Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico

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Between A.D. 900 and 1150, more than 200,000 conifer trees were used to build the prehistoric great houses of Chaco Canyon, New Mexico, in what is now a treeless landscape. More than one-fifth of these timbers were spruce (*Picea*) or fir (*Abies*) that were hand-carried from isolated mountaintops 75–100 km away. Because strontium from local dust, water, and underlying bedrock is incorporated by trees, specific logging sites can be identified by comparing $^{87}Sr/^{86}Sr$ ratios in construction beams from different ruins and building periods to ratios in living trees from the surrounding mountains. $^{87}Sr/^{86}Sr$ ratios show that the beams came from both the Chuska and San Mateo (Mount Taylor) mountains, but not from the San Pedro Mountains, which are equally close. Incorporation of logs from two sources in the same room, great house, and year suggest stockpiling and intercommunity collaboration at Chaco Canyon. The use of trees from both the Chuska and San Mateo mountains, but not from the San Pedro Mountains, as early as A.D. 974 suggests that selection of timber sources was driven more by regional socioeconomic ties than by a simple model of resource depletion with distance and time.

GEOLOGY

Near the middle of the desolate San Juan Basin in northwestern New Mexico, Chaco Canyon was the focus of a spectacular florescence of the Anasazi cultural tradition. Between A.D. 900 and 1150, the Chaco Anasazi developed a complex culture characterized by monumental architecture, advanced agricultural and water control systems, and elaborate road, trail, and signaling networks that integrated numerous communities into a regional exchange, communication, and resource procurement system (1). This regional system was in full swing in the 11th century, but collapsed during a regional drought that lasted from A.D. 1130 to 1180 (2).

Twelve great houses—multistoried masonry pueblos of several hundred rooms each—occupy the Chaco Canyon core of the regional system. A single great house incorporated millions of sandstone fragments from surrounding cliffs and thousands of wood timbers used as primary and secondary roof beams and door and window lintels (3). More than 200,000 timbers, the primary beams averaging 5 m in length, 22 cm in diameter, and 275 kg in weight, were used in the great houses. Most of this lumber was acquired in predetermined lengths and diameters and came from trees that had to be felled, processed, and hauled from distant and widely separated mountaintops. Potential source areas include the La Plata-San Juan, San Pedro-Nacimiento, San Mateo (Mount Taylor), and Chuska mountains (Fig. 1). The absence of appreciable gaps in the sequence of cutting dates indicates that tree felling was virtually an annual activity. Continual repairs and piecemeal additions were interrupted by flurries in large-scale construction (4–6).

Tree species available for construction were, in order of increasing distance from the canyon, cottonwood (*Populus acuminata*, *P. angustifolia*) along Chaco Wash, pinyon pine (*Pinus edulis*) and juniper (*Juniperus monosperma*) in nearby scarp woodlands, isolated stands of Douglas fir (*Pseudotsuga menziesii*) in shady alcoves, ponderosa pine (*Pinus ponderosa*) on high mesas and the lower slopes of mountains, and spruce (*Picea engelmannii*, *P. pungens*), fir (*Abies lasiocarpa*, *A. concolor*) and aspen (*Populus tremuloides*) on

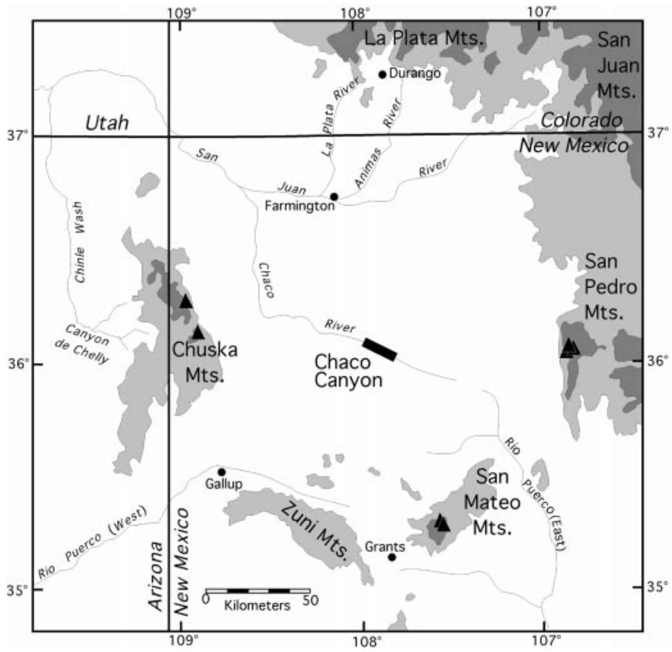

Fig. 1. Map of the San Juan Basin. Dark gray shading indicates spatial extent of modern spruce-fir forests, light gray for continuous stands of ponderosa pine. Triangles are sampling sites for modern trees.

mountaintops more than 75 km away. Empirical evidence (7) and modeling (8) indicate that by A.D. 1000 construction and fuel wood harvesting had eradicated local pinyon-juniper woodlands. These woodlands have yet to recover. After A.D. 1000 the Anasazi relied increasingly on conifers from the surrounding mountains (2, 4). It has been speculated that logging of distant forests for architectural timber had serious ecological consequences, but the emphasis on trees of a limited size range must have produced impacts more comparable to thinning than clear cutting (9). The distance and direction of these montane forests from the canyon is a measure of the energy expended to harvest and move the timbers, of the organization, ability, and determination of the Chaco Anasazi to build monumental architecture, and of economic, political and social relationships across the San Juan Basin.

Background

Mountain ranges in the San Juan Basin are geologically diverse, so geochemical methods could be used to determine the provenance

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of Chacoan timbers. The underlying philosophy is that trees uptake chemical elements from local soils and atmospheric dust and incorporate them into wood. Ideally, the diagnostic chemical parameter should be: (*i*) unaffected by differential elemental uptake, translocation, or isotopic fractionation in different tree species, (*ii*) homogeneous in soils and trees of each potential source area (varies little in time or space), and (*iii*) measurably and statistically different between trees of potential source areas. Provided that these conditions are met, further uncertainties could arise from the geographic scope of the sampling universe. For example, only one match may occur at close range between a potential source area and archeological materials of unknown source, but multiple matches may be possible at increasingly greater distances. In the case of numerous heavy logs, the energetic cost of moving the timber is proportional to both the distance and roughness of the intervening terrain.

Despite recent advances in geochemical provenance methods, there have been few efforts to establish the source of Chacoan timbers. Durand *et al.* (10) used inductively coupled plasma-atomic emission spectrometry to determine the major and trace element chemistry of 62 living ponderosa pine and Douglas fir trees growing on sandstone, basalt, and shale at various sites across the San Juan Basin. They found considerable variations between sapwood and heartwood of ponderosa pine and Douglas fir (see also ref. 11), with the best discriminant of lithology being barium. Durand *et al.* also analyzed 13 beams (species not specified) dated to A.D. 919 from room 320 in Pueblo Bonito and to A.D. 1040–1051 from multiple rooms in Chetro Ketl, the two more prominent great houses at Chaco Canyon. For 11 of the 12 elements analyzed, greater variation was observed in the wood from Pueblo Bonito than from Chetro Ketl. No attempt was made to infer actual beam sources.

Here, we try to improve on the Durand *et al.* (10) study by focusing on spruce and fir and relying on strontium isotopes to determine the source of the Chacoan beams. Although ponderosa pine makes up $\approx$50% of the architectural timber and is thus of primary interest, its distribution spans a wide range of elevations and substrates with many overlapping chemical signatures. On the other hand, spruce and fir comprise only $\approx$20% (40,000 trees) of the architectural wood, but are far more restricted geographically (9). Spruce and fir have not grown near the canyon since the end of the Pleistocene, when Holocene aridity drove these conifers to mountaintops more than 75 km and 600 m up slope from Chaco Canyon (7). Each of these mountaintops has a distinct surficial geology, spanning Precambrian granite to Tertiary sandstones and basalts. We chose $^{87}Sr/^{86}Sr$ ratios as a provenance method because they are specific to both the composition and age of the bedrock and are unaffected by biologically induced mass fractionation or translocation.

The geochemistry of strontium isotopes is relatively well known (12), and $^{87}Sr/^{86}Sr$ ratios have been used routinely as environmental tracers in geology (13, 14), hydrology (15), ecology (16, 17), and archaeology (18). $^{87}Sr/^{86}Sr$ ratios should provide a model system for provenance studies of trees growing on diverse, but unknown, substrates. Strontium, an alkali earth metal, is present in all rocks. The $^{87}Sr/^{86}Sr$ ratio of bedrock is a function of the initial $^{87}Rb/^{86}Sr$ ratio and the age of the rock. Strontium-87 is derived from the radioactive decay of Rubidium-87 ($t_{1/2}$ = 48.8 Ga). Rocks that are older or have higher initial concentrations of ^{87}Rb, such as granites, have higher $^{87}Sr/^{86}Sr$ ratios than younger volcanic rocks derived from the Earth's mantle; sedimentary rocks generally have intermediate values.

In the Sangre de Cristo Mountains, New Mexico, only 200 km east of Chaco Canyon, $^{87}Sr/^{86}Sr$ ratios have been used to study chemical weathering, atmospheric deposition, and solute acquisition in watersheds dominated by Engelmann spruce (*P. engelmannii*) and subalpine fir (*A. lasiocarpa*) (16, 17). Biomass measurements from spruce, fir, and aspen showed little scatter in $^{87}Sr/^{86}Sr$ ratios, suggesting that the bioavailable strontium is isotopically homogenized by atmospheric deposition across a given stand, and that biological cycling is rapid relative to the rates of strontium input into the ecosystem. The $^{87}Sr/^{86}Sr$ ratios in the biomass were the same as in the soil solution. $^{87}Sr/^{86}Sr$ ratios were unaffected by isotopic fractionation during mineral dissolution, absorption by tree roots, and translocation throughout the tree. About 20% of the bioavailable strontium was found to be derived from bedrock and 80% from atmospherically transported dust. Individual trees cycle about one-third of the Sr in the throughfall (bulk precipitation collected under the canopy), whereas the other two-thirds is airborne dust leached from the foliage. Geographic variations in bioavailable strontium could be more a function of local and regional atmospheric dust than of local bedrock. The scale of geographic variability in $^{87}Sr/^{86}Sr$ ratios of atmospheric dust is poorly known, but the few data from the southwestern U.S. seem to indicate significant variations on a scale of 200–300 km, and possibly finer (19).

Materials and Methods

We compared the $^{87}Sr/^{86}Sr$ ratios of bedrock, soil, and stream water, and spruce and fir growing at possible logging sites in the San Juan Basin to those of select timbers from at least three human generations at six of the great houses in Chaco Canyon. Live trees, rocks, stream, and soil waters were sampled from the three most accessible localities for prehistoric logging of spruce fir stands, the San Pedro Mountains $>$85 km to the east, the San Mateo Mountains $>$80 km to the south, and the Chuska Mountains $>$75 km to the west (Fig. 1). We excluded the La Plata-San Juan Mountains because these spruce fir forests were most distant ($>$150 km to the north) and least accessible, requiring transport across deep canyons and flowing rivers (for additional reasons, see ref. 4). Nevertheless, we recognize that extensive spruce fir stands in the La Plata-San Juan Mountains could very well provide an isotopic match for Chacoan beams at twice the distance of the other mountain ranges, and future analyses could resolve this issue.

Cores were extracted from trees of six species growing at various elevations and in a variety of settings separated by $\approx$10 km in the San Pedro Mountains, $\approx$5 km in the San Mateo Mountains, and $\approx$25 km in the Chuska Mountains (Fig. 1). We collected $>$200 tree, rock, and water samples for $^{87}Sr/^{86}Sr$ analyses. Modern tree samples were collected in March, 2000 and May, 2001 by using a 1/4-inch increment borer (lubricants were not used). We sampled Engelmann spruce, subalpine fir (*A. lasiocarpa* var. *lasiocarpa*), and white fir (*A. concolor*) in the San Pedro Mountains, Engelmann spruce, blue spruce (*P. pungens*), subalpine fir and corkbark fir (*A. lasiocarpa* var. *arizonica*) in the San Mateo Mountains, and Engelmann spruce, subalpine fir and Douglas fir in the Chuska Mountains. Rock and water samples were from streams and outcrops adjacent to modern trees.

Dated architectural wood (both cross sections and cores) from six of the 12 Chaco Canyon great houses was obtained from the collections of the Laboratory of Tree-Ring Research (LTRR) at the University of Arizona, Tucson. We analyzed 52 spruce and fir beams from Pueblo Bonito (n = 19), Chetro Ketl (n = 15), Pueblo del Arroyo (n = 12), Wijiji (n = 1), Hungo Pavi (n = 2), and Una Vida (n = 3). The cutting dates of the trees were determined by crossdating; because of possible stockpiling and reuse, the cutting date does not necessarily imply the year that the tree was used in construction. Replicate samples with cutting dates falling between A.D. 974 and 1104 were selected from the same rooms and from different rooms. We tried to span at least three human generations (T = 30 years) at each great house. We chose dated beams labeled "spruce/fir" from the LTRR archive for Chaco Canyon and anatomically segregated spruce (*Picea*) from fir (*Abies*) by using the presence or absence of lateral resin ducts; identification to species or variety may be possible but was not attempted in this study. Fir (n = 37) was more than twice as abundant as spruce (n = 15) in our sample. There was no intentional species bias in sample selection,

Table 1. Strontium isotopic compositions of live tree, rock, and water samples from the three potential source areas for Chaco Canyon timbers

Sample type	Sample ID	$^{87}Sr/^{86}Sr$	$\pm$ (1σ)
Chuska Mountains			
Washington Pass, Tertiary sandstone and basalt, N36°04.793, W108°53.025′, 2575 m			
Abies lasiocarpa	CKAMT-66	0.7097627	0.000015
A. lasiocarpa	CKAMT-67	0.7097534	0.000011
A. lasiocarpa	CKAMT-69	0.7096540	0.000008
Pseudotsuga menziesii	CKAMT-12	0.7096784	0.000010
P. menziesii	CKAMT-14	0.7097635	0.000009
Picea engelmannii	CKAMT-6/1	0.7091645	0.000016
P. engelmannii	CKAMT-7	0.7091195	0.000023
P. engelmannii	CKAMT-8	0.7091226	0.000018
P. engelmannii	CKAMT-9	0.7098975	0.000010
P. engelmannii	CKAMT-11/30	0.7102245	0.000026
P. engelmannii	CKAMT-16/1	0.7097847	0.000048
Sandstone	CKAMT-23	0.7340103	0.000026
Quartzite above CKAMT-23	CKAMT-24	0.7536377	0.000110
Olivine basalt	CKAMT-25	0.7062688	0.000016
Basalt from float near CKBMT-25	CKBMT-26	0.7062845	0.000010
50 ml filtered water: unnamed creek	CKAMT-4	0.7086723	0.000009
Snow from snow bank near lysometer	CKAMT-17	0.7097465	0.000026
50 ml filtered: Crystal Creek	CKCMT-70	0.7092044	0.000008
Porcupine Canyon: Tertiary sandstone, N36°16.20′, W108°59.30′, 2680 m			
A. lasiocarpa	CKJMT-868	0.7094993	0.000024
A. lasiocarpa	CKJMT-869	0.7094309	0.000042
A. lasiocarpa	CKJMT-871	0.7094467	0.000030
A. lasiocarpa	CKJMT-872	0.7095086	0.000010
P. engelmannii	CKJMT-878	0.7096191	0.000018
P. engelmannii	CKJMT-879	0.7096202	0.000064
P. engelmannii	CKJMT-880	0.7095803	0.000032
P. engelmannii	CKJMT-881	0.7095206	0.000030
P. engelmannii	CKJMT-882	0.7094022	0.000031
San Pedro Mountains			
Los Pinos Creek, Precambrian granite, N36°06.138′, W106°54.266′, 2540 m			
A. concolor (granite)	SPAMT-2	0.7170394	0.000022
A. concolor (granite)	SPBMT-1	0.7130257	0.000034
A. concolor (granite)	SPBMT-2	0.7132580	0.000029
A. concolor (granite)	SPBMT-3	0.7142663	0.000010
A. concolor (granite)	SPBMT-4	0.7146339	0.000009
A. concolor (granite)	SPBMT-5	0.7134872	0.000009
San Gregorio Reservoir area, Precambrian granite, N36°01.002, W106°50.870, 2800 m			
A. lasiocarpa (granite)	SPCMT-7	0.7136393	0.000021
A. lasiocarpa (granite)	SPCMT-10	0.7143231	0.000041
Picea pungens (granite)	SPCMT-16	0.7152706	0.000022
P. pungens (granite)	SPCMT-18	0.7154416	0.000038
P. engelmannii (granite)	SPCMT-8	0.7145714	0.000015
P. engelmannii (granite)	SPCMT-9	0.7142189	0.000016
P. engelmannii (granite)	SPCMT-11	0.7130380	0.000021
P. engelmannii (granite)	SPCMT-12	0.7138550	0.000028
50 ml filtered water: Rio de las Vacas	SPCMT-14	0.7152465	0.000011
50 ml filtered water: Clear Creek	SPCMT-15	0.7155773	0.000020
Nacimiento Creek area, Paleozoic limestone, N36°00.419′, W106°52.576, 2565 m			
A. concolor (limestone)	SPDMT-19	0.7129810	0.000020
A. concolor (limestone)	SPDMT-20	0.7133323	0.000010
A. concolor (limestone)	SPDMT-21	0.7141362	0.000011
A. concolor (limestone)	SPDMT-22	0.7132687	0.000013
A. concolor (limestone)	SPDMT-23	0.7136041	0.000011
Clear Creek area, Paleozoic sandstone, N36°01.214′, W106°50.672′, 2782 m			
A. lasiocarpa (sandstone)	SPEMT-28	0.7152808	0.000015
A. lasiocarpa (sandstone)	SPEMT-30	0.7155620	0.000020
A. lasiocarpa (sandstone)	SPEMT-31	0.7132068	0.000018
P. engelmannii (sandstone)	SPEMT-26	0.7152455	0.000021
P. engelmannii (sandstone)	SPEMT-27	0.7143226	0.000017
P. engelmannii (sandstone)	SPEMT-29	0.7153612	0.000011
San Mateo Mountains			
San Mateo Spring, Pliocene basalt and andesite, N35°16.853′, W107°35.983′, 2734 m			
A. lasiocarpa	MTA-34	0.7080143	0.000018
A. lasiocarpa	MTA-37	0.7079377	0.000022
A. lasiocarpa	MTA-38	0.7077849	0.000011
A. lasiocarpa	MTA-41	0.7078883	0.000009
P. pungens	MTA-43	0.7076815	0.000010
P. pungens	MTA-44	0.7079061	0.000045
P. pungens	MTA-45	0.7079552	0.000011
P. pungens	MTA-46	0.7079553	0.000012
P. pungens	MTA-47	0.7079416	0.000009
P. engelmannii	MTA-33	0.7078721	0.000020
P. engelmannii	MTA-35	0.7081503	0.000010
P. engelmannii	MTA-36	0.7077871	0.000009
P. engelmannii	MTA-39	0.7075795	0.000009
P. engelmannii	MTA-40	0.7075784	0.000010
50 ml filtered water: San Mateo spring	MTA-32	0.7075347	0.000010
Mosca Canyon, Pliocene basalt and andesite, N35°15.109′, W107°36.296′, 3090 m			
A. lasiocarpa	MTB-55	0.7081341	0.000016
A. lasiocarpa	MTB-56	0.7076333	0.000020
A. lasiocarpa	MTB-58	0.7085688	0.000028
A. lasiocarpa	MTB-59	0.7083559	0.000060
P. pungens	MTB-60	0.7067913	0.000011
P. pungens	MTB-61	0.7073999	0.000010
P. pungens	MTB-62	0.7071000	0.000000
P. pungens	MTB-63	0.7068774	0.000011
P. pungens	MTB-64	0.7069048	0.000012
P. engelmannii	MTB-50	0.7079198	0.000015
P. engelmannii	MTB-51	0.7075191	0.000037
P. engelmannii	MTB-52	0.7077738	0.000008
P. engelmannii	MTB-53	0.7086757	0.000010
P. engelmannii	MTB-54	0.7086485	0.000014

Abies concolor = white fir; *Abies lasiocarpa* = subalpine fir; *Picea engelmannii* = Engelmann spruce; *Picea pungens* = blue spruce; *Pseudotsuga menziesii* = Douglas fir.

except the availability of an exact cutting date for each sample; in general, spruce is no more difficult to crossdate than fir. Given the small sample size, we can draw no conclusions about species occurrence in the architectural timbers.

Both modern and ancient trees were processed similarly. We sampled the innermost (earliest) rings of sections and cores from both modern and prehistoric tree samples. We shaved and discarded 1–2 mm from the surfaces of all samples to avoid contamination through diagenesis, processing, or storage. After cleaning, 40–70 mg of wood was removed from the cleaned area and placed in a Vicor tube cleaned with 6 M HCl (all acids were doubly distilled) and rinsed with 18 MΩ water. The tubes were vacuum-sealed and baked for 1 h at 500°C. These were cracked and baked for another 5 h at 900°C to volatilize any carbon. The remaining ash was placed in a clean Teflon beaker and dissolved in ≈3 ml of 2.5 M HCl. We rinsed each tube three times with 2.5 M HCl and added sample tube rinse to beaker. Samples were evaporated and reconstituted twice with 3.5 M HNO_3. Strontium from wood, water, and rock digests was separated with Eichrom Sr-specific resin, and $^{87}Sr/^{86}Sr$ ratios were measured on a Micromass Sector 54 thermal-ionization mass spectrometer. The $^{87}Sr/^{86}Sr$ ratio was normalized to 0.1194 and analyses of the NBS-987 standard run on each 20-sample turret yielded a mean ratio of 0.7102453 ± 12 (1σ, n = 16). We used JMP IN 4.0.3 to statistically analyze $^{87}Sr/^{86}Sr$ ratio data. Probabilities were determined by using ANOVA and linear statistics means contrast tests. All data are reported with standard error.

Results

Modern tree $^{87}Sr/^{86}Sr$ ratios are distinct for the San Pedro, San Mateo, and Chuska mountains (Table 1). The San Pedro Mountains represent high, faulted blocks of Precambrian granite and Paleozoic sedimentary rocks. We sampled trees growing on soils underlain by granite, limestone, and sandstone at three sites within a 10-km radius. Creek waters in the San Pedro Mountains have high $^{87}Sr/^{86}Sr$ ratios (0.7152 to 0.7156), reflecting the predominant bedrock, which is granite. Contrary to expectations, there were only slight isotopic differences between trees growing on different substrates in the San Pedro Mountains. The mean $^{87}Sr/^{86}Sr$ ratios of San Pedro Mountain trees do not vary by species (ANOVA; P = 0.18). An average of all sampled trees from the San Pedro Mountains yields a mean of 0.7143 ± 0.0001, similar to values obtained for spruce stands growing in the Precambrian granite of the Sangre de Cristo Mountains (16, 17), 100 km to the east.

The Chuska Mountains are a north-south trending range capped with a thick and flat-lying Tertiary sandstone ($^{87}Sr/^{86}Sr$ = 0.7340 up to 0.7536), occasionally overlain by limited outcrops of Tertiary basalt ($^{87}Sr/^{86}Sr$ = 0.7063). We sampled two main localities, one at Washington (Narbona) Pass and the other 25 km to the north in the headwaters of Porcupine Canyon. At Washington Pass, we sampled trees growing on sandstone immediately downhill from a basalt cap. At this site, snow and creek waters yield $^{87}Sr/^{86}Sr$ ratios (0.7087 to 0.7097) intermediate between the sandstone and basalt. Washington Pass trees yield a mean $^{87}Sr/^{86}Sr$ ratio of 0.7096 ± 0.0001 (Table 1). There is no basalt cap at Porcupine Canyon and the only local bedrock is Tertiary sandstone. At Porcupine Canyon $^{87}Sr/^{86}Sr$ ratios do not vary by species, and the mean from all trees is identical (0.7095 ± 0.0001) to those at Washington Pass, suggesting considerable homogeneity along the western escarpment of the Chuska Mountains. The $^{87}Sr/^{86}Sr$ ratios of Chuska Mountain trees do not vary by species (P = 0.43).

The San Mateo Mountains, commonly referred to as Mount Taylor, represent a succession of lava and ash flows formed from 2 million to 4 million years ago, the oldest of basalt, the younger ones of dacite and andesite. These rocks have intermediate to very low $^{87}Sr/^{86}Sr$ ratios (0.7023 to 0.7142) (20). A sample of San Mateo spring water also yielded a low $^{87}Sr/^{86}Sr$ ratio (0.7075). We sampled two different sites in spruce fir forest (Table 1). The mean $^{87}Sr/^{86}Sr$ ratio of San Mateo Mountain trees differs significantly when grouped by species (P = 0.01). No species difference occurs, however, when we exclude five samples of *P. pungens* taken from a location ≈5 km away from the other samples (P = 0.72). All San Mateo Mountain trees yield a mean $^{87}Sr/^{86}Sr$ ratio of 0.7078 ± 0.0001 (Table 1).

The $^{87}Sr/^{86}Sr$ ratios of trees differ substantially between the three mountain ranges (Fig. 2) and can be used to determine the source of prehistoric spruce and fir timbers in Chaco Canyon. In general, $^{87}Sr/^{86}Sr$ ratios from the great house timbers (Table 2) fall within the range of ratios found in live trees from the San Mateo and Chuska mountains (ANOVA, P = 0.11) (Fig. 3). None of the architectural beams fall within the isotopic range of the San Pedro Mountains (ANOVA, $P < 0.0001$), which are thus eliminated as a possible timber source. Twice as many beams fall in the isotopic range of living trees in the Chuska than in the San Mateo Mountains. The only preference by site is the greater proportion of beams from the Chuska Mountains at Pueblo del Arroyo. There is no obvious temporal preference in the use of timber from one mountain range over the other. Both the Chuskas and San Mateo mountains were being logged simultaneously as early as A.D. 974 and as late as A.D. 1100. There were specific years (cutting dates) when beams from one source area (Chuska Mountains) were incorporated into two great houses (e.g., A.D. 1037: Pueblo Bonito and Pueblo del Arroyo). Likewise, there were specific years when beams from the two sources (Chuska and San Mateo mountains) were incorporated into one great house (e.g., A.D. 1049: Pueblo Bonito). At Pueblo Bonito, one room (room 86) incorporates wood from both the San Mateo and Chuska mountains cut in A.D. 974.

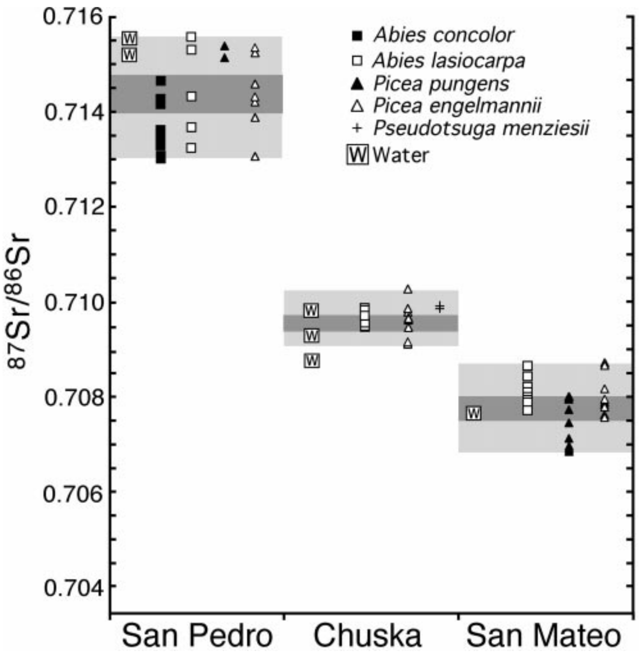

Fig. 2. $^{87}Sr/^{86}Sr$ ratios of live trees and local waters from sampled sites. Dark shading represents the mean $^{87}Sr/^{86}Sr$ ratio (95% confidence interval) of live wood samples analyzed without regard to species. Light shading represents full range of modern wood $^{87}Sr/^{86}Sr$ ratios from each area. Analytical errors are smaller than symbols shown.

Discussion

Previous workers have speculated that early depletion of wood nearby drove selection of sources, either from local to distant stands or conceivably from one mountain to another (2, 4–6, 9, 10). The $^{87}Sr/^{86}Sr$ evidence shows, however, that both the San Mateo and Chuska mountains were providing fir beams in the early construction phases of the great houses such as Pueblo Bonito (A.D. 974). This early reliance on distant sources could have ecological as well as cultural reasons.

Architectural timber at Chaco Canyon included a high proportion (≈50%) of fast-growing and straight saplings to be used as secondary roof beams (4–6, 9). Conifer saplings are most common at higher elevations where climatic conditions favor more frequent regeneration, and wetter conditions reduce natural fire frequencies and associated sapling mortality. Modern forests at lower elevations may not be representative of Precolumbian ones. Heavy grazing by European livestock reduced the fine fuels necessary to sustain episodic surface fires. In Chacoan times, ponderosa pine forests at low to middle elevations would have been open and even-aged, composed of few young trees and many mature ones with thick, protective bark (21–23). Hence,

Table 2. Strontium isotopic compositions of Chacoan architectural wood by great house, room, and age (cutting date in years A.D.)

Sample ID	Age	Genus	Room	$^{87}Sr/^{86}Sr$	± (1σ)	Source
Pueblo del Arroyo						
CNM-2310	1037	*Abies*	8	0.7092265	0.000008	CM
CNM-2500	1038	*Abies*	37	0.7099645	0.000021	CM
CNM-2521	1038	*Abies*	43	0.7097066	0.000021	CM
CNM-479	1039	*Abies*	8	0.7094945	0.000010	CM
JPB-132	1052	*Abies*	46	0.7091587	0.000009	CM
CNM-1398	1100	*Abies*	9A	0.7096449	0.000012	CM
CNM-1033	1104	*Abies*	13	0.7093044	0.000009	CM
CNM-1036	1104	*Abies*	13	0.7098153	0.000012	CM
CNM-1832	1104	*Abies*	8	0.7095573	0.000013	CM
CNM-2539	1063	*Picea*	53	0.7085353	0.000013	SM
CNM-1481	1065	*Picea*	34	0.7083987	0.000024	SM
CNM-1605	1072	*Picea*	62	0.7091699	0.000009	CM
Pueblo Bonito						
PB-436	974	*Abies*	86	0.7085575	0.000009	SM
PB-441	974	*Abies*	86	0.7097658	0.000013	CM
PB-442	977	*Abies*	86	0.7097612	0.000011	CM
PB-585	1033	*Abies*	299	0.7094360	0.000016	CM
CNM-2188	1037	*Abies*	247	0.7093646	0.000009	CM
CNM-3967	1040	*Abies*	14B	0.7089972	0.000026	CM
CNM-3969	1042	*Abies*	14B	0.7095897	0.000019	CM
PB-5666	1048	*Abies*	295	0.7064173	0.000009	?
PB-727	1048	*Abies*	100(?)	0.7097709	0.000024	CM
PB-459	1048	*Abies*	100A	0.7096984	0.000009	CM
PB-445	1049	*Abies*	89	0.7041815	0.000010	?
PB-452	1049	*Abies*	93	0.7085401	0.000011	SM
CNM-970	1049	*Abies*	14B	0.7095651	0.000016	CM
PB-799	1074	*Abies*	171	0.7074873	0.000010	SM
PB-869	1096	*Abies*	Kiva D	0.7089682	0.000014	CM
PB-871	1096	*Abies*		0.7090253	0.000009	CM
PB-567	1048	*Picea*	295	0.7079075	0.000011	SM
GP-2310	1077	*Picea*	105	0.7081833	0.000008	SM
PB-118	1080	*Picea*	3C/III	0.7099523	0.000035	CM
Chetro Ketl						
CK-1294	1032	*Abies*	106	0.7096198	0.000028	CM
CK-1292	1033	*Abies*	106	0.7095441	0.000011	CM
CK-123	1039	*Abies*	44	0.7079472	0.000035	SM
CK-119	1040	*Abies*	44	0.7093084	0.000007	CM
CNM-3797	1042	*Abies*	89	0.7095644	0.000010	CM
CK-117	1047	*Abies*	44	0.7083115	0.000023	SM
CK-60	1099	*Abies*	Kiva G	0.7093382	0.000011	CM
CNM-2664	1042	*Picea*	62	0.7091163	0.000009	CM
CK-136	1049	*Picea*	Kiva G	0.7086831	0.000030	SM
CK-72	1049	*Picea*	Kiva G	0.7086435	0.000010	SM
CK-1215	1056	*Picea*	70	0.7089892	0.000013	CM
CNM-2700	1069	*Picea*	88	0.7079689	0.000012	SM
CK-168	1098	*Picea*	Kiva G	0.7090943	0.000010	CM
CK-309	1100	*Picea*	27	0.7078857	0.000016	SM
CK-319	1100	*Picea*	Kiva N	0.7077295	0.000009	SM
Wijiji						
CNM-1942	ND	*Abies*	81	0.7094644	0.000014	CM
Hungo Pavi						
CNM-1770	ND	*Abies*	3	0.7095589	0.000015	CM
CNM-1771	ND	*Abies*	3	0.7093239	0.000018	CM
Una Vida						
UV-11	ND	*Picea*	N/A	0.7092644	0.000011	CM
UV-16	ND	*Abies*	N/A	0.7072897	0.000010	SM
UV-31	ND	*Abies*	N/A	0.7094081	0.000021	CM

N/A, not available. ND = Not dated. CM = Chuska Mountains, SM = San Mateo Mountains.

ponderosa pine stands within 50 km of Chaco Canyon may not have provided the large numbers of small trees required for construction of the great houses. Certainly, at the height of construction in Chaco Canyon (i.e., 11th century), the crests of the Chuska and San Mateo mountains would have been ideal sites for logging a great variety of conifer species and size classes. The Anasazi may have focused on both mountain ranges because no single forest could satisfy the builders' need for small trees of particular species and dimensions (i.e., cohort).

Timber sources may have been determined by pre-existing sociopolitical ties between Chaco Canyon and outlying communities at the base of the Chuska and San Mateo mountains. The paucity of Chacoan "outliers" or roads east of Chaco Canyon (1) may explain why the San Pedro-Nacimiento mountains were never logged, despite being the same distance from the canyon as the other mountain ranges. Alternatively, pre-existing ties to specific resources may have influenced the placement of certain outlying communities and the destinations of major Chacoan roads, putting

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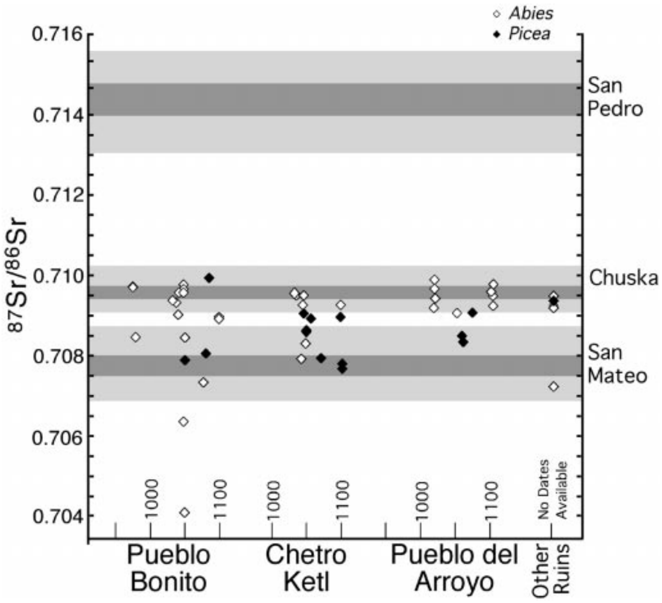

Fig. 3. $^{87}Sr/^{86}Sr$ ratios of great house architectural timbers compared with means and ranges of live trees from the San Pedro, San Mateo, and Chuska mountains. Other great houses are Wijiji, Hungo Pavi, and Una Vida. Means (dark shading) and ranges (light shading) are from live wood shown in Fig. 2.

a permanent stamp on the configuration, direction of growth, and extent of the Chacoan regional system (2). Chacoan outliers within a few hours' walk of the San Mateo or Chuska mountain forests were well positioned to regularly harvest, cure, and stockpile timbers. The synchronous overlap of beams from both sources within and across great houses further suggests that timber procurement and transport was part of a regional system for acquiring a variety of resources including timbers, raw material for chipped stone, pottery, and turquoise. The synchroneity of cutting dates from different mountains could signify a specific demand and supply tied to episodic construction. Coincidence of construction periods at Pueblo Bonito with wet decades suggests that additions to the great houses were driven by food surpluses (4, 5). On the other hand, climate variability tends to synchronize tree recruitment across hydroclimatic areas in the southwestern United States and produces conspicuous cohorts shared among separate mountain ranges (e.g., 1919 for ponderosa pine) (24). The flurries in construction could be tied to maturation of a regional tree cohort into ideal dimensions for architectural use.

Conclusions

Thousands of beams of potentially known cutting date, species, source, and architectural function illuminate the scale and complexity attained by the Chacoan system. The architectural planning and vast distances involved in procuring ≈200,000 beams testify to the system's geographic scope and organization. Rather than one timber source being constrained to a particular construction phase or great house, both sources occur contemporaneously regardless of generation or great house. This reflects the Chacoans' ability to organize large intercommunity labor forces to extract timbers from distant mountains or to motivate the inhabitants of the resource areas to acquire timbers for use in Chaco Canyon.

Finally, $^{87}Sr/^{86}Sr$ ratios in modern trees constitute a surprisingly well-behaved isotopic system. We found little scatter in isotopic ratios among individual trees or different species in the same stand and surprisingly little scatter among stands within a given mountain range. Tree $^{87}Sr/^{86}Sr$ ratios in the San Pedro Mountains vary little despite growing on three different substrates (granite, limestone, and sandstone). This probably reflects the overriding influence of local and regional atmospheric dust sources of strontium, which trees integrate into wood over decades to centuries. We suggest that $^{87}Sr/^{86}Sr$ ratios in atmospheric dust vary on geographic scales perhaps closer to tens than hundreds of kilometers. This subregional-scale variability should be sampled systematically and could abet future use of $^{87}Sr/^{86}Sr$ ratios to trace the provenance of other botanical resources in the Chacoan redistribution system, be they pine logs or corn cobs.

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1. Vivian, R. G. (1990*) The Chacoan Prehistory of the San Juan Basin* (Academic, New York).
2. Dean, J. S. (1992) in *Anasazi Regional Organization in the Chaco System*, ed. Doyel, D. (Maxwell Museum of Anthropological Papers No. 5, Albuquerque, NM), pp. 35–43.
3. Lekson, S. H., Windes, T. C., Stein, J. R. & Judge, W. J. (1988) *Sci. Am.* **259,** 100–109.
4. Windes, T. C. & Ford, D. (1996) *Am. Antiquity* **61,** 295–310.
5. Windes, T. C. & McKenna, P. J. (2001). *Am. Antiquity* **66,** 119–140.
6. Dean, J. S. & Warren, R. (1983) in *The Architecture and Dendrochronology of Chetro Ketl,* ed. Lekson, S. H., Reports of the Chaco Center No. 6 (National Park Service, Albuquerque, NM), pp. 105–240.
7. Betancourt, J. L. & Van Devender, T. R. (1981) *Science* **214,** 656–658.
8. Samuels, M. & Betancourt, J. L. (1982) *Environ. Manag.* **6,** 505–515.
9. Betancourt, J. L., Dean, J. S. & Hull, H. M. (1986) *Am. Antiquity* **51,** 370–375.
10. Durand, S. R., Shelley, P. H., Antweiler, R. C. & Taylor, H. E. (1999) *J. Archaeol. Sci.* **26,** 185–203.
11. Yanosky, T. M. & Vroblesky, D. A. (1995) in *Tree Rings as Indicators of Ecosystem Health*, ed. Lewis, T. E. (CRC, Boca Raton, FL), pp. 177–205.
12. Faure, G. & Powell, J. L. (1972) *Strontium Isotope Geology* (Springer, New York).
13. Quade, J., Roe, L., DeCelles, P. G. & Ojha, T. (1997) *Science* **276,** 1828–1831.
14. English, N. B., Quade, J., DeCelles, P. G. & Garzione, C. N. (2000) *Geochim. Cosmochim. Acta* **64,** 2549–3109.
15. Bullen, T. D., Krabbenhoft, D. P. & Kendall, C. (1996) *Geochim. Cosmochim. Acta* **60,** 1807–1821.
16. Graustein, W. C. (1989) in *Stable Isotopes in Ecological Research*, eds. Rundel, P. W., Ehleringer, J. & Nagy, K. A. (Springer, New York), pp. 491–511.
17. Graustein, W. C. & Armstrong, R. L. (1983) *Science* **219,** 289–292.
18. Price, T. D, Manzanilla, L. & Middleton, W. D. (2000) *J. Archaeol. Sci.* **27,** 903–913.
19. Naiman, Z. E., Patchett, J. & Quade, J. (2000) *Geochim. Cosmochim. Acta* **64,** 3099–3109.
20. Crumpler, L. S. (1982) in *Albuquerque Country II* 33rd *Annual Field Conference*, eds. Grambling, J. A. & Wells, S. G. (New Mexico Geological Society, Albuquerque), pp. 291–298.
21. Savage, M. & Swetnam, T. W. (1990) *Ecology* **71,** 2374–2378.
22. Swetnam, T. W., Allen, C. G. & Betancourt, J. L. (1999) *Ecol. Appl.* **9,** 1189–1206.
23. Grissino-Mayer, H. D. & Swetnam, T. W. (2000) *Holocene* **10,** 207–220.
24. Swetnam, T. W. & Betancourt, J. L. (1998) *J. Climate* **11,** 3128–3147.