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The Colorado Plateaus: Cultural Dynamics and Paleoenvironment

Prehistoric cultural changes on the Colorado Plateaus were contemporaneous with environmental changes.

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Because preindustrial societies interact directly with their environments, the reconstruction of past environmental regimes may help archeologists explain certain types of cultural change. In turn, archeological evidence for cultural changes, such as major shifts in a society's subsistence base, that might be related to environmental fluctuations allow paleoenvironmentalists to focus their attention on critical temporal periods.

Summary. Convergent archeological, geological, palynological, dendrochronological, and radiometric data provide a paleoenvironmental record for the American Southwest at a level of detail and time resolution not previously achieved. Many prehistoric cultural and demographic changes on the Colorado Plateaus coincided with environmental fluctuations defined by precisely dated geoclimatic and bioclimatic indicators. These coincidences support the interpretation that socioeconomic changes and population displacements were commonly triggered by environmental stress.

The relationships between human behavior and environment are complex. While environmental changes of certain magnitudes require adaptive adjustments in subsistence behavior, the nature of the response is determined in large measure by sociocultural rather than by environmental variables. Thus an understanding of the interactions among cultural and natural factors demands detailed knowledge of the affected society's economy, population dynamics, and relationships with other human groups, and of the exploitative potential of the environment. In addition, human behavior can cause as well as respond to environmental changes and caution must be exercised to ensure that such changes are not ascribed to natural causes. Furthermore, culture change can be caused by many factors other than environmental change, and correlations between behavioral and environmental variations do not necessarily imply causality. In spite of these problems, the careful study of prehistoric cultural systems and environmental conditions revealed by archeological, palynological, dendrochronological, and geological studies can provide better understanding of environment-culture interactions.

The American Southwest, and especially the Colorado Plateaus, provides one of the best testing grounds for cooperative research among archeologists and paleoenvironmentalists (*1*, *2*). The archeological and geological records, radiocarbon and tree-ring dates, and fossil pollen sequences available for this region facilitate multidisciplinary research to enhance understanding of prehistoric cultural ecology. Our primary purpose in this article is to synthesize old and new archeological and paleoenvironmental data that indicate a substantial degree of synchroneity in natural and cultural processes on the Colorado Plateaus (*3*).

Cultural Dynamics

Several hypotheses have been advanced to explain rapid changes in population sizes and distributions and cultural changes on the Colorado Plateaus. These hypotheses invoke triggering mechanisms such as environmental change (*4*), inter- and intrasocietal conflict (*5*), and epidemic diseases (*6*). Although some would argue the point (*7*, *8*), there is substantial evidence that prehistoric culture changes in the Southwest were related to environmental changes (*2*, *9*–*11*). These postulated causal relationships are probably not as direct as previously supposed, and many intervening variables critical to understanding cultural processes remain to be investigated (*12*).

The archeology of the Colorado Plateaus has been studied for almost a century. The events, if not the processes responsible for them, are well documented. Most of the prehistoric cultures of this region are assigned to the Anasazi tradition (Fig. 1), which is subdivided into earlier Basketmaker and later Pueblo components (*13*). Archeologists recognize three major geographically bounded variants (subtraditions) of the general Anasazi tradition—Kayenta, Mesa Verde, and Chaco—and at least two mi-

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nor subtraditions—Virgin and Winslow (Fig. 1). At their maximum dispersion, Kayenta peoples occupied an area of more than 10,000 square miles bounded by the Colorado River on the west, Chinle Wash on the east, the Henry Mountains on the north, and the Little Colorado River valley on the south. Mesa Verde population was concentrated in the canyon and mesa country of southwestern Colorado. Chacoan peoples occupied a broad area south of Mesa Verde extending from the San Juan River south to Zuni, with the heaviest population concentration in Chaco Canyon itself. The Virgin subtradition, a peripheral Kayenta manifestation, was located in the part of Arizona and Utah lying northwest of the Colorado River. People of the Winslow subtradition occupied the Hopi Buttes area in the arid Little Colorado region south of Black Mesa.

Although specific differences characterize each subtradition, the cultural configuration was generally similar for all. The Anasazi developed a balanced subsistence economy based on horticulture, with maize, squashes, and beans the major crops. Wild plant foods and large and small game supplemented the diet. Early in their history the Anasazi lived in semisubterranean pit houses, but after about A.D. 900 to 1000 they constructed surface masonry buildings whose development culminated in the spectacular cliff dwellings of the Mesa Verde and the huge, multistoried towns of Chaco Canyon. Subterranean religious structures, kivas and great kivas, were in common use from around A.D. 600. Anasazi artifacts are varied and numerous, but the most diagnostic for delineating spatial and temporal affinities are ceramics. Black-on-white, black-on-red, polychrome, and unpainted wares were produced in abundance.

Five major population developments are notable in general Anasazi culture history: (i) the emergence of the three principal subtraditions (Kayenta, Mesa Verde, Chaco) before A.D. 1, (ii) population increase and geographical expansion after A.D. 550, (iii) occupation of the upland areas of the western Anasazi concurrent with decreasing populations in the northeastern part of the study area between A.D. 900 and 1000, (iv) general abandonment of upland areas and concentration of populations along lowland watercourses after A.D. 1150, and (v) abandonment of the San Juan River drainage basin around A.D. 1300. The following brief summary of Anasazi history, which is based on the extensive Southwestern archeological literature, indicates the magnitude of these events in the major geographical subunits of the Anasazi cultural tradition (Figs. 1 and 2).

Basketmaker II Anasazi populations were present in the Kayenta (*14*), Cedar Mesa (*15*), and Canyon de Chelly (*16*) areas and in the Animas (*17*), Los Pinos (*18*), and Rio Puerco of the west (*19, 20*) river valleys by A.D. 1. These populations, which seem to represent eastern (Animas–Los Pinos), western (Kayenta–Cedar Mesa–Canyon de Chelly), and possibly southern (Rio Puerco) variants of the Basketmaker II horticulture, gathering, and hunting lifeway, provided the basis for subsequent population dispersals and cultural developments on the Plateaus.

Major population expansion and cultural changes marked the transition to the Basketmaker III period, which began around A.D. 550 to 600. Basketmaker III peoples then spread throughout the Plateaus, with especially dense populations in the Kayenta (*14*), Chaco (*21*), Rio Puerco of the west (*20*), and Mesa Verde (*22*) areas. They generally lived in fairly large farming villages, comprised of dispersed pit houses and small surface storage units, located near the floodplains of stream courses. Manufacture and use of ceramics, bows and arrows, and ground stone axes became common during this period.

During the interval A.D. 800 to 1150 the growing Anasazi populations expanded into nearly every habitable part of the Plateaus. The Chaco (*23*), Mesa Verde (*22, 24*), and Kayenta areas were densely inhabited. The Little Colorado and Hopi Buttes areas were occupied by people bearing the architectural and ceramic styles of the Winslow subtradition (*25*). During this period a major population expansion marked the emergence of the Virgin subtradition, an attenuated western manifestation of the Kayenta Anasazi (*26*). Around A.D. 800 expanding Kayenta populations came into contact with non-Anasazi Cohonina people around the South Rim of the Grand Canyon. By A.D. 1100 the gorge and both rims of the Grand Canyon were inhabited primarily by Kayenta peoples, indicating successful adaptations to diverse habitats (*27*). Another non-Anasazi group, the Sinagua of the Flagstaff region, intensified their contacts with the Kayenta after A.D. 1050 (*28*). An important aspect of the general Anasazi dispersal after A.D. 1000 was the occupation of several upland areas, such as the Rainbow (*29*) and Defiance (*16*) Plateaus and northern Black Mesa (*30–32*), that had previously been rather sparsely inhabited.

Cultural diversification increased during the A.D. 900 to 1150 interval as groups of people adapted to the wide variety of habitats that were occupied. In the western part of the study area (Kayenta and Virgin areas) settlement in pit house villages along the floodplains con-

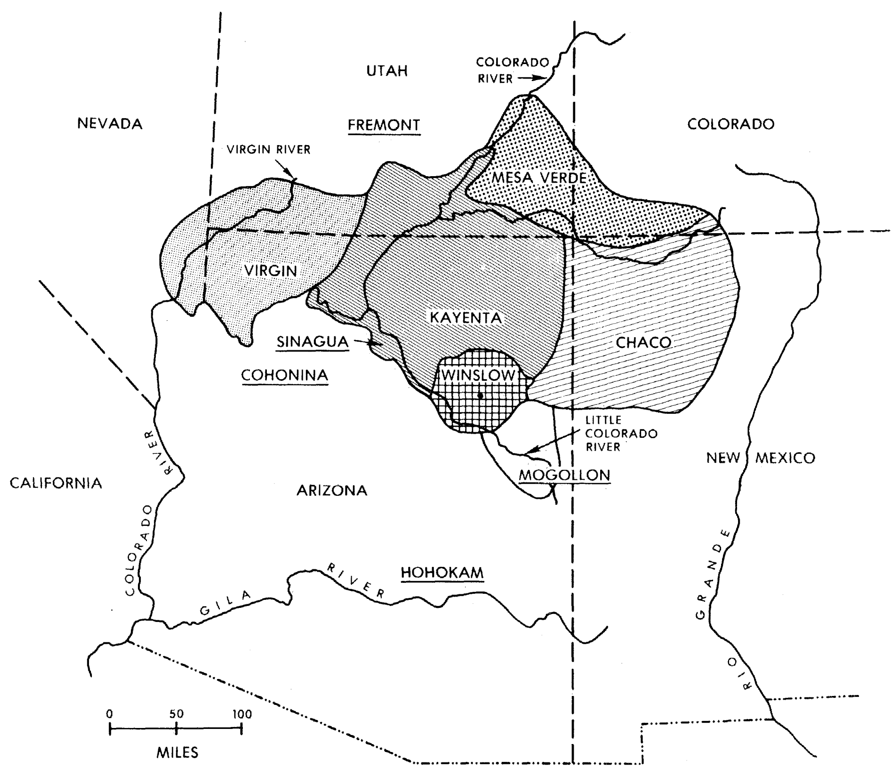

Fig. 1. Areal extent of the major Anasazi subtraditions; neighboring traditions are indicated by underlining.

tinued until A.D. 1000. After that date a pattern of dispersed small "homesteads" consisting of pit houses, masonry surface rooms, and kivas developed concurrently with the rapid population expansion. The Winslow subtradition settlement pattern was one of small dispersed communities situated to take advantage of scarce local water resources and arable land. The use of surface masonry and jacal structures, commonly in conjunction with pit houses, developed earlier in the eastern than in the western part of the Plateaus, and by A.D. 900 much of the Mesa Verde and Chaco populations resided in single-story pueblos comprised on contiguous habitation and storage chambers with detached subsurface kivas in front of the room blocks.

The construction in A.D. 919 of a large, multistoried masonry village at Pueblo Bonito (*33*) signaled the beginning of the precocious Chaco development that culminated two centuries later in the most complex and spectacular manifestation of Anasazi culture. Between A.D. 1050 and 1120 major construction took place at several large Chaco settlements. These towns consisted of multistoried blocks of contiguous rooms and kivas enclosing plazas that contained one or two great kivas. Extensive water control systems, including canals to carry runoff from the upland flanks of the canyon, were built for crop irrigation (*11, 34*). Broad roads connected widely separated areas (*23*), and signaling stations occupied eminences along the canyon walls (*35*). After A.D. 1050 Mesa Verdeans moved into Chaco Canyon and resided in separate villages such as Kin Kletso (*36*).

After A.D. 1150 many areas were abandoned and populations were concentrated along fairly large stream courses in a relatively few lowland areas. The Virgin and Grand Canyon areas were vacated by both the Kayenta Anasazi and Cohonina. The higher parts of Black Mesa and areas north of the San Juan River were also abandoned by the Anasazi. The center of population distribution on Mesa Verde shifted toward the lower end of the mesa (*24*), and by A.D. 1200 many large cliff dwellings were under construction in rock shelters at the bases of the cliffs. At the same time Mesa Verde occupation continued in the lower area west of Mesa Verde proper (*37*). The Chaco phenomenon apparently ended shortly after A.D. 1150 (*38*), although minor reoccupation of the Canyon by San Juan and Mesa Verde immigrants occurred after this date. By A.D. 1300 the latter had moved to "fortified sites" on Chacra Mesa, where they remained until not later than A.D. 1400 (*34*).

Settlement patterns during the period of population displacement from A.D. 1150 to 1300 varied considerably. Kayenta sites were large open pueblos built around enclosed plazas, open pueblos with room blocks oriented to small courtyards, cliff dwellings of the courtyard type, and small pit house villages (*14, 39*). Water control devices, for both irrigation and domestic use, became more widespread throughout the Anasazi domain after A.D. 1050.

By A.D. 1300 the San Juan drainage basin, the ancient homeland of the Anasazi, was largely vacated. The Kayenta peoples moved south from the Tsegi Canyon–Marsh Pass–Navajo Mountain region to the large towns near the Hopi Mesas, where relatively stable land-water relationships facilitated horticulture. The Mesa Verde peoples abandoned the Four Corners area, probably moving to the Rio Grande Valley of New Mexico, where large-scale irrigation could be practiced. After A.D. 1300 Pueblo populations were concentrated in the Hopi Mesas–Little Colorado area, on the Zuni River, along the Rio Grande, and in the mountains of central Arizona (Fig. 2). With the exception of the Arizona mountains, these areas still support Pueblo Indian populations.

The Paleoclimatic Record

Our geological, archeological, pollen, and tree-ring data were integrated into a comprehensive regional reconstruction of both long- and short-term paleoenvironmental trends. These types of records differ in amplitude and frequency characteristics and in time resolution, with dating precision ranging from 1 year (tree rings) to tens or hundreds of years (archeology, geology, and pollen). A significant part of these frequency differences may be attributed to the varying response sensitivities of biological and geological processes to environmental change. By combining the higher and lower frequency records, it is theoretically possible to reconstruct a more detailed picture of past climatic variability. However, frequency differences in some of these records can also result from nonenvironmental factors such as dating imprecision and differences in sampling intervals. The latter is a highly critical variable, for different sampling intervals in the same paleoenvironmental record can produce time series with different numbers of events and different phase trends. These limiting operational factors must be controlled in order to discover relationships among different paleoenvironmental records and reconstruct past climatic changes.

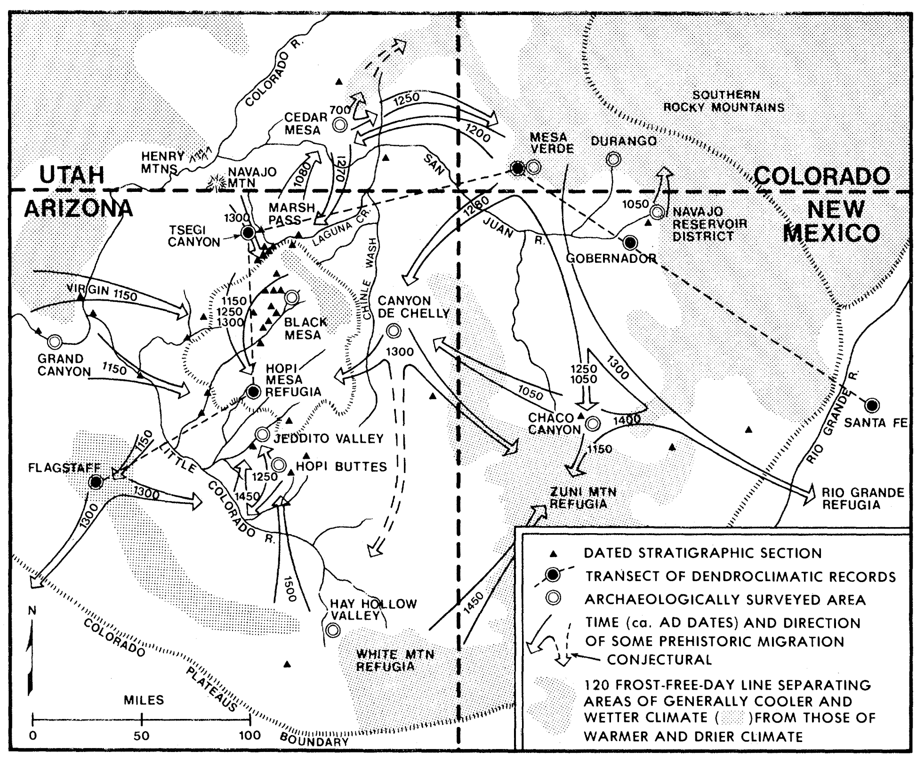

Fig. 2. Map of the southern part of the Colorado Plateaus showing locations of data stratigraphic sections, dendroclimatic stations, archeologically surveyed areas, dates and routes (arrows) of some prehistoric population movements, and present distribution of areas with cooler and wetter weather.

To obtain geological and pollen data that are comparable in high-frequency resolution and dating precision to the regional dendroclimatic and archeological records, special efforts were directed toward increasingly refined subdivision and more precise dating of the alluvial records. Care was exercised to ensure that organic materials collected for radiocarbon dating were uncontaminated. Whenever possible, only the outermost or innermost parts of buried trees or logs were sampled for radiocarbon dating because wood from these sources can represent hundreds of years of growth (*40*). Buried archeological materials in many stratigraphic sections permit precise dating (based on tree ring-controlled ceramic chronologies) of enclosing sediments and provide independent checks on the accuracy of associated ^{14}C dates. The most precise dating controls are provided by dendrochronologically dated wood samples from tightly controlled stratigraphic contexts in the many buried forest localities (Fig. 3) in the region (*41*). The ability to date tree germination and death within 25 years (*42*) allows dating and correlation of alluvial deposits and associated pollen at an unprecedented high level of resolution.

The paleoenvironmental and archeological data plotted in Figs. 4 and 5 are correlated on the vertical scale (time) on the basis of temporal equivalence established by local stratigraphic sequences and by independent dates (*43*, p. 779). Equivalence of data points in the Black Mesa sequences (Fig. 4, columns 2A, 2B, 2C, 3A, and 3B) is ensured by the use of stratigraphic data and paired sediment grain size and pollen samples from single loci in the alluvial deposits. Radiocarbon, archeological, and tree-ring dates from materials collected from stratigraphic contexts provide the time frame for the Black Mesa plots. Similarly, the precision of the tree-ring and archeological dating techniques permits the local stratigraphic, hydrologic, pollen, and tree-ring records from the Plateaus to be correlated on the basis of contemporaneity at a resolution of approximately 25 years or less. Although some nondepositional boundaries are dated solely by the less precise radiocarbon method, the congruence of the ^{14}C dates with their stratigraphic positions indicates that the plotted mean ^{14}C dates (Fig. 4, column 2A) are essentially correct. Therefore, for the purpose of time-frequency analyses (Fig. 4, column 2C), these chronostratigraphically consistent ^{14}C dates are provisionally considered to be accurate at a resolution of approximately 50 years.

Fig. 3. Dead juniper tree buried in alluvium along Dead Juniper Wash.

The paleoenvironmental and archeological data in Figs. 4 and 5 are not equated on the basis of configurational similarities in the plots. Stratigraphic relationships establish the order of data points at each locality and independent dates provide the time frame for plotting the points. The temporal resolution achieved through the use of this procedure more than offsets the drawbacks associated with the irregular spacing of data points in time.

Regional dendroclimatology. The dendroclimatic data used in this study consist of six of a total of 26 long tree-ring chronologies constructed as part of the Southwest Paleoclimate Project of the Laboratory of Tree-Ring Research. Each chronology includes ring records from living trees and archeological materials, and each was constructed to retain a high proportion of climate-related variance and to represent a restricted geographical area (*44, 45*). The six chronologies were selected to represent a staggered east-west transect across the study area (Fig. 2). The chronologies are: Flagstaff, representing the plateaus around the San Francisco Peaks; Tsegi Canyon, in the mesa and canyon country east of the confluence of the San Juan and Colorado Rivers; Hopi Mesas, on the northern margin of the Little Colorado River valley south of Black Mesa; Mesa Verde, at the northern edge of the Colorado Plateaus; Gobernador, on the middle San Juan River; and Sante Fe, in the middle Rio Grande Valley. Each of the chronologies constitutes a continuous local dendroclimatic record from at least as early as A.D. 880 to 1970, and together they are considered to characterize general dendroclimatic variability across the Colorado Plateaus physiographic province.

The methods by which the tree-ring data used in this study were derived are described in detail elsewhere (*44–46*) and are only summarized here. Individual ring-width measurements are converted to standardized indices by a procedure that emphasizes the climate-related variance in the ring series by removing nonclimatic factors such as growth trend and mean ring width. The annual indices of individual wood samples from a particular area are averaged to produce a composite ring-index chronology representing that area.

Because each index chronology has a unique variance, chronologies cannot be directly compared with one another. Interchronology comparability is achieved by converting the annual indices to stan-

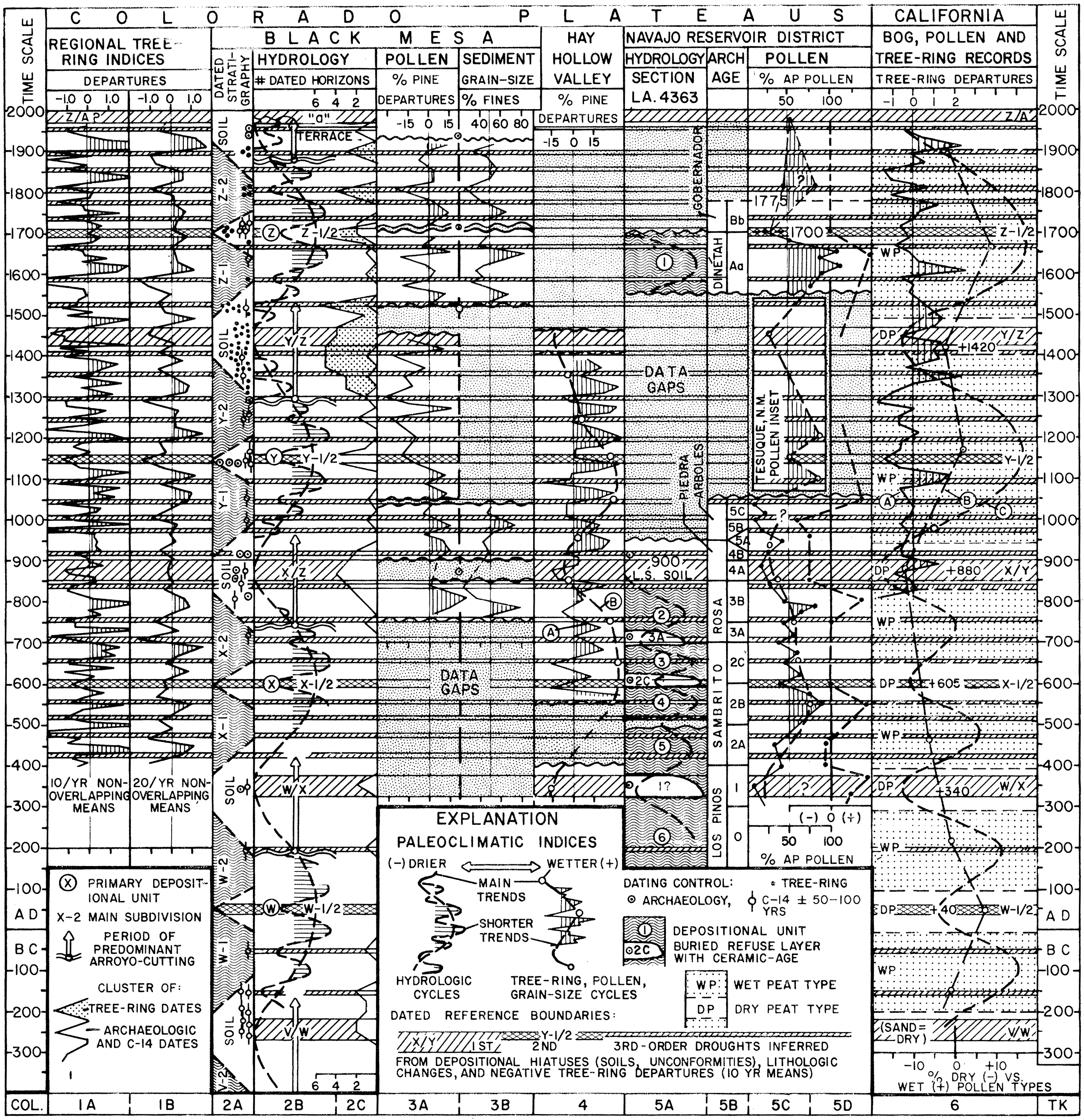

Fig. 4. Paleoenvironmental sequences for the Colorado Plateaus and southern California. (Column 1A) Regional average tree growth departures plotted on centers of absolutely dated 10-year intervals [sources: J.S.D. and (*44, 45*)]. (Column 1B) Regional average tree growth departures plotted on centers of absolutely dated 20-year intervals [J.S.D. and (*44, 45*)]. (Column 2A) Black Mesa area depositional units (hatched) and erosional and soil-forming intervals. Dating control: (⊙) archeological, (○) ^{14}C, and (●) tree ring [T.N.V.K., this article, and (*41*)]. (Column 2B) Long-term Black Mesa area hydrologic cycle with short-term trends superposed in periods for which data are available [T.N.V.K., this article, and (*43*)]. (Column 2C) Number of dated stratigraphic (nondepositional) horizons in Black Mesa area (T.N.V.K. and this article). (Column 3A) Black Mesa area departures of pine proportions in pine to juniper pollen ratios from modern mean of study area. Departures greater than ± 15 are significant at the .05 level (R.H.H. and this article). (Column 3B) Black Mesa sediment grain size data from the samples that produced the pollen data in column 3A (R.H.H., T.N.V.K., this article). Pollen and sediment grain size records after A.D. 1450 are from section 21 in Dead Juniper Wash; records before A.D. 1450 are from section 1 in Coal Mine Wash. Dating control on data in columns 3A and 3B is by associated archeological, ^{14}C, or tree-ring materials. (Column 4, curve A) Hay Hollow Valley departures of pine proportions in pine to juniper pollen ratios from modern mean of study area. Each data point represents samples from different room floors dated by associated tree-ring dates, tree-ring dated ceramics, or ^{14}C dates [(*52, 55, 56, 63*), R.H.H., this article]. (Column 4, curve B) Hay Hollow Valley departures of small pine proportions in small to large pine pollen ratios from modern mean of study area smoothed to 100-year interval [(*55, 56, 63*), R.H.H., this article]. Departures greater than ± 15 are significant at $P = .05$. (Column 5A) Navajo Reservoir area depositional units and erosional intervals; archeologically dated horizons shown in white (*53, 94*). (Column 5B) Navajo Reservoir area archeological phase sequence (*53, 94*). (Column 5C) Navajo Reservoir area pollen curve with data from Tesuque, New Mexico, used by Schoenwetter to fill gap in local Navajo Reservoir sequence [(*53*), T.N.V.K.]. (Column 5D) Generalized pollen curve for Navajo Reservoir area (*79*, figure 2). (Column 6) Sequence of peat deposits from Ralston Ridge Bog, California (*89*). (Column 6, curve A) The 20-year tree growth departure values for lower forest border bristlecone pines in White Mountains, California (*90*, figure 6). (Column 6, curve B) Pollen sequence from Ralston Ridge Bog (*89*). (Column 6, curve C) Relative hydrologic fluctuations inferred from wet-dry peat sequence at Ralston Ridge Bog [T.N.V.K. (*89*)].

dard normal variates (Z scores) (*44*, p. 7; *47*), a procedure that produces a time series of annual values with a mean of 0 and a standard deviation of 1. This operation reduces the amplitude variability in all chronologies to a uniform scale suitable for comparison and preserves the frequency resolution of one value per calendar year. Each local time series of annual Z scores used was smoothed by calculating departure values for precisely dated 10-year intervals, using a procedure developed by Fritts (*47*). This operation produces values that specify positive and negative departures from the chronology mean in terms of standard deviation units. Frequency resolution is in absolutely dated units of 10 years duration. The decade departures of the six chronologies were averaged, a procedure that emphasizes variations common to the chronologies and suppresses interchronology differences. This step was taken to provide an estimate of *regional* dendroclimatic variability during successive decades. Because statistical and physiological studies show that southwestern tree growth is highly correlated with certain climatic variables, principally annual precipitation (*48, 49*), this time series is considered to be an accurate representation of past fluctuations in average annual rainfall across the region. Positive departures indicate greater than average rainfall, and negative departures reflect below average precipitation. This dendroclimatic record is one of high-frequency fluctuations. Periodicities of greater than about 100 years are not reflected in these data because of sampling limitations and because the mathematical transformation of the ring widths and indices tends to suppress low-frequency variability.

The results of these analyses are pre-

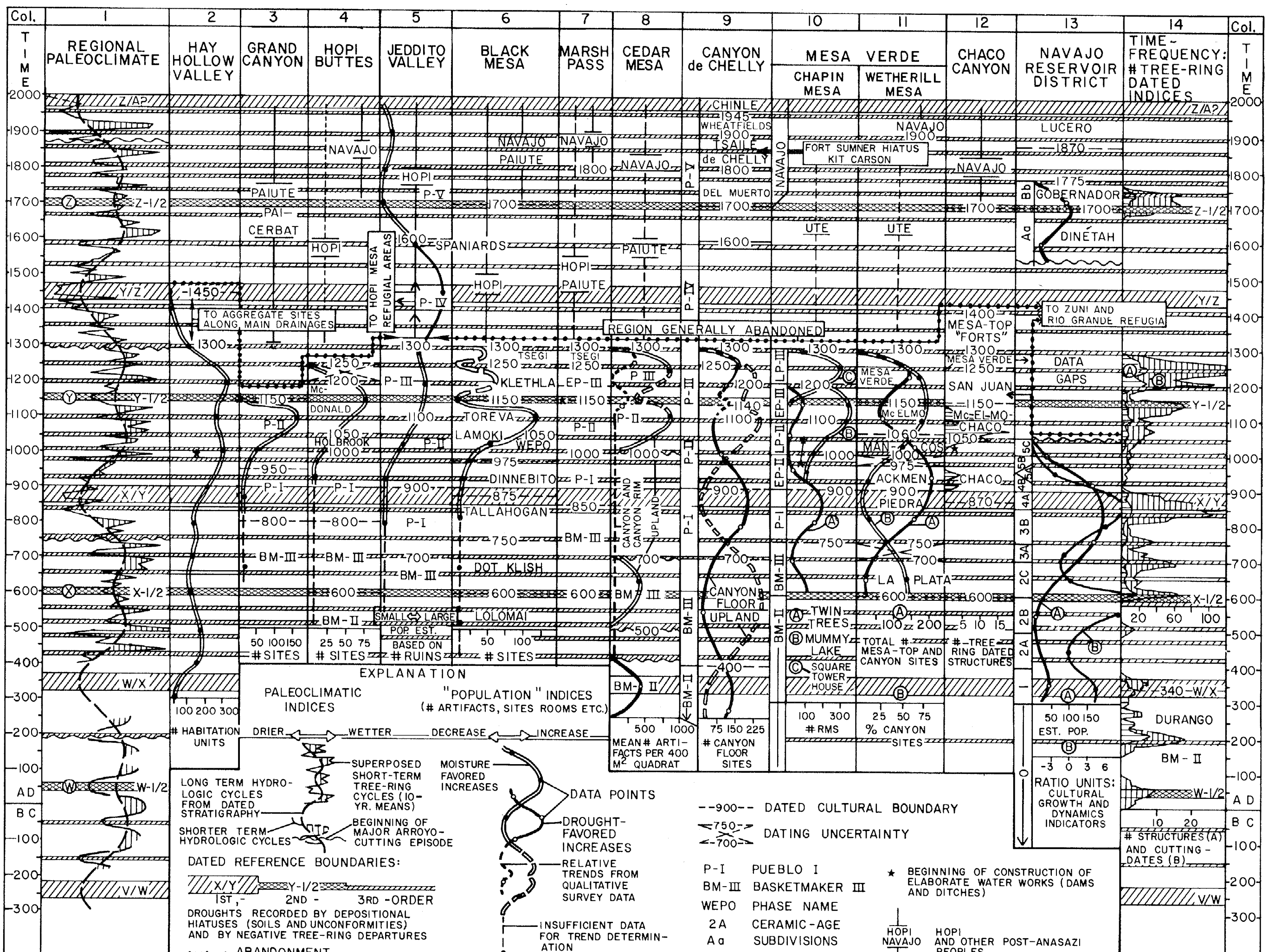

Fig. 5. Paleoenvironmental and archeological relationships on the Colorado Plateaus. (Column 1) Ten-year regional tree growth departures and short-term hydrologic fluctuations (before A.D. 400) superposed on long-term regional hydrologic curve based on dated stratigraphic information. Relative hydrologic trends are redrawn to show the ~ 275-year cycle indicated by the data in Fig. 4. The redrawn hydrologic curve is taken as the zero baseline for plotting the superposed positive and negative tree-growth departure values (sources: T.N.V.K., J.S.D., this article). (Column 2) Inferred population curve for Hay Hollow Valley smoothed to 100-year intervals (*97*). (Column 3) Inferred population curve for Grand Canyon [(*27*), R.C.E., this article]. (Column 4) Inferred population curve for Hopi Buttes area [(*25*), G.J.G., this article]. (Column 5) Inferred population curve for Jeddito Valley (*98*). (Column 6) Phase sequence and inferred population curve for northern Black Mesa (*30, 31, 43*). (Column 7) Phase sequence for Marsh Pass area (J.S.D.). (Column 8) Inferred population curve for Cedar Mesa area (*15*). (Column 9) Inferred population curves for uplands (broken line) and canyon bottoms (solid line) at Canyon de Chelly (*16*). (Column 10) Inferred population curves for Twin Trees (curve A), Mummy Lake (curve B), and Square Tower House (curve C) localities on Chapin Mesa, Mesa Verde (*99*). (Column 11) Phase sequence and inferred population curves for mesa top (curve A) and mesa flank (curve B) localities on Wetherill Mesa, Mesa Verde (*24*). (Column 12) Phase sequence and number of tree-ring cutting dates per decade for Chaco Canyon [(*11, 100*), J.S.D.]. (Column 13) Phase sequence and inferred population curve (curve A) for Navajo Reservoir area (*53, 94*). (Column 13, curve B) Cultural growth and dynamics indicators for the Navajo Reservoir area (*93*). (Column 14) Number of dated structures (A) and number of cutting dates per decade (B) for archeological sites in northwestern New Mexico and southwestern Colorado (J.S.D.).

sented in Fig. 4 and 5. The regional average decade departures are plotted in Fig. 4, column 1A. Twenty-year values, produced by averaging paired decade departures, are plotted in Fig. 4, column 1B. The 20-year interval is employed to make the temporal scale of the tree-ring data conform more closely to the time scales of the other, less temporally sensitive paleoenvironmental indicators. In Fig. 5, column 1, the 10-year departure sequence is superposed on the regional hydrological curve. The great temporal resolution of dendrochronology reveals higher frequency variations than do the other techniques.

Regional palynology and faunal correlates. The distribution of archeological sites on the Colorado Plateaus indicates that the prehistoric inhabitants lived primarily in areas of the present pinyon-juniper woodlands and their ecotones with grasslands and ponderosa pine forests. However, at times the prehistoric peoples expanded farther into areas now characterized by arid grasslands or by mesic pine forests (*50*). The concentration of human groups in the transitional pinyon-juniper vegetation zone was determined in part by climatic, edaphic, and biotic factors that directly affected gathering and dry farming. Population movements and changes in population densities may therefore reflect changes in length of growing season, in seasonal distribution of precipitation, or in soil nutrients that affect maize and other subsistence crops. The climatic and edaphic factors that directly affect horticulture are similar to those that affect species composition, density, growth, and reproduction in the natural plant community. Records of past natural vegetation and faunal changes obtained from sensitive ecotonal sites should yield data that reflect fluctuations in available resources and prehistoric human population changes (*51*).

During the past two decades, studies of pollen in surface sediments have specified the pollen spectra characteristic of the major plant communities presently occurring on or near the Colorado Plateaus. These studies—based on standard and adjusted pollen sums of approximately 200 grains extracted, identified, and counted by standard procedures—have shown that ratios of arboreal pollen (AP) to nonarboreal pollen (NAP), pine to juniper pollen, and large to small pine pollen identify past major plant communities and their associated climates (*52–54*).

Comparison of these modern pollen ratios with pollen spectra from dated lacustrine and archeological sites yields ecologically consistent results (*52, 55*). In many samples from archeological sites, however, NAP components are overrepresented because of human activity. Soil disturbance around activity loci that favored growth of pioneer species, transport of pollen-bearing plant parts into rooms, architectural peculiarities that accentuate differential pollen transport, and human modification of local plant communities by gathering of seeds and wood can produce anomalous AP to NAP ratios (*52, 55–59*). Because of such contamination, simple AP to NAP ratios cannot be used in the reconstruction of past vegetation communities, but adjusted pollen sums or ratios of pine to juniper pollen or of small pine (pinyon) to large pine (ponderosa) pollen can be substituted for the AP to NAP ratio to provide useful indices of community type and of inferred environmental conditions or modifications (*52, 53, 56, 60–64*).

Early studies of alluvial sediments on the Plateaus indicated the presence of ample pollen and its potential utility for detailed reconstructions of past environmental changes. Most pollen studies, however, have been focused on archeological deposits because of the more precise dating of sediments in archeological contexts (*53, 65, 66*). These studies revealed a pattern of fluctuating pollen proportions spanning the last 2000 years (*2, 52, 56, 58, 60, 63*).

The most detailed of these archeological pollen records comes from Hay Hollow Valley (Fig. 4, column 4) and from the Navajo Reservoir area (Fig. 4, column 5C and 5D). Recent analyses of pollen proportions from intensively sampled and tightly dated alluvial sections on Black Mesa provide generally similar patterns of variation in pine to juniper ratios and in sediment grain size (Fig. 4, columns 3A and 3B). In Hay Hollow Valley and on Black Mesa, the observed pollen fluctuations exceed the 95 percent confidence limits of the mean of modern samples from the same areas and are accepted as recording real changes in the vegetational and environmental history of the region. In the Navajo Reservoir area, observed changes in standardized AP proportions in the adjusted pollen sums also exceed the range of values characteristic of the modern pollen rain. The environmental inferences, which can be interpreted in terms of effective moisture changes, are further supported by consistencies with the regional dendroclimatic and hydrologic indices (Fig. 4, columns 1 and 2). Inferred intervals of lower effective moisture (negative pine or lower AP proportions) coincide with tree-ring drought periods and with nondepositional intervals in the alluvial record that have been directly dated by archeological, tree-ring, and ^{14}C materials.

Long-term fluctuations in pollen ratios may represent compositional shifts in the local plant communities. However, the higher-frequency components of the pollen record indicate that, because of the short time intervals involved, factors other than changes in floristic composition must also be important. High-frequency fluctuations in pollen ratios could result from differential production (*60, 67*), transport (*57, 68–70*), or preservation (*71*) of pollen. Pollen preservation in the alluvial sediments is comparable to that in the modern samples, and the percentage of broken pollen grains is approximately the same in the two types of sample. Pollen, particularly that of pine, is commonly more abundant in fine-grained sediments, as noted in other studies (*61, 72*). Quantities of pollen from samples of uniform size vary by as much as a factor of 5 from sample to sample. However, no consistent pattern is apparent between variations in pollen proportions, preservation, or quantities per sample. This suggests that distortion of pollen proportions by either differential pollen destruction or transportation is negligible.

The higher frequency pollen fluctuations thus appear to be best explained by differential pollen production caused by changing temperature and moisture conditions. These changes are similar to but smaller in magnitude than those that determine the vertical stratification of plant communities in the Southwest. The pinyon-juniper woodland, from which most of the pollen samples of this study were obtained, is dominated by two conifer species whose elevational limits and seasons of pollen production differ. The late winter-early spring pollinating junipers require less effective moisture than pinyons and extend beyond the woodland borders downward into the grasslands to form juniper savannas. The late spring-early summer pollinating pinyons require more effective moisture than junipers and extend beyond the woodland borders upward into the higher elevation ponderosa pine forests. Lowered effective moisture during the spring drought typical of the study area could therefore be adequate for juniper pollen production but inadequate for pinyon pollen production, resulting in higher ratios of juniper to pinyon pollen. Increased effective moisture should be reflected by reversed ratios, and the observed close similarity between tree growth and ratios of pinyon to juniper pollen (Fig. 4, columns 1, 3, and 4) supports this ecological interpretation.

Unlike the Black Mesa record, the Hay Hollow Valley pollen sequence contains enough large pine pollen to permit the calculation of small pine to large pine ratios. Here, as in other sensitive sites near the lower limits of the pinyon-juniper forest, these ratios indicate the preponderance of small pine pollen during intervals of locally favorable growth conditions. Alternate intervals are characterized by lower proportions of small pine pollen and corresponding higher proportions of large pine pollen. This indicates a relative increase in the long-distance transport of the latter. The high-frequency pattern has been smoothed by the calculation of 100-year averages (Fig. 4, column 4, curve B). The results reveal long-term trends that parallel those of the hydrologic record. As expected, periods characterized by high proportions of small pine pollen coincide with intervals of deposition.

The interval A.D. 950 to 1150 is one of the best documented periods of increased effective moisture on the Colorado Plateaus. During this period there were noticeable increases in the density and spatial distribution of human populations, probably as a result of increased carrying capacity of the region (*51*). Paleontological data indicate that such increased carrying capacity could have resulted from the introduction of new or improved agronomic plants, from the increased yield of native species, and from the invasion of the area by normally exotic species (*63*, *73-75*). Analysis of faunal material from Hay Hollow Valley archeological sites indicates that fewer species were exploited by the prehistoric populations during major periods of increased effective moisture. In contrast, more species were utilized during the drought intervals. A similar trend is observed in the numbers of wild and cultivated plant species exploited (*63*). Thus it appears that during most favorable environmental episodes the prehistoric people were more selective in their diet, relying mostly on cultivated crops and large mammals. Larger and more dependable yields of both wild and cultivated plants could be expected to support the expansion of human and animal populations. Human disturbance of the environment during periods of burgeoning population seems in some instances to have created conditions that favored the increase of particular species at the expense of others (*63*, *76*).

Analysis of the animal species that temporarily extended their ranges on the Colorado Plateaus and of their food requirements provides additional details of the environmental changes that took place. Three species—marmot, bison, and scaled quail—are particularly noteworthy for their range extensions onto the Plateaus during the period A.D. 950 to 1150 (*63*, *75*, *77*). The last two normally inhabit grasslands, and marmot can extend its range into grasslands if green fodder is available (*73*). Although the grasses normally grazed by these exotic animals now grow in northern Arizona, the grasslands of the Colorado Plateaus are currently dominated by hardier grass species adapted to the present summer temperature and moisture regimes. The current limited distribution of cold season grasses appears to be related to both grazing by introduced livestock and unfavorable climatic conditions (*78*). The prehistoric existence of animal species dependent on grasslands composed of both cool and warm season grasses implies moister, warmer conditions during springs or wetter winters, as suggested by Harris (*73*) on the basis of marmot distributions, and also wetter summers, as inferred from palynological data by Schoenwetter (*79*). In combination, these inferred seasonal patterns of weather variation suggest that annual precipitation was substantially higher in A.D. 950 to 1150 than it is now. This conclusion is compatible with the geological evidence for generally higher hydrologic competence and higher water tables during the same period.

Regional hydrology. In 1974 three of us (*43*) proposed a preliminary hydrologic chronology for Black Mesa, derived by correlating widely scattered stratigraphic sections dated by archeological, tree-ring, and ^{14}C materials. Subsequent redating of some sections and dating of others in the area surrounding Black Mesa (Fig. 2) has required one revision in the previous correlations (*80*) and has added more detail to the chronology of regional hydrologic history.

The main depositional units shown in Fig. 4, column 2A, are designated by capital letters (*W* to *Z* from oldest to youngest). The intervening nondepositional intervals, which are indicated by Fluventic Camborthid soils (*81*) or by unconformities, are designated with lowercase letters that combine the symbols of the bracketing deposits, such as *y*/*z*. Distinct stratigraphic breaks within the main depositional units provide the basis for designating second-order subdivisions such as *Z-1* and *Z-2* and intervening nondepositional intervals such as *z*-$^1/_2$. Each secondary depositional unit is made up of localized subordinate depositional units that fine upward (Fig. 4, column 3B) and are separated by incipient soils, buried root zones, minor erosional discontinuities, or archeological materials that record brief interruptions in deposition.

The dendrochronological germination dates for 27 buried trees that are stratigraphically associated with the *y*/*z* soil at four different localities cluster between A.D. 1325 and 1500. The stratigraphic positions of these buried trees indicate that germination occurred after A.D. 1300 on arroyo floors exposed by a major erosional episode and before burial in the overlying *Z* deposits.

Germination dates of 16 trees rooted in younger stratigraphic horizons within the *Z* sediments at six localities cluster around A.D. 1525, 1600, 1700, and 1800. These trees date secondary depositional breaks in the *Z* deposits that appear to have been contemporaneous throughout the region. Tree-ring dating of other buried forests in the region may define other stratigraphic breaks, including some of local rather than widespread occurrence. The large number of samples, the large area investigated, and the clustering of the dated nondepositional intervals during droughts recorded by the decadal dendroclimatic record (Fig. 4, column 1) indicate that we have probably already defined the main nondepositional intervals in *Z* time.

Germination dates of about A.D. 1900 for three trees partially buried in stabilized arroyo floor terraces (*a*-terrace deposits) are consistent with (i) historical evidence that the major arroyo cutting that terminated the *Z* deposition began in the late 1800's and (ii) dendroclimatic evidence of a decadal shift from drier to wetter conditions about A.D. 1900. The sensitivity of local alluvial response to regional climatic trends is further suggested by a depositional hiatus in the *a*-terrace deposits that is dated at about A.D. 1950 by glass, metal, and plastic materials. This dating equates with the latest dry interval defined by decadal departures in the dendroclimatic record and by meteorological records. Field observations between 1969 and 1975 detected in some arroyos the dissection of *a*-terrace deposits by shallow, headward-extending axial gullies, which suggests a regional trend toward lower water tables and drier conditions that began after A.D. 1970.

The temporal positioning and subdivisions of the earlier W, X, and Y deposits (Fig. 4, column 2A) are based exclusively on ^{14}C and archeologically dated materials. Because some of the ^{14}C samples from fine-grained detrital organic deposits dated anomalously old (probably because of coal contamination), the chronology presented is based only on ^{14}C dates from large, identifiable wood or charcoal fragments. Suitable organic material has not yet been found associated with the distinctive breaks in the W and X depositional units, and the estimated dates of about A.D. 50 and 600 for these two breaks were derived by stratigraphic interpolation between dated horizons and by correlation with the archeological record (*43*). The previous dating of the v/w boundary on Black Mesa at about 250 B.C. was based on geological correlations with other Southwest records. This dating is now supported by nine internally consistent ^{14}C dates from charcoal and wood samples from occupation surfaces (*82*) associated with and overlying a buried Camborthid soil at a Basketmaker II site on Black Mesa.

The hydrologic curve (Fig. 4, column 2B) is inferred from the dated stratigraphic subdivisions according to the following geoclimatic model: alluvial deposition occurs during intervals of increased hydrologic competence, rising regional water tables, and wetter climate. Intervening intervals of nondeposition defined by soils and unconformities represent periods of lower hydrologic competence, lower regional water tables, and drier climate. This interpretive model best satisfies the convergent evidence obtained from tree rings, pollen, and stratigraphy. Interpreted in light of this model, the data indicate that the major arroyo cutting episodes began during transitional periods between major wet and dry intervals or during periods of generally falling water tables (*83*). Present geomorphic conditions of arroyo cutting in axial parts of the valleys concurrent with soil development on the stable surfaces of adjacent terrace and slope deposits are consistent with this model. Although the model is not necessarily incompatible with the hypothesis that arroyo cutting results from shifts from winter dominant to summer dominant precipitation (*53*), no conclusive paleoenvironmental evidence supports this hypothesis, and some evidence appears to contradict it (*84*).

The temporal distribution of the major depositional intervals (Fig. 4, column 2A) suggests that a primary hydrologic cycle recurred on the average about every 550 years. The twofold subdivision of each primary depositional unit suggests that a secondary cycle with a wavelength of about 275 years was superposed on the primary cycle. The dated subordinate horizons suggest that still higher frequency oscillations with wavelengths mainly in the range 50 to 100 years were superposed on the broader hydrologic trends.

Regional Correlations

A few paleoenvironmental sequences from other localities on the Plateaus provide data resolution comparable to that of the records from the Black Mesa area. One of the most detailed paleoclimatic chronologies from the Plateaus is the archeological, pollen, and hydrologic record from the Navajo Reservoir area of northwestern New Mexico (Fig. 4, column 5). This record is characterized by a data gap between A.D. 1050 and 1500 [filled by Schoenwetter (*79*) with the pollen record from Tesuque, New Mexico], by intervals with unresolved dating and interpretive problems (*85*), and by sampling intervals different from those of our records from the Black Mesa area. Nevertheless, comparison of the parts of the two records with comparable sampling intervals reveals that the variability patterns of the Navajo Reservoir sequences resemble those of the Black Mesa area hydrologic and pollen records and that of the regional dendroclimatic record. The agreements among these records seem sufficient to support the conclusion that hydrologic and climatic changes in the eastern and western parts of the Colorado Plateaus were essentially synchronous.

A pollen and alluvial chronology recently constructed by Hall (*61*) for Chaco Canyon in northwestern New Mexico appears to differ from the western Plateaus records. These apparent discrepancies are due primarily to Hall's use of assumptions for stratigraphic subdivision and of a model of the relationships between climate and geomorphological processes that differ from ours (*86*). However, on the basis of Hall's radiocarbon dates, the Chaco Canyon stratigraphic sequence appears to be similar to the western Plateaus records.

Hall's "Chaco" depositional unit is bounded by unconformities that he dates at about 250 B.C. and A.D. 1130. This provides evidence for erosional intervals in Chaco Canyon contemporaneous with the v/w and y-$^1/_2$ nondepositional (erosional and soil-forming) intervals. Dated buried hearths and archeological sites (some associated with fire-baked soils) record distinct interruptions within the Chaco depositional sequence. Radiocarbon determinations indicate that these horizons date to A.D. 15 ± 100, A.D. 295 ± 85 (*87*), A.D. 565 ± 90, and between A.D. 765 ± 85 and 940 ± 85 (four dates). These Chaco horizons coincide, within the limits of dating error, with the w-$^1/_2$, w/x, x-$^1/_2$, and x/y nondepositional horizons in the Black Mesa area sequence. Depositional hiatuses in the Chaco Canyon sequence that correspond to the y/z and z-$^1/_2$ nondepositional intervals cannot now be identified because no evidence dates the base of or subdivisions within the "post-Bonito" sediments that overlie the Chaco unit. Historic records indicate that the recent dissection of the post-Bonito unit began in the 1860's, essentially contemporaneous with the recent cutting of the Z deposits. Thus it appears that the undivided post-Bonito deposits dated by Hall between A.D. 1130 and the 1860's are equivalent to the Z unit and the upper part of the Y deposits. We conclude from this evidence of parallel chronostratigraphy that hydrologic and climatic trends in the Chaco Canyon region were essentially synchronous with those of the Navajo Reservoir area to the north and those of the Black Mesa area to the west.

Most paleoenvironmental records from other parts of western North America are not comparable to the Plateaus sequences either because they do not cover the same time period or because their sampling intervals are two widely spaced to record high-frequency components equal to those of the Plateaus records. The few stratigraphic and pollen sequences for western North America that approach the level of dating control and sample spacing of the Plateaus data reveal environmental fluctuations that appear to be in phase with major variations indicated by the Plateaus records (*88*). However, the resolution of these records precludes recognition of fluctations with frequencies higher than about 550 years.

California provides two paleoenvironmental records that are comparable in terms of sampling interval and time span to the Colorado Plateaus sequences: the pollen and peat record from the spring-fed Ralston Ridge Bog near Lake Tahoe on the eastern side of the Sierra Nevadas (*89*) and the precipitation-sensitive lower forest border bristlecone pine growth departure series from the White Mountains (*90*). These records specify environmental changes at two high-elevation localities (2000 to 2600 meters) in adjacent mountain ranges in the Basin and Range Province west of the Colorado Plateaus. High chronological precision characterizes both records. The Ralston Ridge Bog chronology is based on three closely spaced, internally consistent ^{14}C dates. Serselj and Adam (*89*, p. 739) derive a detailed bog chronology by using the conventional, more or less certain, assumption of uniform depositional rates between sections dated by the three ^{14}C determinations. The White Mountain bristlecone pine growth departure sequence is expressed in terms of absolutely dated 20-year intervals. This degree of chronological control allows matching of these California environmental curves with those of the Colorado Plateaus on the basis of temporal equivalence rather than similarities in configuration. Furthermore, the high temporal resolution of these two California sequences places them among the very few such records that can be used to identify short-term fluctuations comparable to the ~ 275-year cycle and shorter variations inferred from the Plateaus records.

The general agreement of these California records with those from the Plateaus is evident (Fig. 4). Bog-drying intervals, which are inferred to represent lower water tables and a drier climate, dated by Serselj and Adam (*89*) at about A.D. 40, 340, 605, 880, and 1420 coincide with Plateaus drought culminations placed at about A.D. 50, 350, 600, 875, and 1450.

Serselj and Adam suggest that high frequencies of *Gramineae* and *Umbelliferae* pollen represent cool wet intervals, while high frequencies of *Abies* and *Polygonum bistortoides* pollen represent relatively drier or warmer periods. These inferred wet (+) and dry (−) pollen indicators are combined and plotted according to Serselj and Adam's time scale in Fig. 4, column 6, curve B. Sampling intervals of these "moisture" indicators are sufficiently closely spaced to suggest wetter intervals contemporaneous with the *W*, *Y*, and *Z* alluvial epicycles of the Plateaus record. The Ralston Ridge Bog data points are too widely spaced for definition of the *X* epicycle or any of the secondary dry intervals on the Plateaus. However, the higher frequency dendroclimatic sequence from the White Mountains (Fig. 4, column 6, curve A) appears to record, by distinctive negative departures centered around A.D. 1150 and 1700, the y-$^1/_2$ and z-$^1/_2$ dry intervals of the Plateaus composite record. In addition, comparison of the White Mountains and the Plateaus 20-year tree growth departure sequences indicates that 75 percent of the secondary trends in the two records are parallel, although amplitude differences are evident. The most striking discrepancy in trend occurs in the 19th century, the White Mountains record suggesting drier climate and the Plateaus record indicating wetter climate around A.D. 1850 (*91*).

The California bog, pollen, and tree-ring evidence plotted in Fig. 4, column 6, replicates the first- and second-order trends of the Plateaus paleoenvironmental record as well as many of the higher frequency (20-year mean) fluctuations. This parallelism provides independent empirical support for common climatic histories at several frequency levels in two regions whose present climate is dominated for much of the year by cyclonic storms from the Pacific Ocean (*90*, p. 1046).

Cultural Dynamics and Paleoenvironmental Correlates

Three of us have hypothesized that if it can be shown that the paleoenvironmental reconstruction for the Black Mesa area is applicable to other parts of the Colorado Plateaus, "comparable climatic changes may have been in large part responsible for cultural dynamics throughout the region" (*43*). Our present data suggest that environmental variations were indeed generally similar across the broader region and that they did coincide with cultural changes. Archeological chronologies that represent cultural dynamics in different areas of the Plateaus are graphed in relation to our composite paleoenvironmental reconstruction in Fig. 5. Several correspondences are evident in the data compared at different levels of detail.

Major population trends are both parallel and reciprocal to the long-term hydrologic fluctuations. Inferred population trends plotted in Fig. 5 indicate that population tended to increase during wetter periods in the Hay Hollow Valley, Grand Canyon, Hopi Buttes, Black Mesa, Cedar Mesa, and Canyon de Chelly areas. During the intervening dry intervals populations in these areas tended to decrease, either because of abandonment of the areas or because of reduced growth rates, which presumably depended on differing local environmental conditions. Populations in these areas also tended to concentrate along drainages during the major dry intervals. In contrast, the population trends plotted in Fig. 5 for Mesa Verde and the Navajo Reservoir district in the northeastern part of the study area indicate that population maxima tended to occur during the major dry intervals and population decreases tended to occur during wetter periods.

Population increases associated with wetter periods generally occured in areas now characterized by scant surface water supplies, drier weather, and longer growing seasons (more than 120 frost-free days and less than 40 centimeters mean annual precipitation) (Fig. 2). Population decreases associated with wetter intervals generally occurred in or adjacent to the Plateaus region flanking the southern Rocky Mountains that is now characterized by wetter and cooler weather and more abundant surface water. These relationships to current weather zonation and surface hydrology and to paleoenvironmental fluctuations indicate that past environmental changes may have triggered population displacements toward wetter and cooler localities during the major droughts. They also suggest that countermovements toward drier and warmer localities occurred during wetter intervals, when farming became possible in areas that otherwise were too dry to support large numbers of people.

The Wetherill Mesa population curves in Fig. 5 suggest local behavioral adaptation to environmental changes. They indicate that population maxima on the mesa top (curve A) occurred during major drought intervals, while general population contraction and the occupation of rock shelters in the canyon walls (curve B) took place during wetter periods. The population estimates for the adjacent Chapin Mesa in Fig. 5 record a similar tendency toward population expansion on the mesa top during dry intervals. However, because the temporal boundaries of the archeological phases defined for Chapin Mesa differ from those established for Wetherill Mesa, the Chapin Mesa sequence also provides evidence for population increase during the y-$^1/_2$ drought. The construction around A.D. 1000 to 1050 of a water-control system at Mummy Lake apparently increased the carrying capacity of this upland locality (*9, 92*). On both Chapin (Fig. 5, column 10, curve C) and Wetherill (Fig. 5, column 11, curve B) mesas the major movement into canyon wall pueblos occurred during the late part of the *Y* alluvial interval, just before the general abandonment of the region, which coincided with the beginning of major arroyo cutting during the *x/y* interval.

A similar relationship between expanding population and drought intervals can be inferred from the population curves of the nearby Navajo Reservoir area (Fig. 5, column 13). In this locality the San Juan River was a source of permanent water during the major drought intervals when water supplies elsewhere were diminished. Curve A (Fig. 5, column 13) indicates that population increased during the *w*/*x* and *x*/*y* droughts. Eddy's (*93*) more closely controlled "cultural growth and dynamics curve" provides evidence for increased cultural activity during these major droughts and during the x-$^1/_2$ drought. Around A.D. 1050 the Anasazi abandoned the Navajo Reservoir area and moved up the San Juan River valley. This movement has been attributed to environmental changes associated with the headward migration of arroyos in the valley (*94*). However, our regional hydrologic indices indicate that the period A.D. 1000 to 1150 was one of general aggradation and high water tables. Local flooding of the valley floor during this period may have limited farming to upriver areas and to tributary canyons, thereby favoring upvalley population displacements.

Time-frequency diagrams of tree-ring cutting dates from archeological sites in northwestern New Mexico and southwestern Colorado are shown in Fig. 5, column 14. Although these cutting dates are not quantitatively representative of population history, they do indicate intervals of increased building activity. These data appear to be consistent with the other archeological evidence of population increases in the northeastern area during the w-$^1/_2$, *w*/*x*, x-$^1/_2$, *x*/*y*, and y-$^1/_2$ droughts. In addition, the temporal distribution of cutting dates suggests that increased building activity coincided with some of the minor dry intervals specified by the dendroclimatic, hydrologic, and pollen records. The distribution of cutting dates from Chaco Canyon sites (Fig. 5, column 12) suggests construction trends that are parallel to those of the more westerly sites and reciprocal to the Mesa Verde and Navajo Reservoir trends.

The general correspondence shown in Fig. 5 between the minor dendroclimatic droughts and independently dated archeological phase boundaries indicates that cultural changes of the nature specified by these phase transformations may be related to relatively small environmental changes (*95*). The economies of the prehistoric farmers and gatherers of the Colorado Plateaus were adapted to local environmental conditions, and changes in these conditions often required compensating adjustments in the subsistence activities and other behavior of the affected populations. Jorde's (*96*) consideration of possible behavioral responses to environmental change is an example of the kind of cultural adaptation envisioned here.

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54. Southwestern conifer pollen ratios have been successfully employed to characterize modern plant communities and to reconstruct past vegetation at sites in conifer-dominated plant communities at low elevation. However, problems have been noted by some workers at sites that either were historically or now are above timberline or within the boundaries of higher-elevation conifer communities characterized by one or more of the various white pines. The pollen sample sites of the present study are located 40 to 80 miles from the nearest high-elevation forests. It is not likely that such forests have extended their ranges significantly during the last $2\frac{1}{2}$ millennia. However, about 10 percent of the pollen from these trees does not fall beneath the canopy, and some of that 10 percent undoubtedly is transported considerable distances. Fortunately, the pollen of pinyon (small pollen type) is usually separable from that of ponderosa pine (large pollen type) and the white pines by size alone and is further distinguished by a unique combination of other anatomical characteristics. Since poor preservation does not always permit utilization of the anatomical characteristics, the small pine category may include a fractional percentage of pollen from various white pine species or of abnormally small ponderosa pine pollen. Elements of the preceding discussion are covered in (*52, 53*); H. Dixon, thesis, University of New Mexico, Albuquerque (1962); R. H. Hevly, *J. Ariz. Acad. Sci.* **5**, 116 (1968); J. E. King, *Mich. Acad. Sci. Arts Lett.* **52**, 31 (1967); J. West, thesis, University of California, Davis (1978); L. J. Maher, Jr., *Geol. Soc. Am. Bull.* **74**, 1485 (1963); H. E. Wright, Jr., A. M. Bent, B. S. Hansen, L. J. Maher, Jr., *ibid.* **84**, 1155 (1973); B. S. Hansen and E. J. Cushing, *ibid.*, p. 1181.
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64. That trees were harvested by prehistoric people is documented by wood and charcoal from archeological sites, but the effects of such harvest on local pollen rain have remained uncertain until recently. In Hay Hollow Valley, at Flagstaff, and at Mesa Verde, AP to NAP ratios are inversely proportional to population trends. This could result from increased NAP coincident with increased human disturbance or decreased AP due to the harvest of wood and seeds of trees. However, the fluctuating AP to NAP ratios do not show any persistent departures from modern levels, nor do they exhibit any consistent pattern relative to utilized proportions of different woody species. The failure of AP to NAP ratios to reflect lumbering activities is probably due to the general selection of small trees that produced little or no pollen. Pollen from unharvested trees or from trees growing in nearby, less culturally affected localities may mask the effects of prehistoric tree cutting.
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80. Published ^{14}C dates (I-7511, A.D. 935; I-6951, A.D. 1245) of fine-grained detrital organic samples from Dead Juniper Wash (DJW) section $14\frac{1}{2}$ are too old relative to the tree-ring germination date of the associated buried tree (DJW 21). The anomalous ^{14}C dates are probably due to amorphous coal contamination of the samples. Pollen and grain size diagrams of section $14\frac{1}{2}$ (redesignated here as DJW 21), previously thought to cover both *Y* and *Z* time, are now assigned only to *Z* time, as shown in Fig. 4, columns 3A and 3B.
81. Pedological analyses indicate that the buried *x/y* and *y/z* soils in Dead Juniper Wash (E. Karlstrom, personal communication) and comparable soils associated with the *v/w* and *w/x* boundaries are Fluventic Camborthid soils with simple *a/c* horizonation and irregular amounts of organic materials distributed throughout oxidized profiles that commonly are less than 20 centimeters thick.
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83. Our data bear directly on the unresolved problem of whether arroyo cutting occurs during intervals of increasing moisture [(*61*); C. E. Dutton, *U.S. Geol. Surv. Monogr. 2* (1882); E. Huntington, *Carnegie Inst. Washington Publ. 192* (1914); L. H. Quinn, *J. Geol.* **65**, 149 (1957)] or intervals of decreasing moisture [(*43*); E. Antevs, *Am. Antiq.* **20**, 317 (1955); K. Bryan, *J. Geol.* **36**, 265 (1928); J. T. Hack, in *Museum Notes* (Museum of Northern Arizona, Flagstaff, 1939), No. 11, pp. 63–73; C. V. Haynes, Jr., in *Means of Correlation of Quaternary Successions*, R. B. Morrison and H. E. Wright, Jr., Eds. (Univ. of Utah Press, Salt Lake City, 1968), pp. 591–615; S. Judson, *Sci. Am.* **187**, 71 (December 1952); L. B. Leopold and C. I. Snyder, *U.S. Geol. Surv. Water Supply Pap. 1110-A* (1951), pp. 1–19] and provide strong support for the latter interpretation. For a comprehensive summary of the development of this controversy and an evaluation of other factors that influence arroyo cutting in the Southwest see R. U. Cooke and R. W. Reeves [*Arroyos and Environmental Changes* (Clarendon, Oxford, 1976)]. These authors and W. C. Thornthwaite, C. F. S. Sharpe, and E. F. Dosch [*U.S. Dep. Agric. Tech. Bull. 808* (1942)] conclude from historical data alone that vegetation destruction and land surface alterations resulting from the activities of Europeans in the late 1880's probably initiated arroyo cutting. Our prehistoric and historical environmental data suggest that arroyo cutting would have begun at about the same time (earlier in some areas, later in others, due to differing geological environments) even if Europeans had not arrived on the scene, because falling water tables had reached critical levels. Many Southwestern researchers accept the following linkage: destruction of natural vegetation by man and livestock causes exposed ground to erode, leading to lower water tables. Our paleoenvironmental data support the primacy of the reverse linkage: climatically induced subsidence of water tables below plant root zones affects the distribution, density, pollen production, and species composition of vegetation. These changes are accompanied by shifts from aggradation to surface stability to dissection of fine-grained unconsolidated sediments lying above water-saturated strata along axial drainages.
84. Changes in the ratios of Cheno-Am and Composite pollen types from archeological sites have led some researchers to infer systematic shifts in seasonal precipitation patterns on the Colorado Plateaus (*65*). We consider application of these inferences to paleoenvironmental reconstruction on the Plateaus to be premature for four reasons. First, selective in-

troduction of pollen-bearing plant parts into archeological sites by the sites' inhabitants can distort the pollen ratios. Second, the concept of changes in seasonal precipitation patterns was developed on the basis of pollen analyses in the Sonoran Desert (*69*). However, the Cheno-Am and Composite species of the desert differ compositionally and phenologically from their counterparts on the Colorado Plateaus (R. H. Hevly and L. E. Renner, *Mus. North. Ariz. Res. Rep. 18*, in press). Third, reconstructions of dendroclimatic variability for the Mesa Verde [H. C. Fritts, D. G. Smith, M. A. Stokes, *Mem. Soc. Am. Archaeol. 19* (1965), pp. 101-121], Santa Fe (*49*), and northwestern New Mexico (M. R. Rose, in preparation) areas lend little support to the idea of systematic shifts in seasonal precipitation patterns. Fourth, J. E. McDonald [*Univ. Ariz. Inst. Atmos. Phys. Tech. Rep. 1* (1956)] has shown that Southwestern winter and summer precipitation are independent of one another. Thus there is no reason to expect winter precipitation to decrease when summer rainfall increases or vice versa.

85. The most obvious discrepancy between the Black Mesa area and Navajo Reservoir records occurs in the period before A.D. 500 where some ^{14}C dates from Navajo Reservoir archeological wood samples uncorrected for terminal ring dates differ by more than 100 years from associated archeologically dated materials. Schoenwetter's generalized climatic curve (Fig. 4, column 5D) shows wetter than present climate during the late Los Pinos phase (A.D. 300 to 400) and the *w/x* interval. However, some archeologically dated pollen assemblages indicate arid to semiarid conditions during late Los Pinos and early Sambrito phase times (*43*). This appears to be consistent with hydrological evidence for lower San Juan River water levels during the late Los Pinos phase (*43, 53*) and with the *w/x* drought (Fig. 4, column 5C). Other discrepancies are apparent. Pollen spectra for the interval A.D. 950 to 1050 may erroneously indicate drier than actual conditions because of depositional contamination (*79*, p. 24). Two pollen spectra dated to the middle 1800's present conflicting evidence, one indicating moisture conditions similar to those at present, the other conditions wetter than those at present (*79*).
86. Hall divides the Chaco Canyon stratigraphy on the basis of local unconformities. Apparently no consideration is given to the equal stratigraphic importance of soil horizons that occur in broad-floored valley fills adjacent to active arroyos along the axial drainage lines. Hall's climatic inferences seem to be based in part on the assumption that arroyo cutting occurs in response to increasing moisture (*83*). Unfortunately, the Chaco Canyon pollen records of the last two millennia are not dated with the degree of resolution necessary to establish intercorrelations with the other pollen records discussed in this article.
87. Hall rejects this date (sample I-7301) and the date of 220 ± 110 B.C. from sample I-7303 on the basis of their apparent association with younger archeological materials. Sample I-7303 is from a horizon that contains dated archeological materials, and it clearly dates too early, probably because the sample represents old firewood. Sample I-7301 (A.D. 295 ± 85), however, should date earlier than A.D. 600 because it came from a level 22 to 32 centimeters below an archeological horizon dated at A.D. 600 or younger. Therefore, we accept the validity of this date.
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92. Similar population growth followed the construction of water-control systems during the period A.D. 1000 to 1050 in Hay Hollow Valley and in Chaco Canyon.
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101. D. A. Breternitz, F. W. Eddy, W. J. Judge, W. D. Lipe, and A. H. Rohn reviewed all or parts of the archeological summaries. R. Hereford, H. E. Holt, B. C. Philpott, P. J. Schafer, C. G. Ami, and D. A. June—members of the Black Mesa Surficial Geology Project funded by the Energy Lands Program of the U.S. Geological Survey and directed by T.N.V.K.—contributed observations and samples used in the reconstruction of hydrologic history. H. E. Malde, K. L. Pierce, J. A. Schoenwetter, and D. S. Fullerton commented on the final manuscript. Most of the archeological fieldwork on Black Mesa was funded by the Peabody Coal Company of St. Louis. The dendroclimatic research was supported by grants to the Laboratory of Tree-Ring Research, University of Arizona; by the Advanced Research Projects Agency, National Science Foundation, and National Park Service. Support for some of the palynological studies at Northern Arizona University was provided by National Science Foundation grants to the Field Museum of Natural History and by McIntyre-Stennis funds made available to the Department of Biological Sciences by the School of Forestry. In addition, Northern Arizona University provided release time for the palynological studies. The Geological Survey provided support on a cost-share, mutual research interest basis for tree-ring research dating of alluvially buried trees by the Laboratory of Tree-Ring Research and for pollen analyses of Black Mesa samples by the Department of Biological Sciences at Northern Arizona University. We are grateful to these individuals and institutions for their many contributions to our research. This article has been authorized by the director, U.S. Geological Survey.

Economic Benefits from Research: An Example from Agriculture

Robert E. Evenson, Paul E. Waggoner, Vernon W. Ruttan

The nation is worried about productivity. The Council of Economic Advisors wrote in its 1979 report, "Between 1948 and 1965 [labor] productivity growth in the private nonfarm sector averaged 2.6 percent per year. In 1965-73 this rate declined to 2.0 percent. Since 1973, private nonfarm productivity growth has averaged less than 1 percent per year" (*1*). Research leading to technological innovation was identified as the primary source of earlier increases in productivity (*2*). The Administration has responded to the present decline by initiating an intensive review of federal policy affecting innovation (*3*). The three policies that have been suggested for accelerating innovation—government research grants, government laboratories, and tax credits (*4*)—imply a larger role for public research. Thus it is timely to analyze the long experience of public support for agricultural research.

Precisely because the public role is large in agricultural research, the data are available to analyze the economic returns from investment in research (Tables 1 to 3). Beginning in the 1950's with Zvi Griliches' estimation of economic return from research on hybrid corn, a substantial body of knowledge has been developed on rates of return on publicly supported research (Table 2). We now have enough information to test the consistency of the economic returns that have been calculated. Recent research (Table 3) has made it possible to go

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