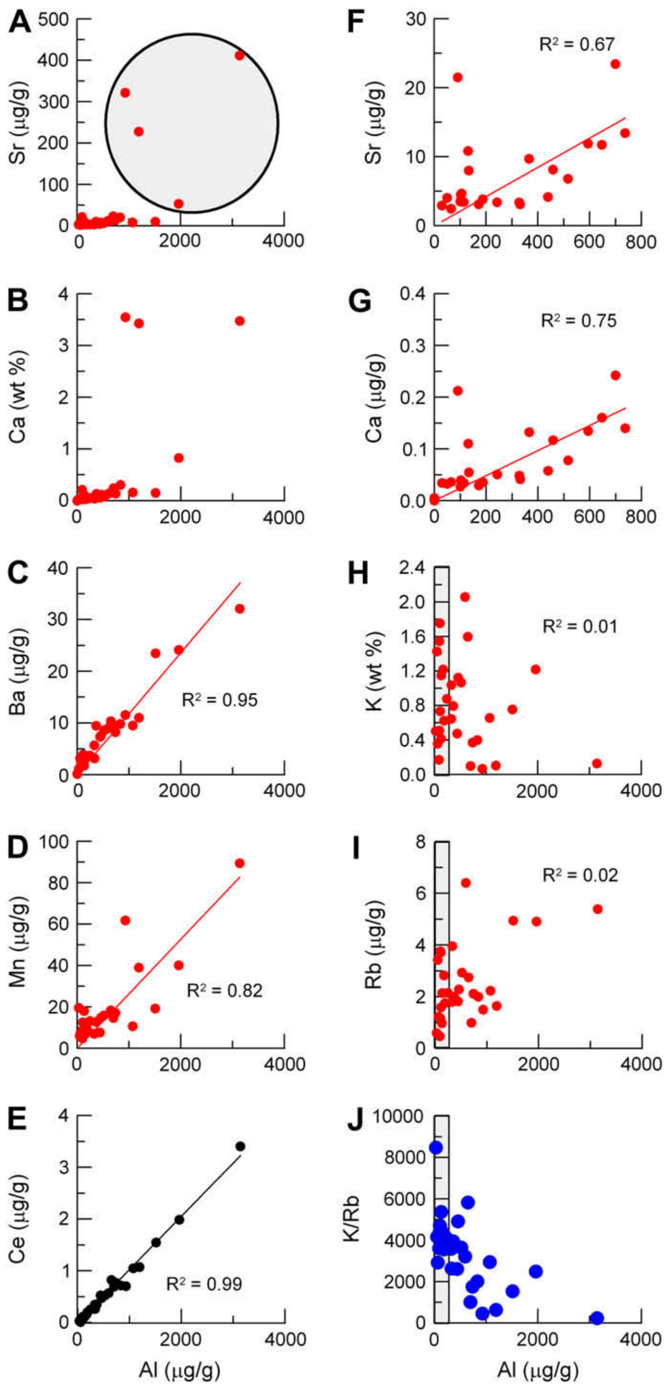

Fig. 3. Trace-metal versus Al correlation plots for archaeological cobs. Shaded circle (A) indicates samples with high Sr contamination. Thin vertical rectangles indicate regions in which K, Rb, and K/Rb are relatively unaffected by metal contamination.

Potential source areas for Pueblo Bonito cobs include four regions: the Chuska slope region, the Upper Rio Chaco region, the Lobo Mesa region, and the Totah region (Fig. 7A). Potential source areas for Chetro Ketl cobs include three regions: the Totah region, the Upper Rio Chaco region (including one site in Chaco Canyon), and the Western Rio Puerco region (Fig. 7B). Potential source areas for cobs from Gallo Cliff Dwelling include seven regions: the Upper Rio Chaco region (including sites within Chaco Canyon), the Totah region, the Mesa Verde region, the McElmo Dome region, the Lobo Mesa region, and the Western Rio Puerco region (Fig. 7C). Potential source areas for Aztec Ruin cobs include five regions: the Defiance Plateau region, the Lobo Mesa region, the Totah region, the Mesa Verde region, and the McElmo Dome region (Fig. 7D). The line-of-sight distances from Aztec Ruin and Chaco Canyon to potential cob source regions have been listed in Table 3.

In Table 4, synthetic soil-water $^{87}Sr/^{86}Sr$ and K/Rb ratios that are consistent with cob-derived soil-water $^{87}Sr/^{86}Sr$ and K/Rb ranges for the pre-A.D. 1130, post-A.D. 1180, and post-A.D. 1300 cob data sets are highlighted in grey. When both $^{87}Sr/^{86}Sr$ and K/Rb ratios of a synthetic soil-water fall within the calculated soil-water ranges of cobs, the $^{87}Sr/^{86}Sr$ and K/Rb values of the synthetic soil-water have been enclosed with a rectangle, which indicates a potential source area for an archaeological cob set.

In terms of their calibrated ages, pre-A.D. 1130 cobs have potential source areas in four regions: the Totah region, the Upper Rio Chaco region and the Lobo Mesa region (Fig. 8A). The post-A.D. 1180 cobs have potential source areas in six regions: the McElmo Dome region, the Mesa Verde region, the Totah region, the Upper Rio Chaco region (including sites in Chaco Canyon), the Lobo Mesa region, and the Western Rio Puerco region (Fig. 8B). Post-A.D. 1300 Athapascan cobs have potential source areas in three regions: the Totah region, the Lobo Mesa region, and the Dinetah region (Fig. 8C).

2.6. Cob $^{87}Sr/^{86}Sr$ ratios >0.71072

The $^{87}Sr/^{86}Sr$ ratios of one uncontaminated cob exceeds a value of 0.71072 (Table 1, CHCU42684-1), the highest synthetic soil-water $^{87}Sr/^{86}Sr$ ratio (Table 2); therefore, it is not possible to use the soil-water $^{87}Sr/^{86}Sr$ contour plot (Fig. 6) to pinpoint the source(s) of this cob. We can only speculate on areas that might match cob $^{87}Sr/^{86}Sr$ values that exceed 0.71072.[2] Two San Juan River tributaries, the Piedra River and Los Pinos Creek, have $^{87}Sr/^{86}Sr$ values (Supplementary Figure 5A) that are similar to the $^{87}Sr/^{86}Sr$ value of the Gallo Cliff Dwelling cob (Table 1). The drainages of these streams flow through and near the Needle Mountains (Fig. 1) in Southwest Colorado; in particular, Los Pinos Creek flows over the Precambrian Eolus granite which is associated with elevated $^{87}Sr/^{86}Sr$ values (0.7181–0.7408) (Bickford et al., 1969).

Generally speaking, the $^{87}Sr/^{86}Sr$ ratio of the soluble mineral component in a soil will dominate the $^{87}Sr/^{86}Sr$ of the soil-water; i.e., the $^{87}Sr/^{86}Sr$ ratio of a soil-water will change to reflect the $^{87}Sr/^{86}Sr$ ratio of soil Sr released to the water during dissolution of soluble Sr-bearing minerals. Benson et al. (2006) mixed 100 mL of runoff from the Chuska slope area with 5 g of soil from two Chaco Canyon sites and showed that about half of the Sr in the leachate was derived from the soil. Given that a water:soil ratio of 50:1 typified the experiment and that a water:soil ratio of ∼1:1 is more likely to occur in an actual field setting, the $^{87}Sr/^{86}Sr$ value of the soluble mineral component in soil is likely to dominant the $^{87}Sr/^{86}Sr$ value of precipitation or irrigation water added to a soil.

There is, however, a situation in which a surface-water's $^{87}Sr/^{86}Sr$ value is primarily controlled by the $^{87}Sr/^{86}Sr$ value of soil-water. This occurs where shallow ground water has reached equilibrium with the soluble Sr in soils through which the ground water has flowed before it enters a surface-water system. For example, by the time ground water reaches the distal end of a side-tributary fan and before it discharges to a perennial or ephemeral stream, it may have acquired the $^{87}Sr/^{86}Sr$ value of the soluble soil minerals through which it passed. In this case, the $^{87}Sr/^{86}Sr$ value of a stream that has receives the majority of its input from such ground water is already in equilibrium with the sediments in its floodplain. Therefore, maize growing in the floodplain will have $^{87}Sr/^{86}Sr$

[2] Bedrock shales and sandstones from Chaco Canyon, of poorly indurated siltstones from north of Aztec Ruin, and of sands and gravels from north of Salmon Ruin have $^{87}Sr/^{86}Sr$ values <0.71072 (Table 21-3 in Benson et al., 2006).

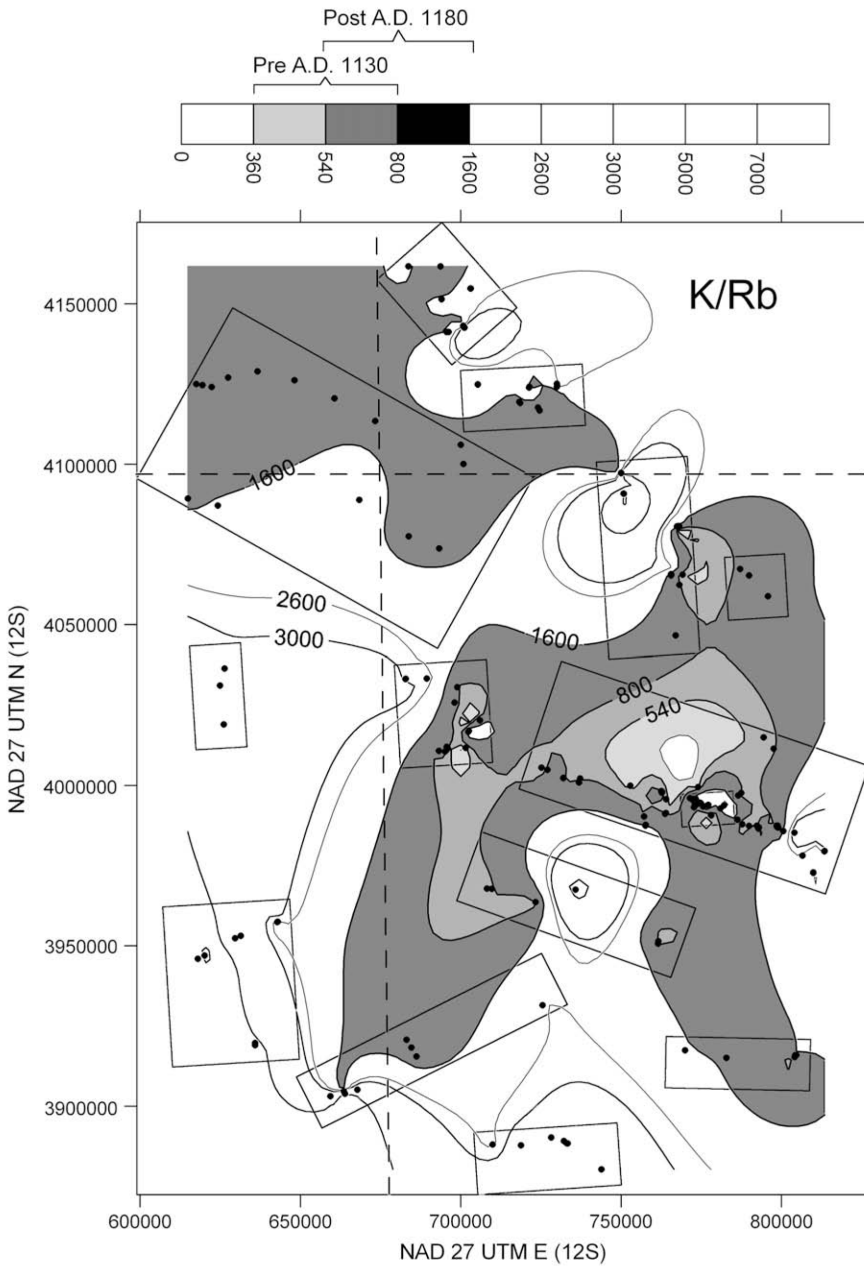

Fig. 4. K/Rb contour plot for synthetic soil-waters in the Southern Colorado Plateau region. Black dots indicate sites where soils were sampled. Rectangles bound sampling regions shown in Fig. 1 and listed in Table 2.

values nearly identical to the $^{87}Sr/^{86}Sr$ value of Sr dissolved in the stream.

English et al. (2001) have shown that Tertiary sandstones and quartzites in the Chuska Mountains (85 km west of Chaco) and Precambrian granites, Paleozoic carbonates, and Paleozoic sandstones in the San Pedro Mountains (90 km east of Chaco) have elevated $^{87}Sr/^{86}Sr$ ratios (Fig. 1). It is possible that fields were established in sediments at the bases of these mountain ranges or at higher elevations that remained productive during drought periods.

3. Summary and discussion

Superimposing Figs. 4 and 6 shows that Anasazi-age cobs from Chaco Canyon have potential source areas that form a "V" with its apex near Pueblo Pintado at the eastern end of the Upper Rio Chaco region (Fig. 8D). The pre-A.D. 1130 Anasazi cobs (five of six which are from Pueblo Bonito) (Table 1) have potential source areas in the upper Rio Chaco and surrounding regions; however, Chaco Canyon itself is not a potential source area (Figs. 7A, 8A). Although we cannot exclude the Totah and Lobo Mesa regions, we suggest that the most probable source(s) for pre-A.D. 1130 Anasazi cobs was the Upper Rio Chaco.

The post-A.D 1180 cobs, which were found in a variety of "Downtown Chaco" sites (Gallo Cliff Dwelling and the Pueblo Bonito, Chetro Ketl, and Kin Klizhin great houses), have potential source areas in the upper Rio Chaco and surrounding regions (excepting the Chuska slope) as well as regions to the northwest (McElmo Dome and Mesa Verde) and to the southwest (western Rio Puerco) (Fig. 8B). Most (15 of 23) of the post-A.D 1180 cobs came from Gallo Cliff Dwelling whose potential cob source regions (Fig. 7C) are nearly the same as the post-A.D 1180 cob source

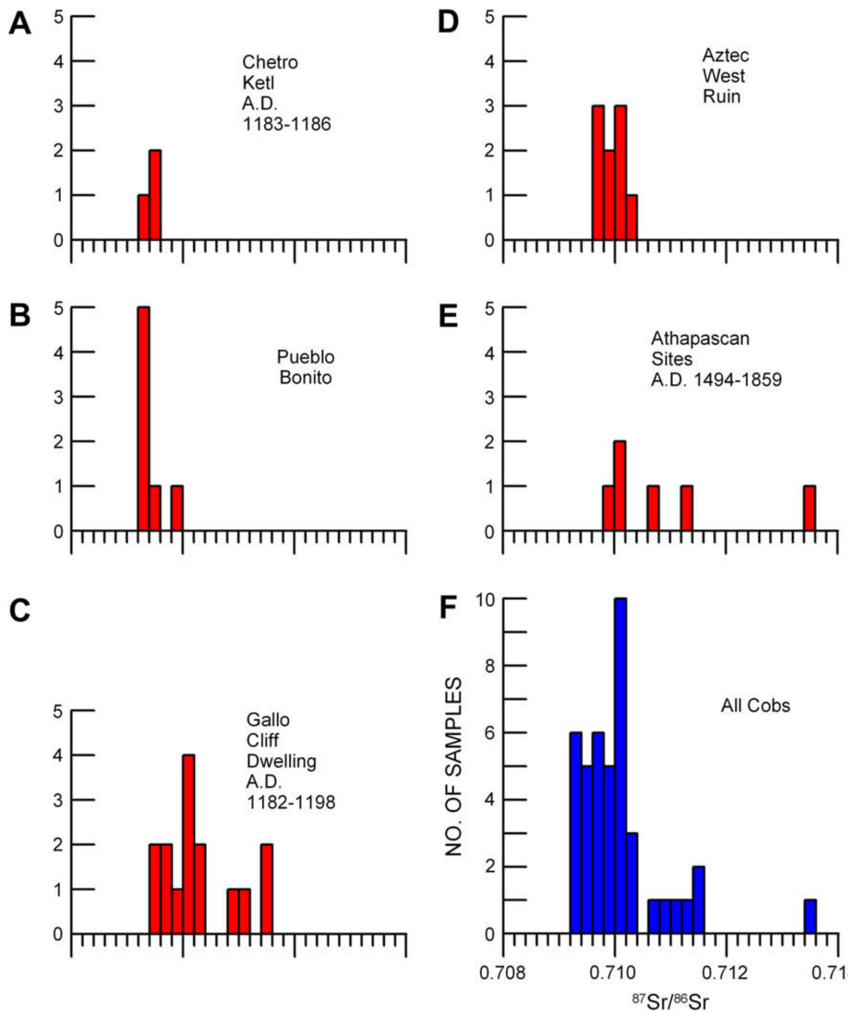

Fig. 5. $^{87}Sr/^{86}Sr$ histograms of archaeological cobs.

regions (Fig. 8B). Thus, the post-A.D. 1180 cobs could have come from any of several sites along the Upper Rio Chaco region (including Chaco Canyon itself) and from regions that lie on southwest and northwest vectors from the Canyon.

Chetro Ketl cobs have potential source areas largely confined to the Upper Rio Chaco region, including one site in Chaco Canyon (Fig. 7B). Given the distribution of potential source areas for both Chetro Ketl and Pueblo Bonito cobs, the Upper Rio Chaco region, together with the Chuska slope, may have functioned as an extended Chaco "Halo" (Doyel et al., 1984) during the pre-A.D. 1130 time period. It also may be that this sociopolitical "connection" was not completely severed by the middle-12th-century drought that resulted in the out-migration of many Anasazi from Chaco Canyon.

Athapascan-age (post-A.D. 1300) cobs have potential source areas within the Totah, Lobo Mesa, and Dinetah regions (Fig. 8C). The latter region is considered to be the traditional homeland of the Navajo.

Cobs from Aztec Ruin, most of which are associated with post-A.D. 1180 timber-cutting dates, can be associated with potential source areas within the Mesa Verde and McElmo Dome regions (Fig. 7D). Only one site in the Totah region (the San Juan River floodplain near Salmon Ruin) has a soil-water chemistry that matches the Aztec Ruin cobs. This suggests the possibility of exchange between Aztec Ruin and other communities that lay to the northwest of Aztec Ruin. The soil in the Mesa Verde and McElmo Dome regions is dominated by a late Pleistocene loess deposit which extends from Blanding, Utah, to Durango, Colorado (Fig. 1) (Price et al., 1988). If this eolian deposit carries the soil-water trace-metal and isotopic signatures associated with Aztec Ruin cobs, it is possible that the source area for these cobs may lie near the Totah region.

Given that Gallo Cliff Dwelling is a Pueblo III (A.D. 1150–1300) structure, it is not surprising that the cobs found in this structure date to the late 1100s. However, it is surprising that cobs with nearly the same ages also were found in three other Downtown Chaco great houses (Pueblo Bonito, Chetro Ketl, and Kin Kletso). Given the multiplicity of potential source regions for post-A.D. 1180 cobs (Fig. 8B), we cannot determine where the cobs were grown with any degree of certainty, although the similarity of cob ages implies that they probably entered Chaco Canyon at the same time. This suggests that residents of all four Downtown Chaco structures may have been cultivating the same field area(s) within or outside the canyon, or that they were receiving maize from the same outlier community, or that a resident of Gallo Cliff Dwelling was disposing of cobs in great house structures. Of interest is the fact that the Sr of the Gallo cobs is a near-linear function of Al. This suggests that the cobs were contaminated where they were deposited by a single mineral having a nearly constant Sr/Al ratio and an elevated $^{87}Sr/^{86}Sr$ ratio.

Provenience data exists for two of the A.D. 1180s cobs. One cob (H254/258A), dating to A.D. 1181 $\pm$ 30, was excavated from the floor of room 3 in Pueblo Bonito. This room, which dates to the A.D. 860s (Chaco digital initiative, 2008), was filled with sand. Thus, the cob was deposited in a very old part of Pueblo Bonito about 300 years

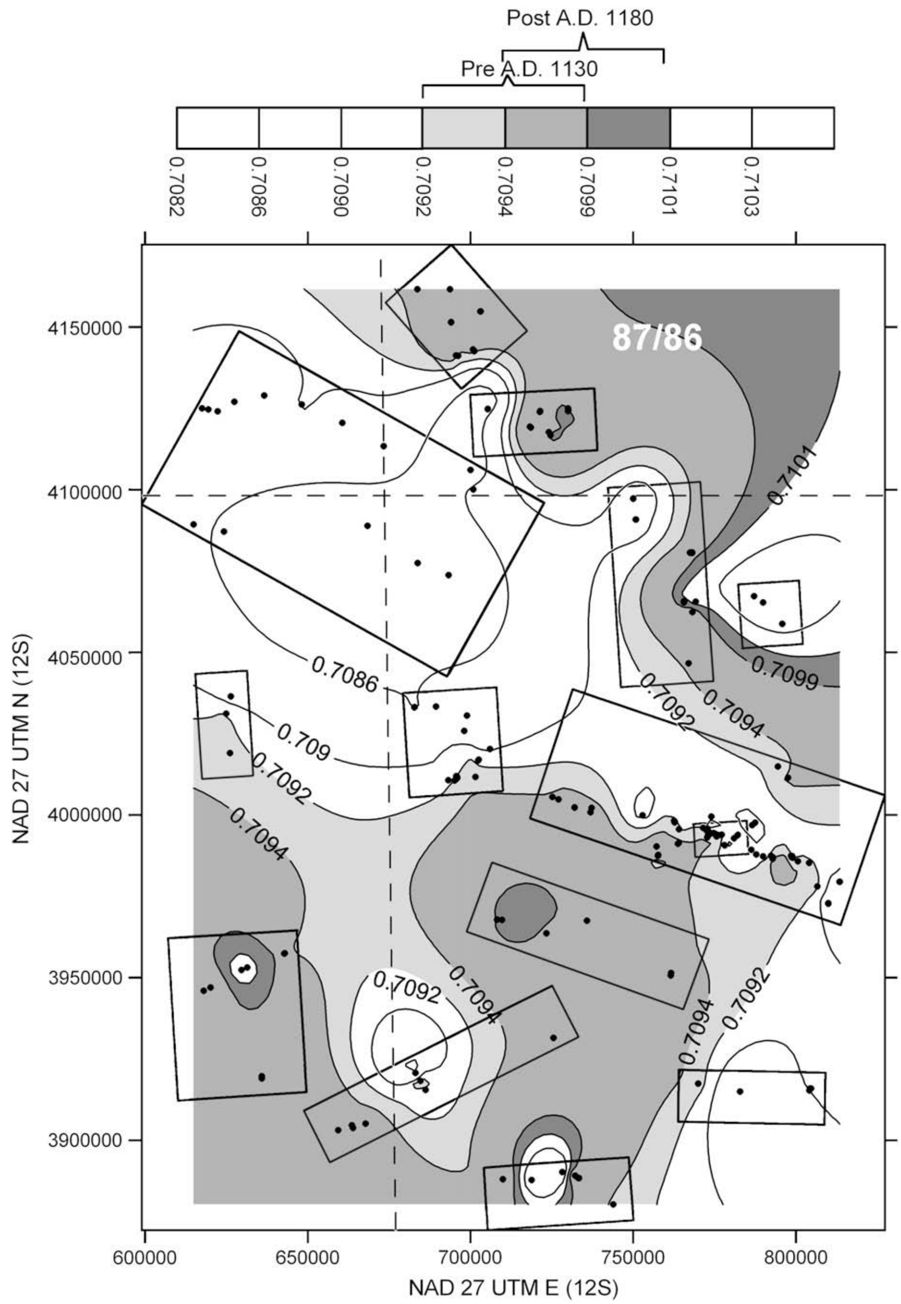

Fig. 6. $^{87}Sr/^{86}Sr$ contour plot for synthetic soil-waters (Table 1) in the Southern Colorado Plateau region. Black dots indicate sites where soils were sampled. Rectangles bound sampling regions shown in Fig. 1 and listed in Table 2.

after the room was constructed. The three cobs from Chetro Ketl, which date to A.D. 1183–1186 (±23), came from room 92, which has tree-ring-cutting dates that range from A.D.1033 to A.D.1070 (Chaco digital initiative, 2008). In this case, the three cobs found in this structure postdate the last phases of room construction/repair by ~100 years.

People may have occupied rooms 3 and 92 long after they were constructed; however, the simplest hypothesis is that the rooms were not occupied in the A.D. 1180s but functioned as trash receptacles. We cannot, however, determine whether the residents of Pueblo Bonito and Chetro Ketl disposed of the cobs in unoccupied rooms in those great houses or whether residents of Gallo Cliff House discarded the cobs in those great houses. One of the underlying tenets of the studies involving $^{87}Sr/^{86}Sr$ as a tracer is that the source of soluble bio-available Sr in the soil zone is mostly in form of windblown carbonate dust that is chemically well mixed on the scale of several kilometers (Naiman et al., 2000). We have demonstrated that $^{87}Sr/^{86}Sr$ values change systematically over the study area; however, continual expansion of the limits of the study area has increased the number of possible field sites having $^{87}Sr/^{86}Sr$ ratios that could be associated with particular groups of cobs. So, in a sense, the more soils we sample, the more choices we have in terms of cob source areas. Thus, we no longer can point to a unique solution in terms of a single source area for a particular grouping of cobs.

This study has several shortcomings, some of which may be resolved by future work. Cob contamination with soil particles prevented the application of three of the trace-metal K_Ds; however, two of the authors of this paper (Benson and Taylor) recently have developed a method for removal of carbonate, sulfate, and silicate

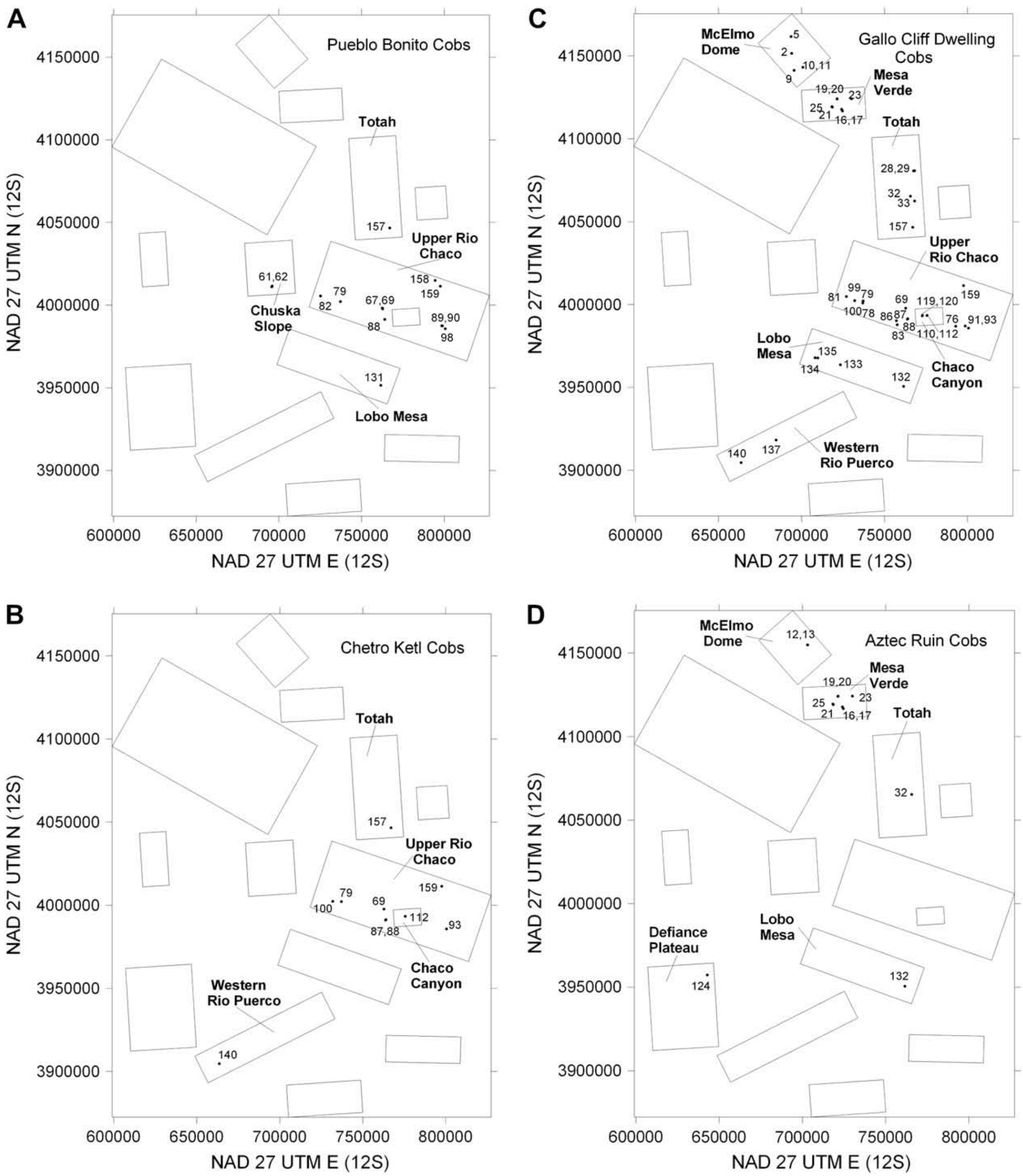

Fig. 7. Possible field sites (numbered dots) for cobs from A. Pueblo Bonito, B. Chetro Ketl, C. Gallo Cliff Dwelling, and D. Aztec Ruin. Rectangles bound sampling regions listed in Table 2.

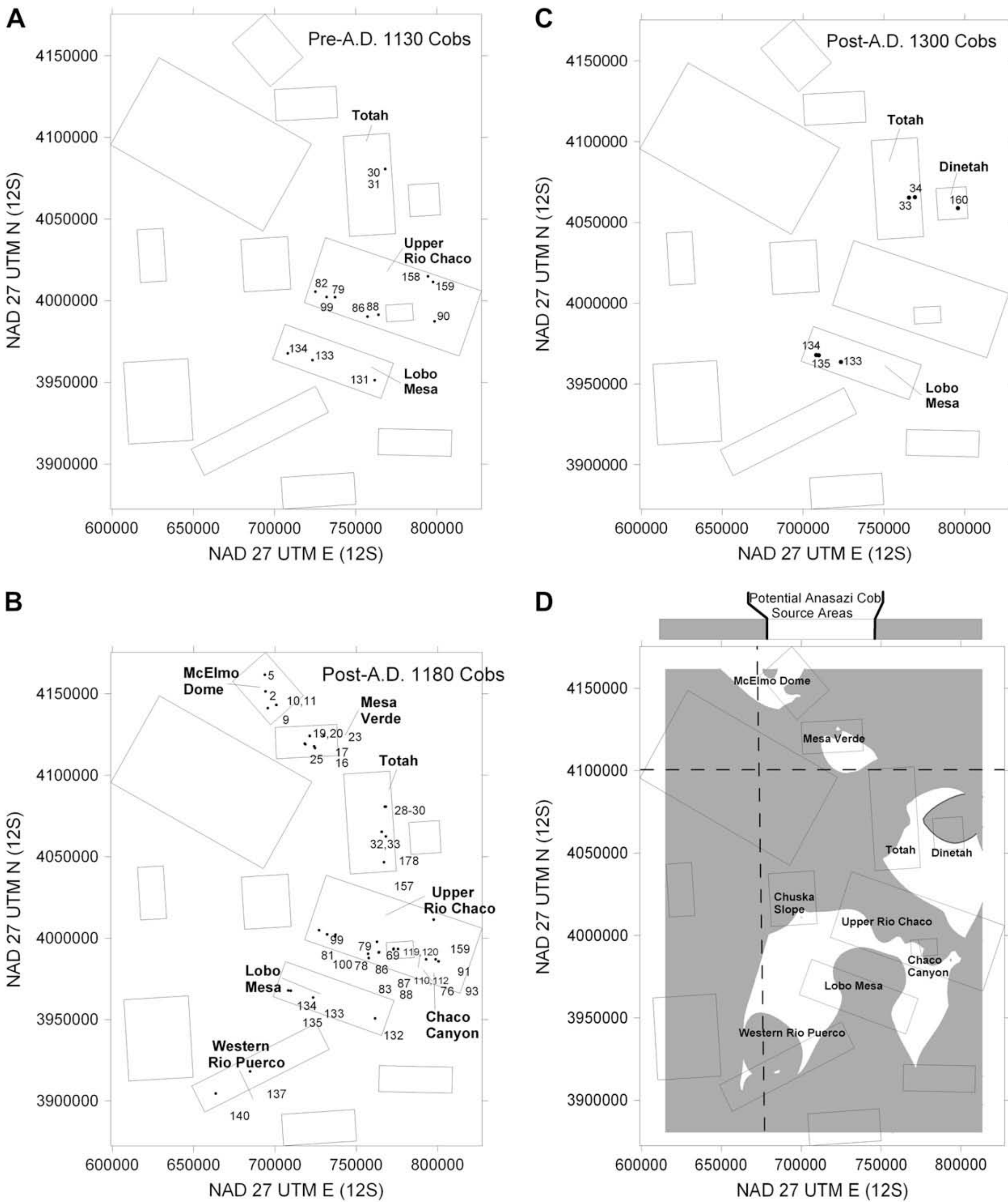

Fig. 8. Possible field sites (numbered dots) for (A) pre-A.D. 1130, (B) post-A.D. 1180, and (C) post-A.D. 1300 cobs. (D) Superimposition of Figs. 4 and 6 where white areas indicate land which could have been the source of Anasazi archaeological cobs.

contaminants from dirty and burnt cobs. Unfortunately, the National Park Service's Chaco Collection does not contain many Chaco Canyon archaeological cobs other than those from Gallo Cliff Dwelling and, for this reason, we may never be able to analyze a substantial number of archaeological cobs that are well-distributed in time between the founding and abandonment of Chaco. Although we have collected a large number of soil samples from the Southern Colorado Plateau region, many areas have not been sampled (Fig. 1); therefore, the existing isotopic and trace-metal contour maps (Figs. 4 and 6) do not adequately characterize the chemical compositions of soils in some areas (e.g., the area between the Dinetah and the Upper Rio Chaco). Lastly, one uncontaminated cob was found to possess a $^{87}Sr/^{86}Sr$ ratio in excess of any analyzed soil-water values. Such elevated $^{87}Sr/^{86}Sr$ ratios have been associated with Precambrian and Paleozoic rocks that lie 80–90 km to the east, west, and north of Chaco. These old rocks (most of which lie at relatively high elevations) may have eroded over time, providing sediments with elevated $^{87}Sr/^{86}Sr$ ratios to field sites at lower elevations. Sampling at the base of the Chuska, San Pedro, and Needles mountains could aid in confirming or refuting the

hypothesis that these areas were field sites for archaeological cobs found in Chaco.

Future application of all four trace-metal K_Ds will greatly assist in the pinpointing of cob source areas. In addition, selective sampling of areas east of the Animas River, across from Aztec Ruin, and south of the San Juan River, between Bloomfield and Shiprock, may prove or disprove a local source of cobs found in Aztec Ruin. In addition, the synthetic soil-water $^{87}Sr/^{86}Sr$ database we have established for the Southern Colorado Plateau region (Fig. 1, Supplementary Table 1) can be applied by other researchers interested in sourcing a variety of organic artifacts; e.g., archaeological textiles or animal bone.

Acknowledgments

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Appendix. Supplementary online material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jas.2008.09.023.

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