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CHAPTER
21

The Agricultural Productivity of Chaco Canyon and the Source(s) of Pre-Hispanic Maize Found in Pueblo Bonito

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Glossary

***Akchin* farming** In true *akchin* farming, the akchin is the specific area on the active alluvial fan where floodwaters spread out (i.e., the akchin area is located between the zone of concentration where wash channels are converging and the zone of distribution where channels are diverging).

Alluvial fan A gently sloping mass of loose rock and sediment shaped like an open fan deposited by a tributary stream at the place it issues from an upland canyon or valley.

Chaco side canyon One of the relatively small canyons on the north or south side of Chaco Wash (e.g., Clys Canyon). These canyons are the sites of alluvial-fan sediments.

Check dam A berm-like structure built across a drainage that impedes the movement of water and sediment.

Great houses Large, multistoried, multiroomed, masonry buildings usually having more or more great kivas (e.g., Pueblo Bonito in Chaco Canyon).

Gridded garden Formal rectangular plots for planting maize and other crops in floodwater irrigated farms. In Chaco the flood water is thought to be supplied by side-canyon tributaries, which empty into a ditch that diverts water to a garden via a headgate system.

Newcomb area An area on the eastern slope of the Chuska Mountains about 100 kilometers north of Gallup, New Mexico. The Newcomb area and the Chuskas probably supplied maize, chert, timbers, and ceramics to Chaco Canyon.

The Totah Navajo word for "rivers coming together." An archaeological area surrounding the confluences of the Animas and La Plata rivers with the San Juan River in the northwestern San Juan Basin. Aztec and Salmon ruins are located in the Totah.

Agricultural productivity estimates suggest that the core area of Chaco Canyon could have sustained only a few hundred individuals. Modern analogues of existing Pueblo populations and their domestic habitations with Chaco structures suggest that Chaco at times had a resident population exceeding 2000 people. These data suggest that maize would have had to be imported to feed permanent residents and those visiting Chaco during ritual–political gatherings and those who participated in the accelerated construction and modification of **great houses** between AD 1030 and 1130. Comparison of strontium-isotope and trace-element ratios of synthetic soil and natural waters from sites within the San Juan Basin of northwestern New Mexico with isotopic and trace-element ratios of seven archaeological corn cobs found in Pueblo Bonito indicate that some maize was imported from either the **Newcomb area** or from side-tributary sites

west of the Chaco Canyon core. These data support the concept that foodstuffs (maize) from outlier communities were transported to a resource-poor Chaco Canyon. However, proof that importation of maize was the rule and not the exception awaits further study of archaeological cobs from both small-house and great-house contexts.

INTRODUCTION

The high-desert San Juan Basin, located in northwestern New Mexico, is the site of numerous Pre-Hispanic American Indian ruins (Figure 21-1). The basin is bounded by mountains, including the La Plata, San Pedro, San Mateo,

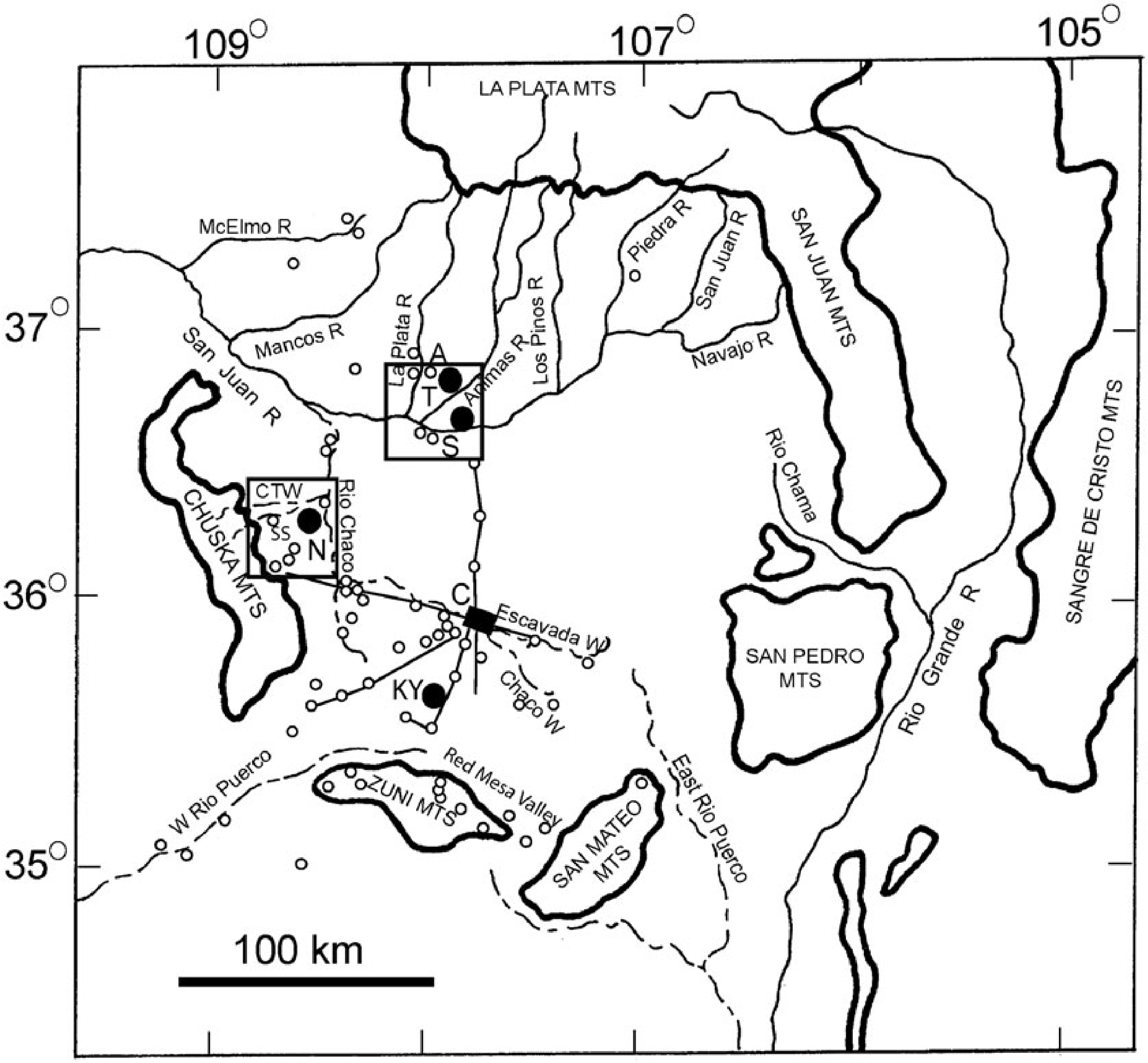

FIGURE 21-1 Site location map, prehistoric great houses (small open circles), and roads (lines emanating from Chaco) in the San Juan Basin area of northwestern New Mexico. Possible sources of archeological corn are A, Aztec Ruin, S, Salmon Ruin, N, Newcomb area (shown in rectangle), T, Totah area (shown in rectangle), K, Kin Ya'a, and C, Chaco Canyon area. CTW is Captain Tom Wash; SS is Skunk Springs Wash. Pueblo Bonito is in Chaco Canyon. Dashed lines indicate ephemeral streams. The Totah area is defined as the confluence of the San Juan River with the Animas and La Plata Rivers and includes the Aztec and Salmon ruins. Mt. Taylor is part of the San Mateo mountains.

Zuni, and Chuska ranges. The San Juan River in the northern part of the San Juan Basin is fed by several perennial tributaries, whereas ephemeral streams, including the Rio Chaco–Chaco Wash, Escavada Wash, and Captain Tom Wash are found in the central and southern parts of the basin.

Strontium-isotope and trace-element compositions were recently used to demonstrate that some archaeological maize found in Pueblo Bonito was not grown in the Chaco Canyon valley floor but possibly came from the Newcomb and Totah areas 80 kilometers to the west and north of Chaco (see Figure 21-1) [5]. In this chapter, we estimate the number of people that canyon-based agriculture could have sustained, and we present new strontium-isotope and trace-element data from additional agricultural sites. For this study, we obtained additional soil samples from **the Totah** area, the Newcomb area, and the Chaco Canyon valley floor. We also expanded our sampling area to include side-tributary areas bordering Chaco Canyon, side-tributary areas bordering the Rio Chaco from Pueblo Pintado on the east to the Great Bend of the Chaco on the west, and the Kin Ya'a area southwest of the canyon (Figures 21-1, 21-2, 21-3).

It has been suggested that some of the side-tributary sites outside the canyon served as agricultural support centers for Chaco [46, 82]. These centers were thought to have reduced the need for transport of food from outliers located at greater distances from the canyon (e.g., the Newcomb and Totah areas). The present study seeks, in part, to determine whether canyon side-tributary fields and other field sites within 8 to 50 kilometers of the canyon could have been the source of archaeological maize found in Pueblo Bonito.

Numerous multistoried great houses are found throughout the basin (see Figure 21-1). Chaco Canyon is unique in its density (13) of great houses. For the purposes of this chapter, when we use the term Chaco Canyon, we are referring to a "core" area that runs from Shabik'eschee on the east to the Chaco-Escavada confluence on the west (Figure 21-4). Pueblo Bonito, one of the earliest great houses built

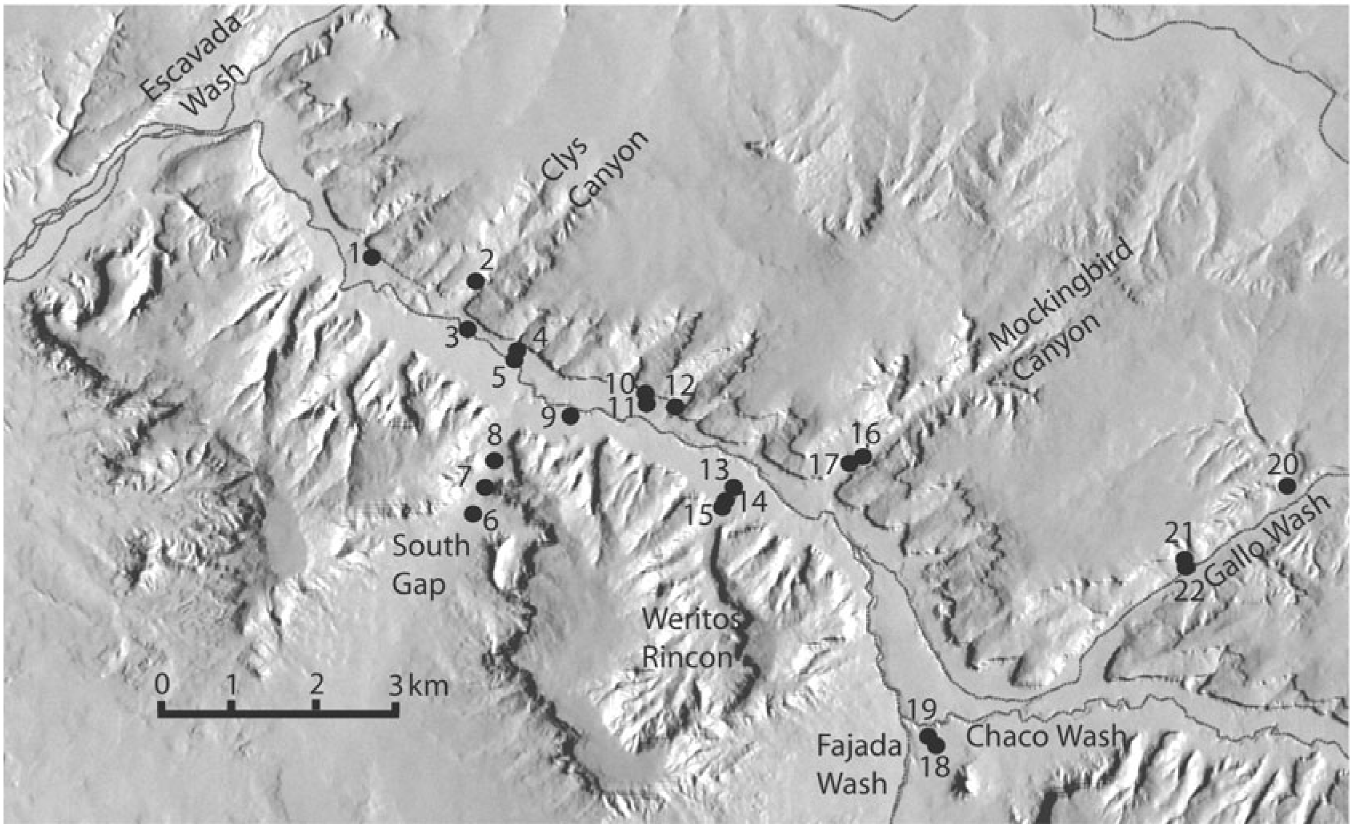

FIGURE 21-2 Soil sample sites in Chaco Canyon valley and Chaco side canyons. Sample name and number relative to figure number are: 1(Penasco Blanco field, S10#1, #2, #3), 2(Clys Canyon, CC04-1), 3(Casa Chiquita, CC#1, #2, #3), 4(Pueblo del Arroyo, PDA#1, #3, #4), 5(Pueblo del Arroyo, PDA#5), 6(South Gap, SG04-1), 7(South Cap, SG04-2), 8(South Gap, SGO4-3), 9(Casa Rinconada field, CR#1, #2, #3), 10(Chetro Ketl field, CK#1), 11(Chetro Ketl field, CKF#1, #2, #3), 12(Lizard House arroyo, LH#1, #2, #3), 13(Weritos Rincon, WR#1), 14(Weritos Rincon, WR#2), 15(Weritos Rincon, WER#1, #2, #3), 16(Mockingbird Canyon, MC04-1), 17(Mockingbird Canyon, MC04-2), 18(Fajada Butte, FB04-1), 19(Fajada Butte, FB04-2), 20(Gallo Wash, GW04-1), 21(Gallo Wash, GW04-2), 22(Gallo Wash, GW04-3).

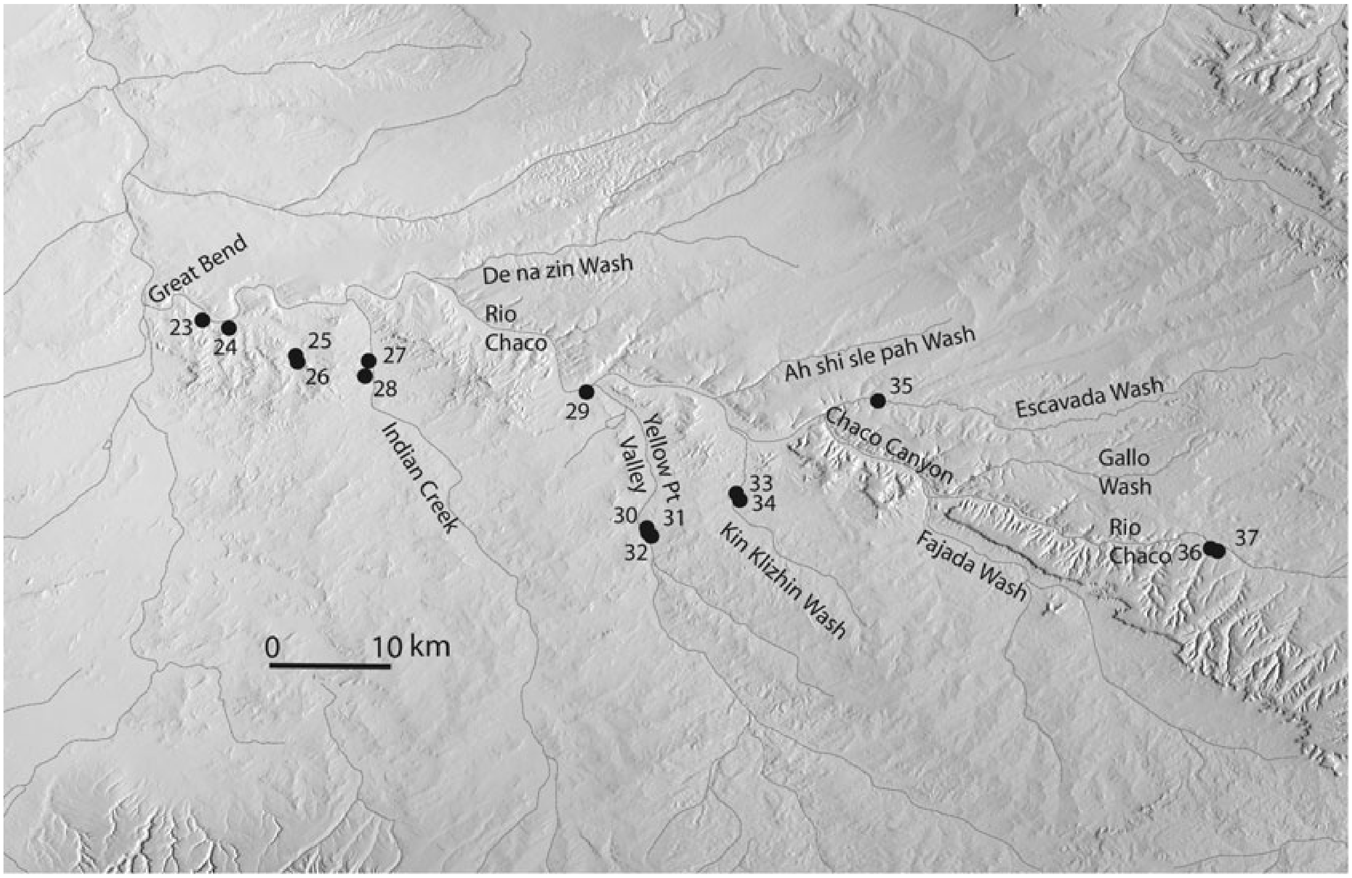

FIGURE 21-3 Soil sample sites east and west of Chaco Canyon core area. Sample name and number relative to figure number are: 23(Great Bend, GB04-2), 24(Great Bend, GB04-1), 25(Willow Canyon, WC04-2), 26(Willow Canyon, WC04-1), 27(Escalon, ES04-2), 28(Escalon, ES04-1), 29(Chaco Wash at HWY 371, CW371), 30(Kin Bineola, KBO4-1), 31(Kin Bineola, KB04-2), 32(Kin Bineola, KB04-3), 33(Kin Klizhin, KK04-1), 34(Kin Klizhin, KK04-2), 35(Escavada Wash, EW04-1), 36(Pueblo Pintado, PP04-1), 37(Pueblo Pintado, PP04-2). The Kin Ya'a (KY04-1, 2) site is shown in Figure 21-1.

in the canyon, and a focal point for archaeological investigation, was constructed in stages (Figures 21-5A, B) [42, 81, 83]. Construction activity in Chaco Canyon escalated between AD 1030 and 1130, during which time six new great houses were built, and six others were enlarged. Great-house construction required millions of pieces of dressed stone and more than 200,000 wooden beams [14, 83, 84]. Pueblo Bonito itself may have incorporated between 25,000 and 50,000 timbers in its construction [81].

Great-house construction in the Chaco Canyon core ceased during a multidecadal drought that affected much of the western United States between AD 1130 and 1170 (Figure 21-6). This drought affected 55% of the western United States [10]. Based on analysis of surface ceramics, only 4 of 25 Chacoan outliers (communities located outside the core area) surveyed in the southern half of the San Juan Basin indicate occupation after AD 1130 [45]. It would therefore appear that most American Indians left the central and southern San Juan Basin within a few decades after cessation of great-house construction [37, 58]. Other multidecadal droughts affected the western United States from about AD 1250 until AD 1300 (see Figure 21-6) and may have led to the wholesale migration of many American Indians out of the San Juan Basin [11, 13, 29, 57, 70].

AGRICULTURAL PRODUCTIVITY AND POPULATION DENSITIES OF THE CHACO CANYON CORE AREA

There are three factors which determine whether the core was agriculturally self sufficient: the core's agricultural productivity (average number of acres in cultivation times per-acre yield of maize), the annual average per person consumption of maize, and the population in the core estimated from masonry structures. These factors have been previously discussed collectively or individually by a number of researchers [16, 25, 42, 43, 60, 61, 74, 76, 79].

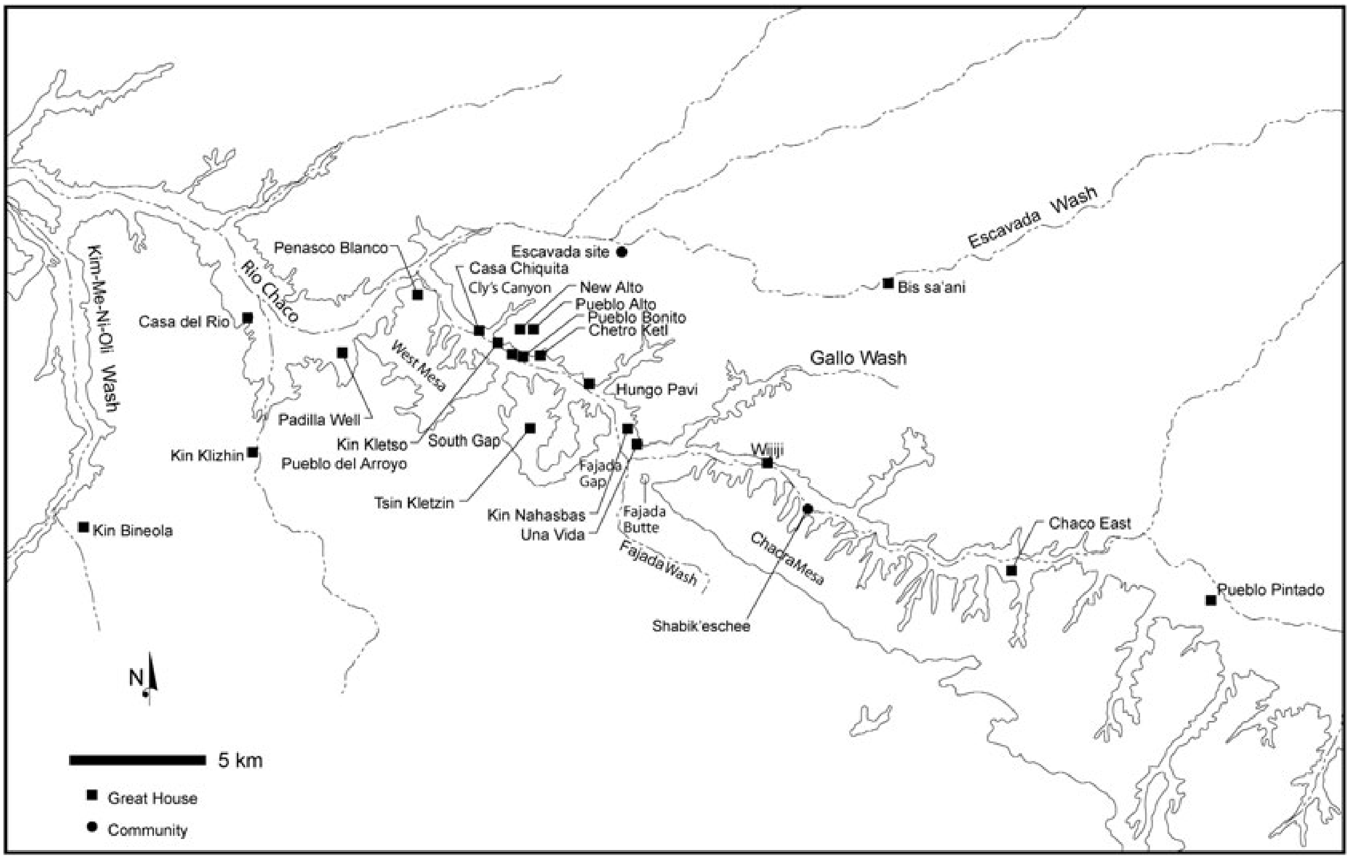

FIGURE 21-4 Great house and community locations in the Chaco Canyon area. Figure courtesy of Robert Schultz, Academic Graphics.

Acres under Cultivation

Factors that Affect the Production of Maize

Maize has two primary requirements for growth: water and sunshine–heat. It has been shown [40] that given sufficient water, similar yields of maize could be obtained from any physiographic slope and soil texture in the Oaxaca Valley of Mexico. Modern maize requires 500 ± 100 millimeters of water during its growing season [39, 47]. During growing season, 150 millimeters of rainfall is considered the lower limit for maize production without irrigation, and maize productivity tends to be greatest where the freeze-free period exceeds 120 days [62].

Maize yields are further limited by soil salinity and nutrient (e.g., nitrogen and phosphorous) concentrations. Most soils in the semiarid Southwest are nutrient poor and the raising of maize leads to nutrient depletion of the soil (e.g., 200 grams of phosphorus and 900 grams of nitrogen are extracted from the soil for each bushel of modern maize that is produced). Upper horizons of prehistoric cultivated soils in the Mimbres area are lower in concentrations of organic matter, nitrogen, and phosphorous than their uncultivated counterparts [59]. Nutrient loss necessitates that soil be left fallow for some period of time until the nutrient balance is restored or field locations can be periodically shifted, substituting for nutrient replacement [65].

For modern forage corn, yield begins to decrease at a salinity (conductivity) threshold of 1.8 deciSiemens per meter (dS/m). Crop loss (%) due to soil-water salinity can be estimated with the following equation:

$$\%\,\text{Loss} = 7.0 \times \Omega - 11.6$$

where Ω = conductivity in dS/m [3].

Dry Land Farming of the Chaco Core

The area of Chaco Canyon's valley floor and its side tributaries within Chaco National Park, between Shabik'eschee Village and the Chaco-Escavada confluence, totals about 4700 acres. However, not all this acreage is suitable for growing maize. The documented areal extent of old fields within Chaco Canyon totals only 73 acres [43, 54]. However, the documented field acreage is a minimum value because alluvial fan and floodplain sediments may have covered the surfaces of many former field systems. For example, it has been suggested that 2670 acres of arable land

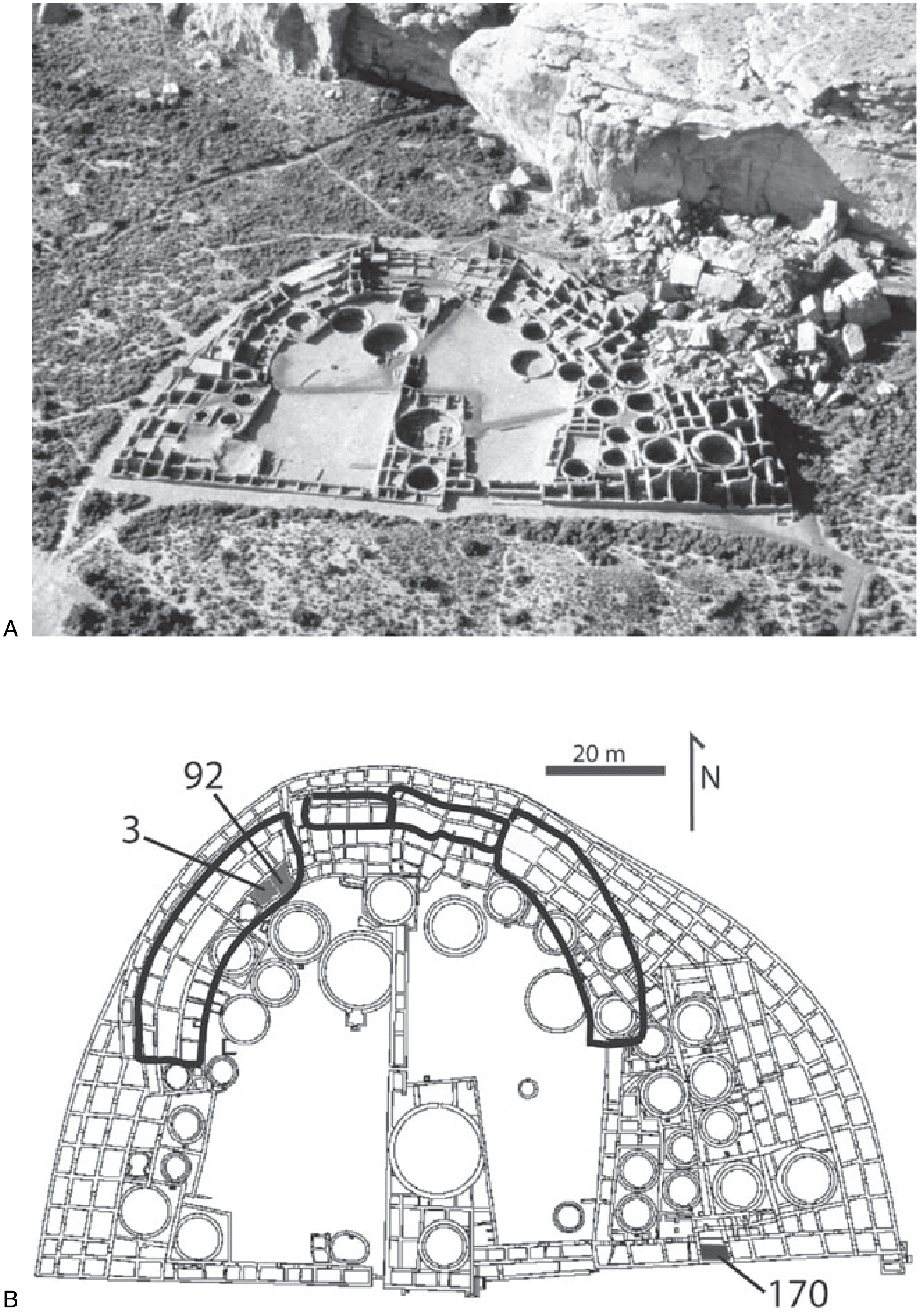

FIGURE 21-5, cont'd **A,** Pueblo Bonito. Photo courtesy of the National Park Service. **B,** Aerial view of room and kiva layout of Pueblo Bonito. Bold outlined room blocks were constructed between AD 860 and the 900s [81]. Rooms 3 and 92 were constructed about AD 860; room 170 was constructed between AD 1077 and 1082.

(Continued)

FIGURE 21-5 **C,** Salmon Ruin. Photo courtesy of the San Juan County Museum Association—Salmon Ruins. **D,** Aztec West Ruin. Photo courtesy of the Aztec Ruin National Monument, National Park Service.

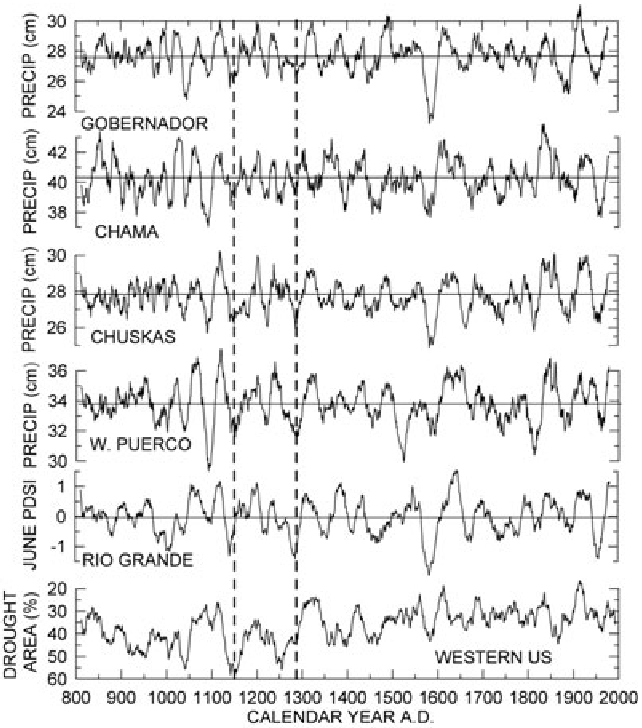

FIGURE 21-6 Tree-ring-based records of drought for the San Juan Basin area, the central Rio Grande, and the western United States [10, 27, personal communication]. Dashed vertical lines connect intervals of drought centered on AD 1150 and 1280. The Gobernador, Chama, Chuskas, and W. Puerco reconstructions indicate annual precipitation values. The June Rio Grande PDSI reconstruction indicates soil-moisture conditions integrated over the previous several months.

existed on both sides of the canyon between Shabik'eschee Village and the Chaco-Escavada confluence [74, 76].

On average, July through October include the wettest months in Chaco. The increased rainfall in July, August, and September is the result of the incursion of the summer monsoon into the San Juan Basin. Since 1922, precipitation at Chaco Canyon in May through September has averaged only 119 millimeters (Western Regional Climate Center, Desert Research Institute, 2004; http://www.wrcc.dri.edu/). Thus, even if Pre-Hispanic strains of maize were more drought tolerant, direct precipitation on Chaco Canyon fields would have fallen far short of their growing season requirement.

During the available 61 years for which monthly precipitation data are available, 16% of the time growing season precipitation was less than 50% of the minimum amount required, and 56% of the time growing season precipitation was less than 75% of the minimum amount required for borderline maize production. Only 26% of the time did growing season precipitation exceed the 150 millimeter minimum.

Given the minimal precipitation and short growing season, Chaco Canyon has been climatically marginal for the production of maize during the past several decades. In addition, paleoclimatic reconstructions [24] indicate that sustained production of maize at Chaco has always been precarious (e.g., 12 multiyear droughts occurred between AD 850 and 1130, some lasting from 15 to 18 years) [12, 15, 24]. Although not all years in a drought interval were "dry," the total time occupied by drought intervals totaled 135 out of 280 years or nearly 50% of the time. Since 1922, the probability is only 43% that 120 consecutive days will be frost-free at Chaco (Western Regional Climate Center, Desert Research Institute, 2004).

We also use historic Zuni and Hopi agricultural practices as analogs to Pre-Hispanic agricultural practices in the Chaco core area. Most traditional fields at the Zuni reservation in west-central New Mexico are on valley-marginal **alluvial fans** and mesa footslopes [49]. At Zuni, May–September rainfall averages 158 millimeters, and there is a 90% probability that a period of 112 days will be frost-free (Western Regional Climate Center, Desert Research Institute, 2004). Maize (white, blue, and red) cultivars take approximately 125 days to mature, and the fields in which the maize grew were generally cropped for 2 to 3 years and then left fallow for 1 to 4 years [49]. Hopi blue corn requires 115 to 130 frost-free days to fully mature [6].

The optimum pH for the raising of maize ranges from 5.5 to 7.0 [51], whereas measured soil-water pH at four sites in Chaco Canyon (Weritos Rincon, Yellow House, Casa Rinconada, and Penasco Blanco field) range from 8.1 to 8.6. Elevated soil pH causes reduction in the bioavailability of phosphorous and nitrogen, because it leads to the precipitation of calcium phosphate and the volatilization of nitrogen.

The earliest measured soil-water salinity from the main valley floor of Chaco Canyon had a conductivity of 11.2 dS/m [6]. To determine if soil salinity affects the potential agricultural production of Chaco, 15 possible field sites within the canyon were sampled and conductivities measured on water extracted from 29 saturated soil pastes (Table 21-1). The quantity of deionized water, used in preparing a saturated paste, is about twice the quantity of water held by the soil at the upper limit of field capacity. Field capacity is defined as "the amount of water held in the soil after excess gravitational water has drained away and after the rate of downward movement of water has materially decreased" [71].

Saturated soil pastes are prepared using deionized water; therefore, laboratory conductivities of the pastes represent minimum field values because actual soil-water conductivities reflect the addition of saline irrigation water or runoff. In addition, field conductivities increase during the process of evapotranspiration. Conductivity data for side tributaries, collected as part of this study, range from 0.33 to 1.19 dS/m (Table 21-2). If we adopt a conductivity value of 0.5 dS/m for side-tributary water and adjust the soil-water conductivities to field capacity, 17 of 29 Chaco Canyon soil waters are found to exceed the salinity threshold of 1.8 dS/m, and 6 soil waters indicate crop loss in excess of 50%

TABLE 21-1 Conductivities, Sample Depths, and Locations (North American Datum 27) of San Juan Basin Soil Samples. Conductivity values are given for (1) a saturated paste made using deionized water, (2) a soil at field capacity (half the water at saturation) calculated using an irrigation water with a pore fluid conductivity of 0.5 dS/m, and (3) a soil at half-field capacity (wilting point) calculated using an irrigation water with a pore fluid conductivity of 0.5 dS/m. [UTM, Universal Transverse Mercator; N, north; E, east; cm, centimeter; dS/m, deciSiemens/meter].

Soil site	Sample	UTM grid	UTM E	UTM N	Depth (cm)	Conductivity (dS/m)		
						Saturation	Field capacity	Wilting point
						Deionized water	(Plus irrigation water)	
Newcomb area								
Two Grey Hills Basketmaker	TGHBM#8	12S	695817	4011912	10 to 20	0.2	0.9	1.8
Two Grey Hills Basketmaker	TGHBM#9	12S	695960	4011496	10 to 20	1.0	2.5	5.0
Two Grey Hills Basketmaker	TGHBM#10	12S	695326	4010669	10 to 20	0.7	1.9	3.8
Skunk Springs modern sediments	SS#2	12S	701539	4011733	0 to 3	0.8	2.1	4.2
Captain Toms Wash	CT#2	12S	702574	4017016	2 to 7	1.1	2.6	5.2
Captain Toms Wash	CT#3	12S	706010	4020290	2 to 7	0.8	2.1	4.2
Captain Toms Wash	CTW#1A	12S	702364	4016768	25 to 35	2.2	4.9	9.8
Captain Toms Wash	CTW#2A	12S	702569	4017023	25 to 35	2.2	4.9	9.8
Captain Toms Wash	CTW#2B	12S	702569	4017023	55 to 65	1.3	3.1	6.3
Captain Toms Wash	CTW#2C	12S	702569	4017023	85 to 95	1.5	3.6	7.1
Captain Toms Wash	CTW#3A	12S	705994	4020307	25 to 35	0.9	2.3	4.6
Aztec Ruin Area								
Aztec Ruin floodplain	AZRO4-1	13S	233056	4080737	10 to 15	0.8	2.1	4.2
Aztec Ruin floodplain	AZRO4-2	13S	233038	4080645	10 to 15	1.0	2.5	5.0
Aztec Ruin floodplain	AZRO4-3	13S	233000	4080565	10 to 15	3.7	7.8	15.6
Aztec Ruin alluvial fan	AZR#3	13S	232890	4080730	5 to 10	1.2	2.9	5.8
Aztec Ruin alluvial fan	AZR#4	13S	232890	4080730	20 to 25	0.8	2.2	4.3
Aztec Ruin alluvial fan	AZR#5	13S	232890	4080730	45 to 50	0.7	1.9	3.7
Aztec Ruin alluvial fan	AZR#6	12S	767483	4080660	5 to 10	1.1	2.6	5.3
Salmon Ruin area								
Salmon Ruin alluvial fan	SR#1	12S	765635	4065725	5 to 10	1.3	3.1	6.2
Salmon Ruin alluvial fan	SR#2	12S	765635	4065725	20 to 25	1.4	3.3	6.6
Salmon Ruin alluvial fan	SR#3	12S	765635	4065725	80 to 85	2.3	5.1	10.2
Salmon Ruin floodplain	SR#4	12S	765658	4065573	10 to 15	11.7	23.9	47.8
Salmon Ruin floodplain	SR#5	12S	765658	4065573	50 to 55	7.7	15.9	31.9
Salmon Ruin floodplain	SR#6	12S	765658	4065573	85 to 90	7.6	15.6	31.2
Chaco drainage								
Within Chaco Canyon								
Casa Rinconada	CR04-1	13S	233310	3994016	10 to 20	5.6	11.7	23.4
Casa Rinconada	CR#1	13S	233347	3994068	25 to 35	5.3	11.1	22.2
Chetro Ketl field	CK#1	13S	234220	3994314	2 to 7	0.9	2.3	4.6
Chetro Ketl field	CKF04-1	13S	234268	3994198	10 to 20	1.0	2.5	5.0
Clys Canyon	CCO4-1	13S	232365	3995664	10 to 15	0.4	1.3	2.6
Fajada Butte	FBO4-1	13S	237467	3990189	10 to 15	1.1	2.7	5.3
Fajada Butte	FBO4-2	13S	237405	3990275	10 to 15	1.1	2.7	5.5
First unnamed canyon west of Mockingbird	UNC104-1	13S	235481	3993659	10 to 20	0.2	0.9	1.8
Gallo Wash	GWO4-1	13S	241605	3993062	10 to 15	0.9	2.3	4.6
Gallo Wash	GWO4-2	13S	240445	3992205	10 to 15	0.5	1.5	3.0
Gallo Wash	GWO4-3	13S	240482	3992157	10 to 15	0.5	1.5	3.1
Kin Kletzo/Yellow House	YH04-1	13S	232846	3994888	10 to 20	0.2	0.9	1.8
Kin Nahasbas	KN04-1	13S	237292	3992239	10 to 20	0.5	1.5	3.0
Lizard House arroyo	LH#1	13S	234505	3994110	23 to 28	3.3	7.1	14.2
Mockingbird Canyon	MC04-1	13S	236731	3993531	10 to 15	1.2	2.9	5.8
Mockingbird Canyon	MC04-2	13S	236575	3993476	10 to 15	4.0	8.5	17.0
Penasco Blanco field	PBF04-1	13S	231232	3995927	10 to 20	1.6	3.7	7.4
Pueblo del Arroyo	PDA#4	13S	232762	3994785	17 to 22	15.0	30.5	61.0
Pueblo del Arroyo modern sediments	PDA#5	13S	232729	3994743	0 to 3	0.5	1.5	3.0

(Continued)

TABLE 21-1 *(continued)*

						Conductivity (dS/m)		
						Saturation	**Field capacity**	**Wilting point**
Soil site	**Sample**	**UTM grid**	**UTM E**	**UTM N**	**Depth (cm)**	**Deionized water**	**(Plus irrigation water)**	
South Gap	SGO4-1	13S	232246	3992989	10 to 15	8.2	16.8	33.6
South Gap	SGO4-2	13S	232379	3993290	10 to 15	0.5	1.5	3.0
South Gap	SGO4-3	13S	232507	3993607	10 to 15	0.7	1.9	3.8
Topographic section 10	S10#1	13S	231128	3995963	25 to 35	4.8	10.1	20.2
Weritos Rincon	WR04-1	13S	235114	3993073	10 to 20	0.2	0.9	1.8
Weritos Rincon	WER#1	13S	235167	3993084	25 to 35	0.5	1.5	3.0
Weritos Rincon	WER#2	13S	235167	3993084	55 to 65	0.5	1.5	3.0
Weritos Rincon	WER#3	13S	235167	3993084	85 to 95	0.7	1.9	3.8
Weritos Rincon	WR#1	13S	235191	3993200	2 to 7	1.1	2.7	5.4
Weritos Rincon	WR#2	13S	235123	3993080	2 to 7	0.6	1.7	3.4
Outside Chaco Canyon								
Chaco Wash at HWY 371	CW371-04-1	12S	752926	3999894	10 to 15	0.3	1.1	2.2
Escalon	ESO4-1	12S	736928	4000890	10 to 15	8.1	16.7	33.4
Escalon	ESO4-2	12S	737206	4002189	10 to 15	2.9	6.2	12.4
Escavada Wash	EWO4-1	13S	233851	3999233	10 to 15	1.5	3.5	7.1
Great Bend	GBO4-1	12S	727046	4004855	10 to 15	2.4	5.4	10.8
Great Bend	GBO4-2	12S	725178	4005576	10 to 15	2.0	4.5	9.1
Kin Bineola	KBO4-1	12S	757669	3987748	10 to 15	5.5	11.5	22.9
Kin Bineola	KBO4-2	12S	757663	3987602	10 to 15	5.0	10.4	20.8
Kin Bineola	KBO4-3	12S	757633	3987480	10 to 15	10.2	20.9	41.8
Kin Klizhin	KKO4-1	12S	763797	3991159	10 to 15	2.4	5.3	10.6
Kin Klizhin	KKO4-2	12S	763995	3991388	10 to 15	0.2	0.9	1.8
Kin Ya'a	KYO4-1	12S	761678	3951444	10 to 15	3.1	6.6	13.2
Kin Ya'a	KYO4-2	12S	761533	3950674	10 to 15	1.5	3.5	7.0
Pueblo Pintado	PPO4-1	13S	257878	3985676	10 to 15	0.7	1.8	3.6
Pueblo Pintado	PPO4-2	13S	257622	3985718	10 to 15	1.1	2.7	5.4
Willow Canyon	WCO4-1	12S	732062	4002278	10 to 15	1.8	4.1	8.2
Willow Canyon	WCO4-2	12S	731985	4002361	10 to 15	1.7	3.9	7.8

(conductivity ≥8.6 dS/m). At minimum field capacity (wilting point), most soil waters exceed the salinity threshold, implying some crop loss at all sites, and conductivities of seven samples exceed 14 dS/m, indicating near-total crop loss (see Table 21-1). Although our conductivity data are from point samples and do not represent integrated field values, the data suggest that the relatively high salinities of many Chaco Canyon soils would have negatively affected maize production during the Pre-Hispanic period.

Within the Chaco core we obtained conductivity readings from soils in nine field areas (we combined samples from the small field sites of Kin Kletzo, Kin Nahasbas, and the first canyon west of Mockingbird Canyon, Table 21-1). Samples S10#1 and PBF04-1 came from the same Penasco Blanco field. We excluded conductivity data from incised sites such as Pueblo del Arroyo and Lizard House Arroyo. Because we do not know the area that was under cultivation at each of the nine sites, we assumed that the cultivated areas were similar in size. We calculated crop loss at each field by assuming that each wilting-point conductivity represents a field area whose size is inversely proportional to the number of measurements made at each field. For example, the three wilting-point conductivities for South Gap are 3.0, 3.8, and 33.6 dS/m, representing yield losses of 10, 15, and 100% or an average crop loss of 42%. Averaging data from the nine fields allows us to estimate an average Chaco Canyon crop loss of 38%.

In conclusion, the small amount of precipitation falling on the Chaco core, its abbreviated growing season, and the high salinity and pH of its soils suggests that it is highly unlikely that Pre-Hispanic corn could have been grown in the canyon without recourse to effective water-control systems.

Irrigation of the Chaco Core

The surface hydrology of Chaco canyon suggests two sources of agricultural water, including occasional flows of the Chaco River and side-tributary runoff that could supplement on-field precipitation.

TABLE 21-2 Conductivities of Water Samples from the Chaco Canyon, Newcomb, and the Totah. [UTM, Universal Transverse Mercator; N, north; E, east; cm, centimeter; dS/m, deciSiemens/meter].

Site	Sample	UTM grid	UTM E	UTM N	Depth (cm)	Conductivity (dS/m)
Chaco Canyon well water (6/16/2004)						
Historic masonry well east	HME#1	13S	236863	3991160	720	0.68
Historic masonry well middle	HMM#1	13S	236858	3991157	no data	1.17
Historic masonry well west	HMW#1	13S	236841	3991154	810	4.64
Casa Chiquita well southeast	CCSE#1	13S	231834	3995510	915	4.44
Casa Chiquita well middle	CCM#1	13S	231836	3995516	880	1.01
Casa Chiquita well northwest	CCNW#1	13S	231838	3995529	700	6.66
Shabik'eschee well east	SHE#1	13S	243200	3989760	1110	1.79
Shabik'eschee well middle	SHM#1	13S	243198	3989755	990	3.45
Fajada View well south	FVS#1	13S	237931	3991000	1590	16.4
Chaco Canyon well water (8/11/2004)						
Historic masonry well east	HME#2	13S	236863	3991160	757	0.79
Historic masonry well middle	HMM#2	13S	236858	3991157	759	1.25
Historic masonry well west	HMW#2	13S	236841	3991154	821	5.24
Casa Chiquita well southeast	CCSE#2	13S	231834	3995510	922	4.81
Casa Chiquita well middle	CCM#2	13S	231836	3995516	891	3.51
Casa Chiquita well northwest	CCNW#2	13S	231838	3995529	961	5.79
Chaco Canyon side-tributary water						
Fourth Canyon NW of visitor center	CTR03-1b	13S	237720	3992405	0	1.19
Fifth Canyon NW of visitor center	CTR03-2b	13S	237199	3992722	0	0.46
Gallo Wash tributary #1 Aug 14, 2004	GWT#1a	13S	240739	3992300	0	0.39
Gallo Wash tributary #2 Aug 14, 2004	GWT#2a	13S	242794	3993328	0	0.33
Chaco Canyon Wash water						
Fajada Wash Apr 2002	FW#1	13S	236948	3992700	0	2.48
Fajada Wash Feb 2003	FW#2	13S	237141	3990531	0	2.06
Fajada Wash Jul 18, 2004	FW#3	13S	237141	3990531	0	0.56
Fajada Wash Jul 26, 2004	FW#4	13S	237141	3990531	0	0.89
Chaco Wash Oct 2002	CW#2	13S	236948	3992700	0	0.53
Chaco Wash Aug 2003	CW#3	13S	236948	3992700	0	0.47
Chaco Wash Jul 18, 2004	CW#4	13S	236948	3992700	0	0.73
Fajada Wash July 26, 2004	CW#5	13S	236948	3992700	0	0.60
Gallo Wash Aug 14, 2004	GWH#1	13S	241656	3992794	0	0.32
Waters outside Chaco Canyon						
Animas River at Aztec Ruin May 2003	AR#3	12S	749932	4067336	0	0.35
San Juan River at Bloomfield May 2003	SJR#5	13S	233200	4065549	0	0.42
Captain Toms Wash Aug 2003	CTW03-1Pb	12S	696343	4011748	0	1.00

The Chaco River is an ephemeral stream, which does not experience sustained or reliable runoff during the growing season, limiting its usefulness as a source of irrigation water. From before AD 900 to 1090 and from before 1500 to the present day, the Chaco River floodplain was incised, negating the dependable use of river water for irrigation [8, 19; Kirk Vincent, personal communication]. When the wash was not incised and the groundwater surface was within a meter or two of the land surface, salts would have concentrated in the root zone by evaporative pumping of shallow groundwater (see the soil-water conductivity data for the San Juan River floodplain near Salmon Ruin in Table 21-1.). Historical U.S. Geological Survey conductivity data for Chaco (*n* = 103) and Fajada (*n* = 6) washes indicate average conductivity values of 0.46 and 0.41.

G. Vivian [75] proposed that runoff from 28 side tributaries on the north side of the canyon between the Gallo-Chaco and Chaco-Escavada confluences was channeled to **gridded gardens** via ditch systems. Some diversion features have been illustrated in Lagasse and colleagues [41]; however, collection and diversion features have been documented in some but not all 28 drainages, and a number of the "canals" were later discovered to be segments of the Chacoan road network [41, 73, 74, 77]. In addition, the irrigation systems documented by Vivian [74] were not always capable of handling runoff, which accompanied intense precipitation events that affected side-tributary drainages on the north side of the canyon [1, 41, 66].

With the exception of the Casa Rinconada field, Pre-Hispanic irrigation features such as ditches and gridded gardens have generally not been documented on the south side of the canyon. For this area, Vivian [75] proposed that **akchin** plots were employed, wherein fields received water along the edges and at the mouths of drainages.

The 12-acre Chetro Ketl gridded field [74] was photographed from the air by Charles Lindbergh in 1929 and is thought to be the most thoroughly documented and defined agricultural feature in the canyon [28, 74]. Alternative explanations exist for the gridded feature, although a head gate has been reported from this area field area [64; Vivian, written communication, 2004]. One way to estimate the total gridded-field area is to assume that field size is proportional to catchment area. The Chetro Ketl field drained either the entire valley northwest of Chetro Ketl ruins (180 acres), or it received half of its water from the two drainages that bracket the field (about 180 acres). Thus, the catchment-to-field area ratio is 15 : 1. Assuming that approximately 10,500 acres of catchment occupy the north side of Chaco Canyon, the total calculated potential gridded-field area along the north side of the canyon is about 700 acres [77].

How much side-canyon runoff could then be expected to reach Chaco Canyon's gridded gardens? Runoff per-unit drainage area decreases with increasing watershed size, primarily because of ephemeral channel losses and partial coverage of the drainage area by thunderstorms. For example, a relatively large basin (149 km^2) such as the Walnut Gulch experimental watershed, in Arizona, has a runoff–rainfall ratio of only 0.006 [26]. Assuming that the smaller subdrainages within Walnut Gulch have similar hydrologic properties as **Chaco side-canyon** drainages, the Chetro Ketl drainage area (0.73 km^2) can be assigned a runoff–rainfall ratio of about 0.030 (calculated using the drainage area mean annual runoff relationship illustrated in Figure 4 of Goodrich and colleagues [26] and a mean-annual Walnut Gulch precipitation rate of 324 mm/yr). This implies that the 12-acre (0.049 km^2) Chetro Ketl gridded garden would receive 171 millimeters of water (runoff plus direct on-field precipitation) in an average water year, less than 162 millimeters of water 56% of the time, when precipitation is less than 75% the minimum amount required to grow maize, and less than 108 millimeters 16% of the time, when precipitation is 50% the minimum amount required to grow maize. Under these conditions, total crop failure would result at least 16% of the time.

Because the total amount of water available for watering gridded gardens was generally close to the minimum amount required for growing of maize, and because hand watering is so labor intensive, reduction in field size is necessary to achieve semioptimal yields of maize. To achieve more optimal moisture levels (275 mm), without recourse to hand watering, field sizes would have had to have been reduced by a factor of approximately 3. This allows about 235 acres of gridded fields along the north side of Chaco Wash to receive 250 millimeters of water and amounts to fallowing two thirds of each field each year.

Water storage (a reservoir) would have increased the productivity of field sites by increasing the total amount of water available to crops and by helping regulate the timing of moisture input to the fields. Chaco Canyon receives about twice its growing season rainfall or 225 millimeters of precipitation in an average year. Reservoirs could be used to store this water for later release during the growing season. In addition, the stored water could be released at intervals between irregularly timed storm events that occurred during the growing season. However, evidence for the existence of Pre-Hispanic reservoirs in the core area is not overwhelming. Structures thought to be reservoirs have been documented for only Clys Canyon and Weritos Rincon; however, the Weritos Rincon dam may have been used as a domestic not an agricultural water source [41]. If the topographic feature at the downstream end of Clys Canyon was a dam, it is difficult to understand how it could have resisted, even for a short period of time, downcutting by water that overflowed it. Vivian [72] has stated that "dating of these (Chaco Canyon water-control systems) systems is tenuous and has been based on masonry styles and a limited number of sherds recovered from water-control structures."

How much land on the south side of the canyon was devoted to akchin–alluvial-fan floodwater farming? The West, South, and Chacra Mesa catchment areas on the south side of the canyon total 6130 acres. A 15 : 1 catchment to field area ratio implies that a maximum of 409 acres could have been under cultivation on the south side of the canyon, and this value does not account for minimal runoff in most years; nor does it take into account the effects of fallowing, salinity, and shortened growing season on maize productivity. Given a runoff coefficient of 0.03, only about 370 acres on both sides of the Chaco core could have been optimally watered.

Another way to estimate Pre-Hispanic field acreage is to examine the agricultural practices of American Indians who are thought to have descended from southwestern Pre-Hispanic cultures. For example, modern Zuni individuals have been shown to have mtDNA haplogroup frequencies nearly identical to Pre-Hispanic Anasazi individuals [9]. Pueblo people do not generally farm large continuous fields, but instead plant in relatively isolated patches chosen for their soil and drainage properties. Only 7.5% of the Oraibi valley was cultivated by the Hopi before incision of the floodplain between 1901 and 1906 [6]. It has bee estimated that runoff on the Zuni reservation could have supported between 20,000 and 26,600 cultivated acres [56], which represent 4.9 to 6.5% of the available 410,000 acres. If these percentages are applicable to the Chaco Canyon core, the Hopi and Zuni agricultural practices imply that ≤350 acres of the 4700 acres in the core were planted in maize during

Pre-Hispanic times. Obviously these estimates are not totally applicable to the Chaco core given the differences in climate, soils, and hydrology of the three areas; however, they do reinforce the possibility that only a few hundred acres of cultivated fields may have characterized the Chaco core during its Pre-Hispanic occupation.

Some Uncertainties in Maize Productivity Estimates

There are uncertainties in extrapolating historical climate data and agricultural practices to Pre-Hispanic agriculture in Chaco Canyon. Although Hopi and Zuni blue corn take approximately 120 freeze-free days to fully mature, there exist "short season" Southwestern (Arizona) maize cultivars that mature in only 60 to 90 days. Maize survival and yields are not strictly defined by frost-free periods or precipitation (e.g., early summer frosts at Zuni are not uncommon and often result in tissue damage but not plant death [49]). On the other hand, a comparison of the climate of Chaco Canyon and the salinity and pH of its soils with conditions, which promote good yields of Hopi and Zuni corn, suggest that production of maize within the canyon would have been marginal at best during Pre-Hispanic times.

Southwestern American Indian Maize Yields and Rates of Consumption

The annual consumption of maize by the Hopi of Oraibi valley between 1851 and 1865 was 12 bushels per person; 12 bushels was also the average yield per acre [6]. An additional 6 bushels per person were required for barter and another 6 for storage in case of future crop failure. In addition, one half acre per person was required for vegetables such as beans, melons, and squash. Therefore, it took, on average, two acres of arable land per year dedicated to maize to support one Hopi.

Other acre-per-person estimates are available for modern pueblos and include 1.1 for the Zia, 1.1 for the Zuni, and 1.4 for the Acoma, Laguna, and Santa Ana Pueblos [69, 78]. Given that the diets of historic Pueblo people were not confined to what they could grow, kill, or forage for, we adopt a value of 1.5 acres of land per person to represent Pre-Hispanic Chacoan maize-growing practices.

Estimated Population Densities Supported by Chaco Canyon Maize Production

The productivity of Chaco Canyon remains an issue of great debate. Some scholars believe that the core's agricultural productivity was sufficient to support a fluctuating resident–nonresident population between AD 850 and 1300 [76]. Others have suggested that the core's relatively cool-dry climate coupled with its saline soils rendered the core marginal for agriculture [6, 25, 60, 61]. Given the acreage estimates discussed in the previous section, if it takes 1.5 acres a year to support an inhabitant of the canyon, there was enough maize, on average, to support about 250 individuals. These data support those who believe that the Chaco core was marginal in terms of its agricultural potential. The difficulty of producing a reliable maize crop in Chaco is amply illustrated by Marietta Wetherill, who stated, "In the last sixteen years, there have been (the local Navajos have raised) only two good crops" [33].

The number of people supported by canyon agriculture is an order of magnitude smaller than calculations of the canyon's resident population based on room, hearth, or kiva numbers. D. Drager [16] applied S. Stubbs' [67] correlations of modern Pueblo populations with room number, floor space, and structure area to estimate that Chacoan great houses had a population of approximately 3000. This combined with A. Hayes' [31] estimate of about 2900 small-house occupants yields an eleventh century population of about 5900 for the canyon [76]. T. Windes [79] estimated a canyon-wide population of less than 2000 for the late eleventh century by equating firepit rooms with single households each containing six people. In fact the population in the Chaco core area may have been less than 2000 given that the populations of three of the communities studied by Windes [79] lay outside the core [80]. In addition, some of the sites may have been only seasonally occupied.

These data suggest that the resident population was much smaller than that estimated from building features and also lend support to J. Judge's [35, 36] concept wherein Chaco was a "vacant city" whose population swelled when pilgrims came from outlying areas to participate in organized ritual and construction activities. It has also been suggested that outlier sites were public buildings used for storage of surplus foodstuffs that were taken to the Chaco core for redistribution [45]. We suggest that increases in Chaco's population during pilgrim fairs and major construction intervals (e.g., between AD 1030 and 1130) would have necessitated the importation of maize even if only a few hundred individuals resided in the canyon. We acknowledge that the residential population of Chaco was not static between AD 850 and 1130 and may have fluctuated a number of times; therefore, canyon-based agriculture may have been able to sustain its residents when their numbers were low.

Areas from which Maize May Have Been Imported

The Totah region, the area surrounding the confluences of the Animas and La Plata rivers with the San Juan River and which includes both Salmon and Aztec Ruins (see Figures 21-1, 21-5C, 21-5D), is an excellent area for maize agriculture and exportation. Both ruins are on alluvial fan sediments that grade to nearby floodplains. Thus, both Pre-Hispanic sites have a perennial source of water. In addition, there is a 98% probability of 120 consecutive frost-free days and precipitation from May through September has averaged 105 millimeters during the last 90 years (Western Regional Climate Center, Desert Research Institute, 2004).

The base of the Chuskas, which we refer to as the Newcomb area, is also climatologically superior to Chaco in that there is a 100% probability of greater than 120 consecutive frost-free days. In addition, between 1949 and 1968 Newcomb averaged 1719 ± 159 corn growing degree days (CGDD °C) whereas Chaco Canyon averaged only 1235 ± 127 CGDD. The Chuska Mountains immediately to the west of Newcomb act as an orographic barrier to winter-westerly storms; therefore, May through September precipitation averages only 86 millimeters at Newcomb. Snow precipitated along the crest of the Chuskas melts in the late spring and early summer and flows through the ephemeral Captain Tom and Skunk Springs wash systems (see Figure 21-1). This provides a fairly reliable source of irrigation water for fields adjacent to the washes. The existence of three large field systems at Newcomb, one of which covered 19 km^2 (4700 acres) and contained 74 kilometers of main irrigation ditches has been reported [22]. It has not been demonstrated that these large field systems are Pre-Hispanic in age; however, their existence indicates that the Newcomb area was and is extremely productive. For example, when J. Simpson [63] crossed the Newcomb area in AD 1849, he noted the presence of "very extensive and luxuriant cornfields." Samuel Stacher, who was given charge of the Eastern Navajos (including Chaco Canyon) in 1909, found that agriculture was of little importance to most of the Navajo population; however, he soon learned that some of the Navajos traveled 80 kilometers to the west of Pueblo Bonito where they raised considerable maize, suggesting that this area was Newcomb [7].

Additional sites that may have supplied maize to Chaco includes those great-house communities that lie relatively close (<50 km) to the canyon (e.g., Kin Klizhin, Kin Bineola, and Pueblo Pintado) (see Figure 21-3). Historically, Navajos successfully farmed some of the side tributaries west of Chaco Canyon, including Kin Bineola and Kin Klizhin, both of which possessed relatively large irrigated fields. For the purposes of this chapter we analyzed soils from several sites between the Great Bend of the Rio Chaco and Pueblo Pintado (see Figure 21-3).

ARCHAEOLOGICAL MAIZE SAMPLES

Most archaeological maize has been burned (e.g., all cobs excavated from Newcomb area great houses and from Salmon Ruin are carbonized). The bulk of the biological materials archived from Pueblo Bonito excavations by George Pepper, as part of the Hyde Expedition (1896–1890), consists of unburned cobs. However, Pepper may not have archived any of the burned organic material he excavated, and N. Judd [34] found mostly charred archaeological cobs at Pueblo Bonito. Burned cobs have the properties of activated charcoal (i.e., they absorb organic and inorganic chemicals, e.g., Strontium [Sr] and other trace metals) from their environment, especially if water enters that environment. Thus Sr isotope and trace-element ratios from burnt cobs may indicate where they were buried and not where they were grown.

To determine where Chacoan archaeological cobs were grown, seven unburned cobs excavated by the Hyde Expedition from three rooms in Pueblo Bonito (see Figure 21-5B) were obtained from the American Museum of Natural History [5]. Cobs H-242 (244A and 244B) and H-254 (258A, 258B, and 258C) were excavated from the floor of room 3 and cob H-7673 was excavated from the floor of room 92. Both rooms are part of the oldest section of Pueblo Bonito, constructed about AD 860 [81]. Cob H-10648 came from room 170, which was built between AD 1077 and 1082 [83].

Chemical Tracing of Biological and Archaeobiological Materials

In this section, we discuss the application of elemental distributions, elemental ratios, and radiogenic isotope ratios in chemical tracing of biological materials such as maize.

Trace Elements

Whereas trace elements have routinely been used to source inorganic materials such as obsidian and ceramics, their application to biological materials is limited [2, 21, 38, 44, 52]. This is because tracing of inorganic material usually amounts to locating a source with a chemical composition matching the sample in question, whereas the tracing of biological materials may involve plants that no longer exist in their archaeological source areas. In addition, plant chemistry can vary greatly over small spatial scales as the result of plant physiology (including environmental stress) and soil heterogeneity.

In using trace elements to determine the source of archaeological plant material, we seek to link the chemical composition of archaeological plants to the chemical compositions of living plants found in archaeological source areas, or alternatively, we seek to link the archaeological plants to their former soil substrates. The former procedure requires that the plant in question is today found in all possible archaeological source areas. If so, one can obtain elemental concentrations of several plants from each site and use site-specific elemental distributions to distinguish between sites [17]. The elemental distributions in the archaeological plants can then be statistically compared with the site-specific modern plant elemental distributions to determine the source(s) of the archaeological plants.

In terms of our study, maize is not present in all possible source areas; therefore, a direct link must be forged between the chemistry of the archaeological cob and the chemistry of the soil or soil water from which the plant obtained its chemistry. L. Benson and his colleagues [5] employed the use of the trace-element distribution coefficient (K_D), a coefficient commonly used in low-temperature geochemistry to describe the partitioning of trace elements between liquid and solid phases [53]. For our purposes, the distribution coefficient is defined by

$$K_D(C_{TE1}/C_{TE2})_{Soil\ Water} = (C_{TE1}/C_{TE2})_{Plant}$$

where C_{TE1}/C_{TE2} = the concentration (µg element/g soil) ratio of trace elements 1 and 2.

The use of the distribution coefficient accounts for the bioavailability of chemical species (they are part of the soil-water solution), and the use of an elemental ratio negates the effect of changes in soil-water concentration on the concentrations of individual dissolved trace elements. However, K_D is not constant for all element ratios. Element pairs that contain a trace nutrient or a trace element that the plant prefers to exclude (e.g., lead) will exhibit widely varying K_D values. However, the Kd value will tend to be constant for element pairs that have similar chemical properties (e.g., the Sr-barium [Ba] pair) if those properties are neither essential nor harmful to the plant. The use of an elemental ratio also allows us to work with synthetic soil solutions produced by leaching a soil with a weak acid (see Sampling and Laboratory Methods section). Given the small number of samples available to calculate K_D*s,* the differences in the values calculated from the two field sites [5], and the small number of cobs, we suggest that a comparison of synthetic soil-water trace-element ratios with calculated cob soil-water trace-element ratios can be done only in a semiquantative way (see Results and Discussion section).

Radiogenic Isotopes

In this section, we discuss the application of the radiogenic and stable isotopes of Sr. A radiogenic isotope is one that was produced by the decay of a radionuclide, but which itself may or may not be radioactive. In the case of Sr, there are two isotopes of interest ^{87}Sr and ^{86}Sr. ^{86}Sr is a stable isotope, whereas ^{87}Sr is a stable radiogenic isotope produced by the radioactive decay of ^{87}Rb with a half life of 48.8 billion years. Thus the ^{87}Sr/^{86}Sr ratio of a rock and the soil derived from it is a function of the initial ^{87}Sr/^{86}Sr ratio of the rock, its age, and the amount of ^{87}Rb initially present in the rock. However, the rate of production of ^{87}Sr is so slow that the ^{87}Sr/^{86}Sr ratio can be considered invariant over archaeological timescales.

The use of radiogenic isotopes as tracers is much more straightforward than the use of trace elements. The isotopes of Sr are nearly identical in their physical and chemical properties; therefore, isotopic fractionation does not occur during chemical and physical transformations. In terms of Sr delivery to a plant, the soil water takes on the ^{87}Sr/^{86}Sr ratio of the soluble soil component (carbonates and other more soluble salts) which is, in turn, transferred unchanged to the plant.

There have been numerous archaeological applications of Sr isotopes during the past decade, most of which involve defining a person's or animal's origin or migration pattern [4, 32, 48, 55]. Perhaps the most well known of such studies is that performed on the remains of the Alpine Iceman in which not only radiogenic Sr and lead (Pb) isotopes were used, but so were stable oxygen and carbon isotopes [50].

In terms of the San Juan Basin, Sr isotopes have been used to demonstrate that some of the spruce and fir trees used to construct Chacoan great houses were probably harvested in the Chuska and San Mateo mountains [18], and Sr isotopes and element ratios in cobs found in Pueblo Bonito were used to determine the probable areas in which the maize was grown [5]. Those latter data indicate that the Pueblo Bonito cobs were not grown in the Chaco Canyon valley but may have come from the Newcomb and Totah areas. In the following section, we discuss the provenance of the Pueblo Bonito cobs in light of new chemical data from Newcomb, the Totah, and side-canyon sites along the Rio Chaco and Chaco Wash.

Methodological Considerations: Sampling and Laboratory Methods

Soil samples were collected from floodplain sites in the Totah and Newcomb areas and from side canyons that border Chaco Wash and the Rio Chaco (see Figures 21-1, 21-2, 21-3). Most of the soil samples were taken from a depth of 45 to 50 centimeters and never exceeded 85 centimeters; thus, the samples were all in the 1-meter root-depth range (Table 21-3). Some of the side-canyon sites were near great houses located close to the canyon (compare Figures 21-2 and 21- 4). Water samples were obtained from perennial streams, ephemeral streams, side-canyon tributaries, and from shallow wells in the Gallo, Fajada, and Chaco washes.

Soils were air dried and homogenized, and a 5-gram subsample of each soil was leached for 48 hours with constant agitation using 500 millimeters of 1-M acetic acid prepared from distillation-purified glacial-acetic acid. These samples were sequentially filtered through 0.4- and 0.1-micrometer pore-size membrane filters. All water samples were vacuum filtered through 0.1-micrometer-diameter pore-size polycarbonate membrane filters. All perennial and some ephemeral stream waters were field filtered through a 0.4-micrometer-diameter pore-size polycarbonate membrane filter. Most

TABLE 21-3 ^{87}Sr/^{86}Sr Ratios for 7 Pueblo Bonito Archeological Cobs, 95 Synthetic Soil Waters, and 30 Natural Waters from Potential Maize Source Areas in the San Juan Basin. [cm, centimeter; UTM, Universal Transverse Mercator; E, east; N, north]

Site	Sample	Depth (cm)	^{87}Sr/^{86}Sr	Error	UTM grid	UTM E	UTM N
Pueblo Bonito cobs							
Room 3	H242/244A		0.709319	0.000016			
Room 3	H242/244B		0.709475	0.000042			
Room 3	H254/258A		0.709394	0.000010			
Room 3	H254/258B		0.709225	0.000018			
Room 3	H254/258C		0.709280	0.000014			
Room 92	H7673		0.709328	0.000011			
Room 170	H10648		0.709892	0.000016			
The Newcomb area							
Newcomb soils							
Skunk Springs, Blackhouse Valley	SS#1	95 to 100	0.709331	0.000022	12S	701539	4011733
Skunk Springs, Blackhouse Valley	SS#2	0 to 5	0.709119	0.000020	12S	701539	4011733
Skunk Springs, Blackhouse Valley	SS#3	105 to 110	0.709349	0.000022	12S	701539	4011733
Captain Toms Wash, old wash sediments	CT#1	95 to 100	0.709289	0.000018	12S	702365	4016771
Captain Toms Wash, modern field	CT#2	0 to 10	0.709062	0.000023	12S	702574	4017016
Captain Toms Wash, historic field	CT#3	0 to 10	0.709028	0.000017	12S	706010	4020290
Captain Toms Wash, CT#1 site	CTW#1A	25 to 35	0.709018	0.000009	12S	702364	4016768
Captain Toms Wash, CT#1 site	CTW#1B	55 to 65	0.709240	0.000012	12S	702364	4016768
Captain Toms Wash, CT#1 site	CTW#1C	85 to 95	0.709290	0.000017	12S	702364	4016768
Captain Toms Wash, CT#2 site	CTW#2A	25 to 35	0.709046	0.000009	12S	702569	4017023
Captain Toms Wash, CT#2 site	CTW#2B	55 to 65	0.709215	0.000015	12S	702569	4017023
Captain Toms Wash, CT#2 site	CTW#2C	85 to 95	0.709083	0.000019	12S	702569	4017023
Captain Toms Wash, CT#3 site	CTW#3A	25 to 35	0.708830	0.000021	12S	705994	4020307
Captain Toms Wash, CT#3 site	CTW#3B	55 to 65	0.708760	0.000008	12S	705994	4020307
Captain Toms Wash, CT#3 site	CTW#3C	85 to 95	0.708709	0.000016	12S	705994	4020307
Two Grey Hills Basketmaker, upstream of trading post bridge	TGHBM#1	70 to 75	0.709040	0.000020	12S	695786	4011891
Two Grey Hills Basketmaker, upstream of trading post bridge	TGHBM#2	80 to 85	0.709170	0.000020	12S	695816	4011920
Two Grey Hills Basketmaker, upstream of trading post bridge	TGHBM#3	65 to 70	0.709120	0.000020	12S	695619	4012007
Two Grey Hills Basketmaker, groundwater discharge area	TGHBM#4	70 to 75	0.709230	0.000020	12S	695965	4011503
Two Grey Hills Basketmaker, groundwater discharge area	TGHBM#5	55 to 60	0.709200	0.000020	12S	695631	4011075
Two Grey Hills Basketmaker, groundwater discharge area	TGHBM#6	65 to 70	0.709300	0.000020	12S	695131	4010586
Two Grey Hills Basketmaker, wash at Toadlena	TGHBM#7	65 to 70	0.709060	0.000020	12S	693258	4010745
Newcomb wash water							
Basketmaker site	BMS#2	0	0.709366	0.000010	12S	696343	4011300
Toadlena bridge	TLB#2	0	0.709864	0.000008	12S	689420	4011145
Captain Toms Wash	CTW03-1Pb	0	0.709480	0.000020	12S	696343	4011748
Newcomb well water							
Skunk Springs Well	SSW#2	0	0.709242	0.000015	12S	700685	4011904
The Chaco Canyon Valley							
Chaco Canyon Valley soils							
Chetro Ketl Field, G. Vivian site F-4	CK#1	5 to 10	0.709190	0.000017	13S	234220	3994314
Chetro Ketl Field, G. Vivian site F-4	CKF#1	25 to 35	0.709170	0.000012	13S	234222	3994178
Chetro Ketl Field, G. Vivian site F-4	CKF#2	55 to 65	0.709065	0.000015	13S	234222	3994178
Chetro Ketl Field, G. Vivian site F-4	CKF#3	85 to 95	0.709053	0.000009	13S	234222	3994178
Lizard House Arroyo	LH#1	25 to 30	0.708965	0.000015	13S	234505	3994110
Lizard House Arroyo	LH#2	62 to 67	0.709347	0.000020	13S	234505	3994110
Lizard House Arroyo	LH#3	145 to 150	0.709165	0.000013	13S	234505	3994110
Pueblo del Arroyo	PDA#1	435 to 445	0.709077	0.000023	13S	232762	3994785
Pueblo del Arroyo	PDA#3	320 to 330	0.709155	0.000017	13S	232762	3994785
Pueblo del Arroyo	PDA#4	15 to 25	0.709093	0.000014	13S	232762	3994785
Pueblo del Arroyo	PDA#5	0 to 3	0.709044	0.000017	13S	232729	3994743
Weritos Rincon	WR#1	0 to 10	0.709570	0.000021	13S	235191	3993200

(Continued)

TABLE 21-3 (*continued*)

Site	Sample	Depth (cm)	$^{87}Sr/^{86}Sr$	Error	UTM grid	UTM E	UTM N
Weritos Rincon	WR#2	0 to 10	0.709465	0.000008	13S	235124	3993080
Weritos Rincon	WER#1	25 to 35	0.709590	0.000010	13S	235167	3993084
Weritos Rincon	WER#2	55 to 65	0.709606	0.000018	13S	235167	3993084
Weritos Rincon	WER#3	85 to 95	0.709549	0.000001	13S	235167	3993084
Casa Rinconada, G. Vivian site C-10	CR#1	25 to 35	0.709159	0.000009	13S	233347	3994068
Casa Rinconada, G. Vivian site C-10	CR#2	55 to 65	0.709088	0.000017	13S	233347	3994068
Casa Rinconada, G. Vivian site C-10	CR#3	85 to 95	0.709108	0.000017	13S	233347	3994068
Section 10, G. Vivian site A-16, Penasco Blanco field	S10#1	25 to 35	0.709204	0.000015	13S	231128	3995963
Section 10, G. Vivian site A-16, Penasco Blanco field	S10#2	55 to 65	0.709121	0.000017	13S	231128	3995963
Section 10, G. Vivian Site A-16, Penasco Blanco field	S10#3	85 to 95	0.709078	0.000012	13S	231128	3995963
Casa Chiquita	CC#1	67 to 72	0.709036	0.000013	13S	232192	3995089
Casa Chiquita	CC#2	97 to 102	0.709083	0.000015	13S	232192	3995089
Casa Chiquita	CC#3	127 to 132	0.709066	0.000011	13S	232192	3995089
Fajada Butte	FB04-1	45 to 50	0.708973	0.000014	13S	237467	3990189
Fajada Butte	FB04-2	45 to 50	0.709005	0.000018	13S	237405	3990275
Chaco side-canyon soils							
Gallo Wash	GW04-1	45 to 50	0.709311	0.000014	13S	241605	3993062
Gallo Wash	GW04-2	45 to 50	0.708963	0.000018	13S	240445	3992205
Gallo Wash	GW04-3	45 to 50	0.708996	0.000012	13S	240482	3992157
Mockingbird Canyon	MC04-1	45 to 50	0.709144	0.000013	13S	236731	3993531
Mockingbird Canyon	MC04-2	45 to 50	0.709208	0.000019	13S	236575	3993476
Clys Canyon	CC04-1	45 to 50	0.708792	0.000022	13S	232365	3995664
South Gap	SG04-1	45 to 50	0.709421	0.000020	13S	232246	3992989
South Gap	SG04-2	45 to 50	0.709617	0.000029	13S	232379	3993290
South Gap	SG04-3	45 to 50	0.709709	0.000020	13S	232507	3993607
The Rio Chaco area outside the Chaco core							
Rio Chaco side-tributary soils							
Kin Klizhin	KK04-1	45 to 50	0.709527	0.000011	12S	763797	3991159
Kin Klizhin	KK04-2	45 to 50	0.709474	0.000016	12S	763995	3991388
Kin Bineola	KB04-1	45 to 50	0.709438	0.000013	12S	757669	3987748
Kin Bineola	KB04-2	45 to 50	0.709310	0.000012	12S	757663	3987602
Kin Bineola	KB04-3	45 to 50	0.709324	0.000012	12S	757633	3987480
Escalon, Indian Creek drainage	ES04-1	45 to 50	0.709637	0.000017	12S	736928	4000890
Escalon, Indian Creek drainage	ES04-2	45 to 50	0.709489	0.000018	12S	737206	4002189
Willow Canyon	WC04-1	45 to 50	0.709547	0.000013	12S	732062	4002278
Willow Canyon	WC04-2	45 to 50	0.709503	0.000015	12S	731985	4002361
Great Bend	GB04-1	45 to 50	0.709557	0.000012	12S	727046	4004855
Great Bend	GB04-2	45 to 50	0.709408	0.000019	12S	725178	4005576
Pueblo Pintado	PP04-1	45 to 50	0.709199	0.000018	13S	257878	3985676
Pueblo Pintado	PP04-2	45 to 50	0.709318	0.000025	13S	257622	3985718
Escavada Wash	EW04-1	45 to 50	0.709073	0.000028	13S	233851	3999233
Chaco Wash at highway 371	CW371-04-1	45 to 50	0.708888	0.000028	12S	752926	3999894
The area southwest of Chaco Canyon							
Kin Ya'a	KY04-1	45 to 50	0.709462	0.000027	12S	761678	3951444
Kin Ya'a	KY04-2	45 to 50	0.709737	0.000022	12S	761533	3950674
Chaco Canyon waters							
Chaco Canyon wash water							
Chaco wash water	CW#2	0	0.709089	0.000018	13S	233302	3994430
Chaco wash water	CW#3	0	0.709040	0.000014	13S	236948	3992700
Chaco wash water	CW#4	0			13S	237165	3990500
Fajada wash water	CW#5	0			13S	237109	3990468
Fajada wash water	FW#1	0	0.709274	0.000018	13S	236948	3989704
Fajada wash water	FW#2	0			13S	237141	3990531
Fajada wash water	FW#3	0			13S	237165	3990500
Fajada wash water	FW#4	0			13S	237165	3990500
Gallo wash water	GWH#1	0			13S	241656	3992794

(*Continued*)

TABLE 21-3 (*continued*)

Site	Sample	Depth (cm)	$^{87}Sr/^{86}Sr$	Error	UTM grid	UTM E	UTM N
Chaco shallow groundwater							
Historic masonry well west	HMW#1	810			13S	236885	3990943
Historic masonry well middle	HMM#1	?			13S	236905	3990952
Historic masonry well east	HME#1	720			13S	236911	3990955
Casa Chiquita well southeast	CCSE#1	915			13S	231881	3995303
Casa Chiquita well middle	CCM#1	880			13S	231884	3995309
Casa Chiquita well northwest	CCNW#1	700			13S	231887	3995324
Shabik'eschee well east	SHE#1	1110			13S	243249	3989555
Shabik'eschee well middle	SHM#1	990			13S	243247	3989549
Fajada View well south	FVS#1	1590			13S	237978	3990793
Chaco side-canyon tributary water							
Fourth Canyon NW of visitor center	CTR03-1b	0	0.70969	0.000020	13S	237720	3992405
Fifth Canyon NW of visitor center	CTR03-2b	0	0.70999	0.000020	13S	237199	3992722
Gallo Wash tributary 1	GWT#1	0			13S	240739	3992300
Gallo Wash tributary 2	GWT#2	0			13S	242794	3993328
The Totah Area							
Aztec Ruin soils							
Aztec Ruin floodplain	AZR#1	22 to 27	0.709899	0.000020	13S	233052	4080570
Aztec Ruin floodplain	AZR#2	52 to 57	0.709557	0.000017	13S	233052	4080570
Aztec Ruin alluvial Fan	AZR#3	5 to 10	0.709581	0.000013	13S	232890	4080730
Aztec Ruin alluvial Fan	AZR#4	20 to 25	0.709560	0.000021	13S	232890	4080730
Aztec Ruin alluvial Fan	AZR#5	45 to 50	0.709577	0.000019	13S	232890	4080730
Aztec Ruin alluvial Fan	AZR#6	5 to 10	0.709650	0.000011	12S	767483	4080660
Aztec Ruin alluvial Fan	AZR#7	30 to 35	0.709600	0.000017	12S	767483	4080660
Aztec Ruin alluvial Fan	AZR#8	75 to 80	0.709558	0.000020	12S	767483	4080660
Aztec Ruin floodplain	AZR04-1	45 to 50	0.709573	0.000012	13S	233056	4080737
Aztec Ruin floodplain	AZR04-2	45 to 50	0.709525	0.000031	13S	233038	4080645
Aztec Ruin floodplain	AZR04-3	45 to 50	0.709587	0.000022	13S	233000	4080565
Animas River at Farmington							
Animas River February 2002	AR#1	0	0.709495	0.000008	12S	749916	4067341
Animas River April 2002	AR#3	0	0.709661	0.000021	12S	749932	4067336
Salmon Ruin soils							
Bank of San Juan River at Bloomfield	SJS#1	45 to 50	0.710237	0.000019	13S	233202	4065534
Salmon Orchard alluvial fan	SR#1	5 to 10	0.710148	0.000013	12S	765635	4065725
Salmon Orchard alluvial fan	SR#2	20 to 25	0.710157	0.000007	12S	765635	4065725
Salmon Orchard alluvial fan	SR#3	80 to 85	0.710095	0.000023	12S	765635	4065725
Edge of San Juan floodplain	SR#4	10 to 15	0.710089	0.000019	12S	765658	4065573
Edge of San Juan floodplain	SR#5	50 to 55	0.710106	0.000022	12S	765658	4065573
Edge of San Juan floodplain	SR#6	85 to 90	0.710043	0.000020	12S	765658	4065573
floodplain	SAL#1	60 to 65	0.710060	0.000020	12S	765623	4065336
floodplain	SAL#2	55 to 60	0.710010	0.000020	12S	765627	4065331
San Juan River at Bloomfield							
At San Juan River bridge	SJR#1	0	0.710288	0.000014	13S	233202	4065534
At San Juan River bridge	SJR#5	0	0.710376	0.000021	13S	233200	4065549
San Juan River below Farmington							
1 km below confluence with Animas R.	SJR#2	0	0.709912	0.000017	12S	747834	4067530
Bedrock Samples							
Chaco Canyon bedrock							
Tsin Kletzin Stairway, Menefee Shale	TKS#1	0 to 5	0.709599	0.000012	13S	233847	3993881
Tsin Kletzin Stairway, Sandstone	TKS#2	0 to 5	0.710547	0.000011	13S	233847	3993881
Cliff House Sandstone	CHS#1	0 to 5	0.709256	0.000018	13S	234612	3994116
Menefee Shale	M#1	0 to 5	0.709955	0.000019	13S	234612	3994116
Selenite in Menefee Shale	M#2	0 to 5	0.708971	0.000013	13S	234612	3994116
Aztec bedrock							
Outcrop in bluffs north of ruin	AZ#1	800 to 1000	0.709096	0.000017	13S	236531	4081200
Bloomfield bedrock							
Sand and gravel east of Salmon Ruin	BL#1	200 to 400	0.710121	0.000013	12S	765218	4066674
Sand east of Salmon Ruin	BL#4	600 to 800	0.710368	0.000011	12S	765552	4066691

ephemeral waters, including turbid wash and side-tributary waters, were filtered later in the Boulder U.S. Geological Survey laboratory. After filtration, samples were preserved for trace-metals analysis by the addition of high-purity HNO_3 to a sample pH of less than 2. Multielement trace metal determinations were performed using inductively coupled plasma-mass spectrometric (ICP-MS and ICP-AES) methods [23, 68]. All measurements were made without preconcentration using direct pneumatic nebulization with a Perkin Elmer Elan 6000 instrument.

Outer cupules from archaeological specimens of corncobs were removed using a ceramic knife. A 0.25-gram subsample was transferred to a clean platinum crucible for dry ashing in a muffle furnace. Ashing was accomplished by ramping the temperature of the furnace in 50°C increments every 30 minutes from a starting temperature of 100°C to a final temperature of 450°C. After cooling to room temperature in the furnace, 2 millimeters of deionized water, 3 millimeters of high-purity–concentrated HNO_3, and 2 millimeters of HF were added to the crucible. This solution was evaporated to dryness under an infrared heating lamp. The residue was dissolved in 2 millimeters of concentrated HNO_3 and 20 millimeters of deionized water, transferred to a 100-millimeter volumetric flask, and diluted to volume using 1% HNO_3. For quality-assurance purposes, National Institute of Standards and Technology Standard Reference Material Trace Elements in Corn Bran (http://webbook.nist.gov/chemistry/) was ashed using the same procedure as the samples. ICP-MS and ICP-AES analysis was done for 51 trace elements. Only those element ratios that resulted in similar K_Ds are reported in this chapter.

Strontium chemical separations and isotopic determinations were conducted in a Class 1–10,000 clean room at the University of Colorado, Boulder. Sr separates were obtained using a Sr specific resin (Sr resin SPS, Eichrom Technologies, Inc.). The total procedural blank for Sr was approximately 30 picograms. Sr isotopic measurements were obtained using a Finnigan-MAT 261 thermal-ionization mass spectrometer in 4-collector static mode. During the study period, 31 measurements of the SRM-987 Sr isotopic standard yielded a mean $^{87}Sr/^{86}Sr$ value of 0.710276 ± 0.000016 (2σ-mean) compared with reference value of 0.71028.

To determine the principal source (irrigation water or soluble mineral component of soil) of Sr in soil water, we equilibrated a small amount (5 g) of soil from each of two field sites (CR#2 and CKF#3) with 100 millimeters of water from Captain Tom Wash for about 24 hours and then measured the $^{87}Sr/^{86}Sr$ ratios of the two leachates after approximately 24 hours. We also measured the $^{87}Sr/^{86}Sr$ ratios of the wash water and the synthetic soil waters obtained by equilibration of 5 grams of each soil with 500 millimeters of 1-M acetic acid prepared from distillation-purified glacial-acetic acid. The results of the experiment indicated that $50 \pm 5\%$ of the Sr in the leachates was derived from the wash water. The experiment used a water-to-soil volume ratio of 50 : 1; however, even in the case of optimum watering (see Irrigation of the Chaco Core section), the water-to-soil ratio in an actual field setting is less than 1, indicating that the $^{87}Sr/^{86}Sr$ ratio of the soluble mineral component in the soil will usually dominate the $^{87}Sr/^{86}Sr$ ratio of the actual soil-water solution in the natural environment. This is obviously true when one considers that precipitation has little dissolved Sr; thus runoff that reaches a field obtains its Sr from reaction of Sr-poor precipitation with Sr-rich carbonate minerals in the soil. This implies that the synthetic soil solutions made by reacting the soil with a weak acid provide a good approximation of the actual $^{87}Sr/^{86}Sr$ soil-to-water ratio if the field is irrigated with side-tributary runoff that contains dissolved Sr or if the field receives water in the form of precipitation. It is possible in a water-dominated system such as a floodplain that much of the Sr in a cob derives from river water not the silt–sand substrate in which the maize grows. However, the $^{87}Sr/^{86}Sr$ ratio of the river water is itself derived from the dissolution of soluble salts and minerals during the flow of water from its watershed to the irrigated field.

Soil salinity (conductivity) of water extracted from saturated soil pastes was done at the Utah State University analytical laboratory under the supervision of Jan Kotuby-Amacher. Reproducibility of these analyses is limited to about two significant figures. Conductivities of natural water samples were done at the USGS Boulder Laboratory and are accurate to at least three significant figures.

Results and Discussion

In this section, we first compare the $^{87}Sr/^{86}Sr$ ratios of synthetic soil and natural waters from potential agricultural sites with the $^{87}Sr/^{86}Sr$ ratios of archaeological cobs from Pueblo Bonito. We then calculate soil-water trace-element ratios associated with archaeological cobs using estimated distribution coefficients for Ba/Sr (0.30), Y/Yb (2.0), and Mg/Sr (7.2) and the measured trace-element ratios of the cobs; (the K_D for Y/Yb used in Benson and colleagues [5] and in this chapter is 2.0; not 16.1 as listed in Table 1 of Benson and colleagues). Next we compare soil-water trace-element ratios associated with the Pueblo Bonito cobs with measured soil-water trace-element ratios from field sites whose $^{87}Sr/^{86}Sr$ ratios fall within the $^{87}Sr/^{86}Sr$ range of Pueblo Bonito cobs.

Strontium Isotopes

Strontium in cobs comes from three principal sources within the soil, including soluble minerals (such as calcite), clay exchange sites, and irrigation water.

A comparison of Bonito cob $^{87}Sr/^{86}Sr$ ratios with Aztec and Salmon soil $^{87}Sr/^{86}Sr$ ratios and Animas and San Juan River $^{87}Sr/^{86}Sr$ ratios indicates that cob H-10648 has a ratio

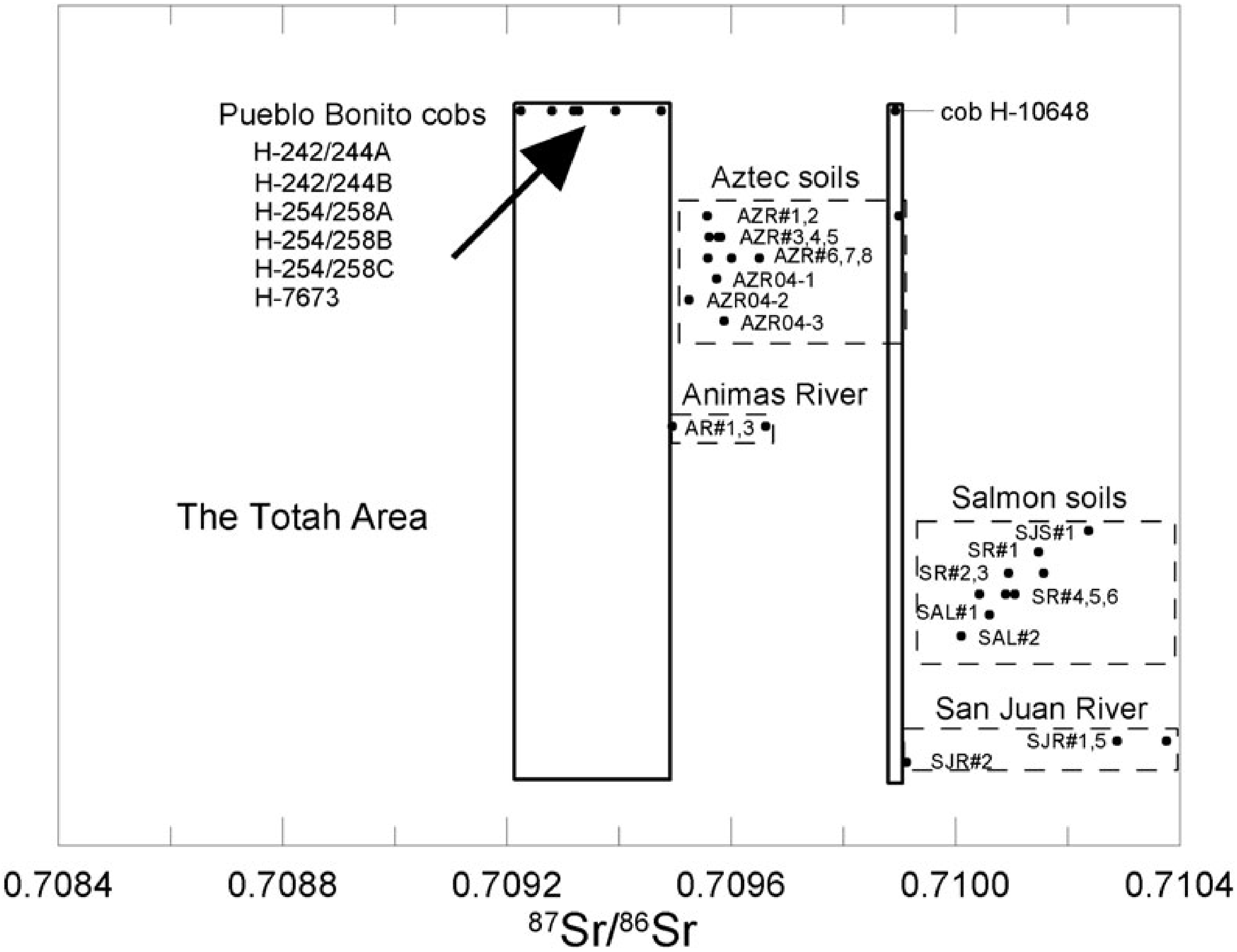

FIGURE 21-7 $^{87}Sr/^{86}Sr$ ratios of Totah area Aztec Ruin and Salmon Ruin area soils and waters compared with $^{87}Sr/^{86}Sr$ ratios of Pueblo Bonito archeological corn cobs. The two rectangles enclose the $^{87}Sr/^{86}Sr$ range of Pueblo Bonito cobs. Cob H-10648 with an intercept date of AD 1010 was found in room 170 constructed between AD 1077 and 1082.

that falls between soil-water ratios of Aztec and Salmon soils (Figure 21-7). However, cob H-10648 has a ratio almost identical to that of AZR#1 a sample from the bank of the Animas River and to that of SJR#2, a San Juan River sample taken 1 kilometer below its confluence with the Animas River. Although we can not pinpoint the exact source of H-10648, it probably came from the Totah (Salmon or Aztec ruins) area (see Figure 21-7).

The $^{87}Sr/^{86}Sr$ data (see Table 21-3) indicate that nine Newcomb soil waters, nine soil waters from Rio Chaco side tributaries between Chaco and the Great Bend, three Chaco valley soil waters, three Chaco side-canyon soil waters, and one Kin Ya'a soil water have isotopic ratios that fall within or just outside the isotopic range of the other six Pueblo Bonito cobs (Figure 21-8). Newcomb waters from Captain Tom and Skunk Springs washes also have $^{87}Sr/^{86}Sr$ ratios that fall within the isotopic range of the six cobs. In general, samples of Chaco Canyon wash water and Chaco Canyon side-tributary water have $^{87}Sr/^{86}Sr$ ratios unlike those of the Bonito cobs (see Figure 21-8).

Some Chaco Canyon waters that have $^{87}Sr/^{86}Sr$ ratios similar to the Pueblo Bonito cob ratios (see Figure 21-8). Fajada Wash samples FW#1 and FW#2 and three masonry-well groundwater samples (HMM#1, HME#1 and HMW#1) have a $^{87}Sr/^{86}Sr$ ratio within the isotopic range of the six cobs. The masonry-well samples probably represent a combination of Chaco and Fajada Wash recharge. Fajada Wash has a small drainage area in comparison with that of Chaco Wash and usually accounts for less than 10% of the total flow in Chaco Wash. Samples from Gallo Wash (GWH#1), one of its tributaries (GWT#2) and a Fajada View (FVS#1) well in the Gallo Wash area also plot in the vicinity of cob H-10648, suggesting the possibility that this cob was grown in the Gallo Wash drainage. However, soluble mineral

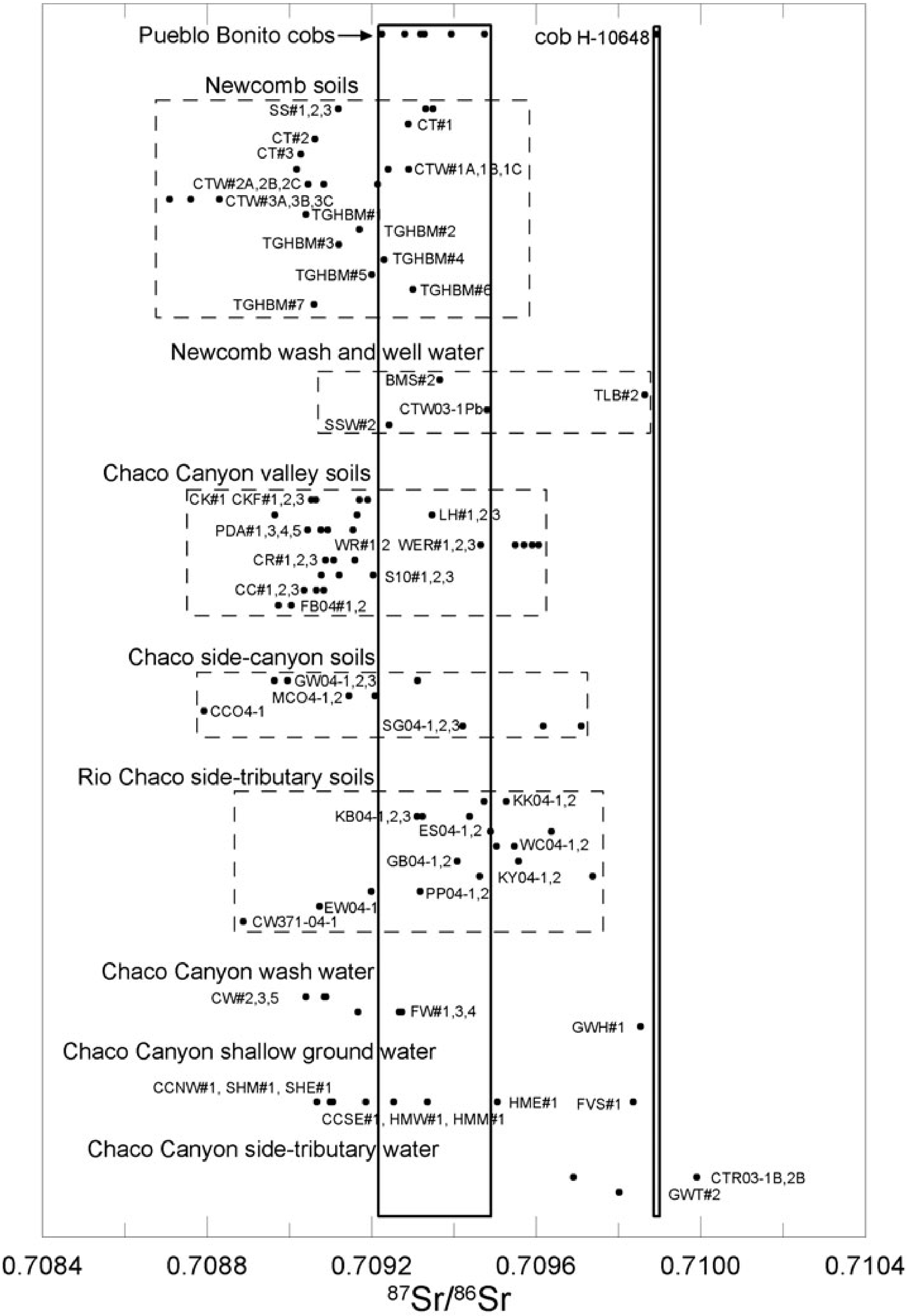

FIGURE 21-8 ^{87}Sr/^{86}Sr ratios of Newcomb soils, Newcomb well and wash water, Chaco Canyon valley soils, Chaco side-canyon soils, Rio Chaco side-tributary soils, Chaco Canyon wash water, Chaco groundwater, and Chaco side-tributary water compared with ^{87}Sr/^{86}Sr ratios of Pueblo Bonito archeological corn cobs. Rectangles enclose the ^{87}Sr/^{86}Sr range of the Pueblo Bonito cobs. Note that the KY04-1, 2 samples came from Kin Ya'a, 48 kilometers southwest of Chaco Canyon, and not from a Rio Chaco side-tributary area.

components in a soil dominate the ^{87}Sr/^{86}Sr ratio of a soil water (see Sampling and Laboratory Methods section), and Fajada Butte (FB04#1, 2) and Gallo Wash (GW04-1, 2, 3) soil solutions have ^{87}Sr/^{86}Sr ratios that do not fall within the Pueblo Bonito cob ^{87}Sr/^{86}Sr field, suggesting that H-10648 probably did not come from either of these two fields (see Figure 21-8).

Trace-Element Ratios

Chaco Canyon valley and Chaco side-canyon soil-water trace-element ratios do not match soil-water ratios associated with the six cobs (Table 21-4). However, five soil waters from Newcomb (SS#1, #3; TGHBM #4, #5, #6) and six soil waters from five side-canyon sites west of Chaco Canyon (GB04-2, WC04-2, ES04-2, KB04-2, 3, KK04-2) have trace-element ratios that match or, in the case of Y/Yb, nearly match the range of calculated cob soil-water ratios (Table 21-4). These data suggest that the Pueblo Bonito cobs did not necessarily come from the Newcomb area; instead, they may have come from one or more sites located between the Great Bend and Chaco Canyon (see Figure 21-3). A Navajo by the name of Tom Chischilly-begay successfully farmed the Kin Bineola valley between 1918 and the late 1920s, using a system of **check dams** and embankments located a few kilometers below the Kin Bineola great house [34]. A 1 : 25,000-scale aerial photo taken in 1980 indicates evidence of a former seven-acre field located downvalley of Kin Klizhin great house. This field system was established by Dan Cly's brother and was later laid claim to and presumably farmed by Richard Wetherill [34]. Thus, at least some of the side-tributary sites downstream from Chaco Canyon have proven agricultural potential.

Soil Conductivities of Newcomb Sites and Sites between Chaco Canyon and the Great Bend

In general, most Newcomb soils are only moderately saline, and, in particular, soils from the area southwest of Two Grey Hills (TGHBM#8, #9, #10) and near-surface soils from modern and former field sites along Captain Tom (CT#2, #3) and Skunk Springs washes (SS#2) have relatively low wilting-point salinities, ranging from 1.8 to 5.2 dS/m (Table 21-1). In terms of modern forage corn, yield losses in these fields would range from 0 to 25%, assuming an irrigation-water conductivity of 0.5 dS/m. In fact, the TGHBM #9 and #10 sites are located at the base of the Chuska Mountains in a broad area of groundwater discharge, possibly having a low salinity.

The five sites along the Rio Chaco, to the west of the canyon, tend to have more saline soils. Kin Bineola (KB04-1, 2, 3) and Escalon (ES04-1, 2) soils have extremely high wilting-point conductivities compared with most other soils that were sampled, ranging from 12.4 to 41.8 dS/m. Great Bend soil conductivities are relatively high (9.1 and 10.8 dS/m), Willow Canyon soil conductivities are somewhat high (7.8 and 8.2 dS/m), and Kin Klizhin soils have variable conductivities (1.8 and 10.6 dS/m) (see Table 21-1). In general, the low salinity values of the Newcomb area indicate that it is the most desirable area for growing maize.

TABLE 21-4 Comparison of Trace-Element Ratios in Newcomb, Chaco Canyon Valley, Chaco Side-Canyon, and Rio Chaco Side-Tributary Synthetic Soil Waters with Calculated Trace-Element Ratios in Soil Waters Associated with Pueblo Bonito Archaeological Cobs. All synthetic soil waters have ^{87}Sr/^{86}Sr ratios within or just outside the ^{87}Sr/^{86}Sr range of six Bonito cobs. Samples having soil-water trace-element ratios that nearly match Bonito cob calculated soil water trace-element ratios are shown in bold. Failure to match is indicated by numbers in italics.

Sample No.	Ba/Sr	Mg/Sr	Y/Yb
Calculated soil-water trace-elements for Pueblo Bonito cobs			
H-242/242A	**0.66**	**16**	No data
H-242/242B	**1.13**	**3.8**	**7**
H-254/258A	**0.59**	**3.0**	**11**
H-254/258B	**0.54**	**9.8**	**7**
H-254/258C	**0.84**	**4.5**	**9**
H-7673	**0.45**	**9.1**	**12**
Newcomb soil-water trace-element ratios			
SS#1	**0.57**	**12**	**15**
SS#3	**0.35**	**12**	**17**
CT#1	**0.11**	**22**	**15**
CTW#1B	**0.19**	**21**	**14**
CTW#1C	**0.11**	**23**	**16**
CTW#2B	*0.43*	*45*	*17*
TGHBM#4	**0.16**	**15**	**16**
TGHBM#5	**0.21**	**10**	**11**
TGHBM#6	**0.10**	**11**	**13**
Chaco Canyon Valley soil-water trace-element ratios			
LH#2	*1.46*	*130*	*24*
WR#2	*3.91*	*14*	*21*
S10#1	*0.67*	*33*	*19*
Chaco side-canyon soil-water trace-element ratios			
GW04-1	*3.14*	*71*	*25*
MC04-2	*1.70*	*104*	*24*
SG04-1	*1.11*	*36*	*19*
Rio Chaco side-tributary soil-water trace-element ratios			
KK04-2	**0.46**	**6.8**	**19**
KB04-1	*0.52*	*7.0*	*49*
KB04-2	**0.36**	**5.8**	**19**
KB04-3	**0.45**	**8.4**	**17**
ES04-2	**0.17**	**16**	**19**
WC04-2	**0.68**	**14**	**19**
GB04-2	**0.40**	**14**	**17**
PP04-1	*1.13*	*21*	*18*
PP04-2	*0.56*	*54*	*22*
Chaco soil-water trace-element ratios from southwestern area			
KY04-1	*0.42*	*71*	*19*

SUMMARY AND CONCLUSIONS

The valley floor and side-canyon areas in the Chaco core total about 4700 acres; however, wall-to-wall cultivation of maize in the Chaco core simply was not feasible. Our calculations indicate that there were only about 370 acres of land that could have been cultivated on a semioptimal basis in the Chaco core area. This value is consistent with early historic Zuni and Hopi pueblo agricultural land-use practices wherein only 6.5 to 7.5% of the available land area was under cultivation at any particular time. Although primitive, our calculations indicate that maize production in the core may have been sufficient to support approximately 250 individuals, not the few to several thousand residents estimated by other scholars [16, 79].

We suggest that Chaco's inhabitants practiced a diverse form of agriculture, using many of the techniques established by their neighbors to the southwest, the Hohokam [20, 30]. Although the implementation of gridded garden systems may have occurred in Chaco, we believe it likely that the Chacoans practiced a "patchy" form of farming in both alluvial fan and floodplain environments. It is much easier to access side-canyon runoff by constructing check dams and contour terraces on the up-canyon surface of an alluvial fan, than it is to harvest runoff at the distal end of a fan after infiltration losses have been maximized. Navajo historical agricultural practices documented by Judd [34] provide examples of the implementation of check dams and embankments in Chaco side canyons and in Kin Bineola and Kin Klizhin valleys.

To determine the source of archaeological corn found in Pueblo Bonito, we expanded our sampling area to include Chaco side-canyon sites, new sites in the Animas River and San Juan floodplains, and side tributary and floodplain sites between Pueblo Pintado and the Great Bend of the Chaco. We also sampled the Satan Wash floodplain near the Kin Ya'a great house, and new field sites within the Newcomb area.

None of the Chaco core area soil waters have ^{87}Sr/^{86}Sr and trace-element ratios consistent with the ^{87}Sr/^{86}Sr and trace-element ranges of the Pueblo Bonito cobs. The ^{87}Sr/^{86}Sr data indicate that at least one Pueblo Bonito cob (H-10648) probably came from the Totah area and that the other six cobs could have come from either the Newcomb area or from sites bordering the Rio Chaco west of Chaco Canyon. The application of trace-element ratios served to narrow the possible field sites to Newcomb, Kin Klizhin, Kin Bineola, Escalon, Willow Canyon, and the Great Bend. Soil conductivity data (see Table 21-1) indicate high soil-water salinities at the Rio Chaco side-tributary sites and low-to-moderate soil-water salinities at most potential Newcomb field sites. This suggests that the Newcomb area would have produced the highest yields of maize.

The ability of our study to answer questions regarding the source(s) of maize consumed by Pre-Hispanic Chacoans is limited by the small number of cobs we have studied, and, at this point, we cannot say whether the Bonito cobs are remnants of maize consumed by elite or common Chacoans or whether the cobs represent ritual offerings or seed corn. However, food would have had to be imported to support those involved in the spike in construction between AD 1030 and 1130 and also to feed those journeying to Chaco for religious–political purposes. We suggest that maize was stored in the great houses for redistribution to other communities at times of environmental stress as a form of reciprocity. Having storage houses of maize and other consumables to offer to different groups during times of drought would have been crucial to the long-term survival of the Chacoan system.

The amount and source of maize imported to Chaco should have varied as a function of both Chaco's population and the occupation and utilization of productive areas outside the canyon. Our data, to this point, lend support to the hypothesis that maize from outlier communities was being transported to a resource-poor Chaco core [45]. Proof of this concept awaits further study of archaeological cobs from both small-house and great-house contexts within the canyon and the linking of those cobs to their agricultural source areas.

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