FINAL REPORT

A 1,373 YEAR RECONSTRUCTION OF ANNUAL PRECIPITATION FOR THE SOUTHERN RIO GRANDE BASIN

submitted by

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EXECUTIVE SUMMARY

The purpose of this project was to develop a detailed, high-resolution, millennial-length regional reconstruction of precipitation for the southern New Mexico/Rio Grande Basin area, with particular reference to Fort Bliss, White Sands Missile Range, and Holloman Air Force Base. Based on a network of sites containing trees where growth is largely determined by precipitation, this reconstruction is to be used by natural and cultural resources managers of these and other agencies to:

(1) *document changes in settlement and subsistence patterns of local prehistoric populations possibly due to changes in the past environment,*

(2) *interpret past physical changes in the environment (e.g., arroyo cutting, channel entrenchment, soil erosion, and desertification) in light of possible past changes in climate, and*

(3) *better understand the relationship between past climate and fire patterns, and help develop fire management strategies and policies.*

We targeted specific sites from strategic locations in southern and central New Mexico where we hoped to locate samples that would eventually yield exceptionally long tree-ring chronologies to extend the precipitation reconstruction as far back in time as possible. We sampled at several promising locations, including the Sacramento, Magdalena, San Mateo, and Organ Mountains. Primary tree species sampled included ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), southwestern white pine (*Pinus strobiformis* Engelm.), and Colorado pinyon (*Pinus edulis* Engelm.). In addition, we used previously collected tree-ring material excavated from archeological sites of varying age located throughout the target area. These samples had been used to date the construction events of these sites, but had never been measured and used for any long-term (century-scale) climate reconstruction. The primary tree species used at the archeological sites was Colorado pinyon.

During our field collections, we found living trees of remarkable age and remnant wood that was exceptionally old for this region. In the Magdalenas, we located an exceptional site at South Baldy and another at Timber Peak that yielded living Douglas-fir and southwestern white pine trees that extended continuously into the 1100s, some of the oldest trees for these species ever located in the Southwest (one white pine tree collected in the San Mateo Mountains is now officially listed as the oldest representative of its species). More importantly, the unique geology of this mountain range helped preserve remnant wood sections that eventually yielded numerous samples that extended well prior to AD 1000. The Magdalena chronology extends to AD 622, the longest tree-ring chronology yet developed for southern/central New Mexico. In the San Mateos, we also located an exceptional site that yielded a continuous tree-ring chronology back to AD 925. These data were combined with the Magdalena material to improve the climate signal retrieved from these trees for climate reconstruction purposes and to strengthen the sample depth (the number of samples in any one year) prior to AD 1100. This combined chronology forms one of two primary millennium-length tree-ring chronologies developed for this study.

The second primary tree-ring data set developed for this study used the archeological pinyon material from 12 sites throughout southern and central New Mexico. Between September 1996 and April 1997, 244 tree-ring series (from well-preserved specimens that were primarily charcoal) were measured from these sites, and eventually yielded a continuous tree-ring chronology back to AD 532. The pinyon chronology extends outward to AD 1550 with an adequate number of samples, but was extended to the present with the statistically-similar Organ Mountains ponderosa pine chronology (*i.e.*, both had similar statistical attributes) for calibration with historical climate records. The Organ Mountains chronology was also developed for this study, and extends back to AD 1306 with adequate sample depth, again one of the longest chronologies yet developed for this portion of the Southwest. Between these two exceptionally long chronologies – the Magdalena/San Mateo and archeological pinyon data sets – we were able to reconstruct both short-term (*i.e.*, decadal time scale, generally 25 years or shorter) and long-term (*i.e.*, century-scale, generally 50 years or longer) trends in past precipitation with excellent clarity.

To maximize the quality of the final reconstruction, the majority of variance in the two primary data sets was concentrated into one time series back to AD 622 using principal components analysis. Correlation and response function analyses between various climate variables and this time series indicated a significant relationship with an annual, water-year precipitation total from the previous year's August through the current year's July ($r = .71$, $p < .0001$). Calibration of the tree-ring time series with annual rainfall using the 1931-1995 regional climate record (obtained from the National Climatic Data Center in Asheville, North Carolina) revealed that 80% of the variance in rainfall could be explained by the tree-ring data, an exceptionally high value for dendroclimatic reconstructions in the American Southwest. An equation relating precipitation as a function of tree growth was then developed using regression techniques, generating a reconstruction of precipitation back to AD 622.

The reconstruction revealed that the most severe long-term drought during the last 1,373 years occurred between AD 940-1040, which may have impacted, to some degree, the demographic, settlement, and interaction patterns of the ancient Native American Mogollon culture. Periods of stress and deteriorating environmental conditions are believed to have prompted regional interactions between ancient cultural groups to help overcome shortages of food and supplies. Between AD 750-1000, the Mimbres interacted with the Hohokam of southern Arizona at unprecedented levels, perhaps in response to the generally unfavorable climate conditions that existed during this period. Furthermore, the population for the region as a whole was well below its effective carrying capacity, indicating some factor, such as hydrologic drought, may have contributed to keeping population densities low.

This long-term drought was followed by the wettest long-term period in the 1,373 year reconstruction between AD 1040-1210. Interestingly, this period is nearly coeval with the Differentiation Period (AD 1000-1150) that occurred in most portions of the Southwest. This period witnessed the development of the Classic Mimbres period that was marked by three major cultural shifts *ca.* AD 1000: the use of above ground dwellings as opposed to pithouses, increased populations densities, and the emergence of finely detailed Mimbres pottery. However, the Classic Mimbres period would decline *ca.* AD 1150, in part because a major drought of unprecedented duration occurred within this long-term wet period that almost certainly impacted the Mogollon. Between *ca.* AD 1125, rainfall began to fall to unprecedented low annual totals, concurrent with a change from low climate variability (and therefore reliable from one year to the next) to high climate variability (and therefore unpredictable from one year to the next). The drought lasted until *ca.* AD 1140, the longest drought ever witnessed by the Mogollon, and may have encouraged increased trade with Casas Grandes further to the south in an effort to procure food and supplies that were in short supply.

A second major long-term drought period occurred between AD 1210-1305, a century that culminated in the worst decades-long drought during the last 1,373 years (based on both magnitude and duration) between AD 1270-1295. This drought is known in the Four Corners region as the "Great Drought" and is believed to be a primary factor that caused the abandonment of major Anasazi occupation sites. Our findings revealed, for the first time, that this drought was prominent in the southern portions of the Southwest, and could again have impacted to some degree the cultural patterns of the Mogollon culture. The extreme below-average rainfall could have induced a decrease in population and a more migratory lifestyle. Deteriorating climate conditions in the 13th century may partially explain the proliferation of archeological sites throughout the area that apparently were abandoned by the 14th century. Following a wet period from AD 1485-1545, another major long-term drought occurred between AD 1560-1600, which also occurred throughout the northern portions of the Southwest, although this drought did not reach the magnitude nor severity of the "Great Drought."

The entire 17th century saw generally above-average rainfall while the 18th century saw generally below-average rainfall. Following a wet period that lasted from AD 1780-1840, the latter half of the 19th century was very dry. Precipitation then recovered to above-average conditions beginning in the 1890s, which lasted until *ca.* 1940. The most severe drought period based on magnitude alone occurred during the 20th century between 1946-1965, a period marked by significant dieback of pinyon and juniper species in the lower elevations of the southern Southwest, likely due to the intensity of this drought. For the first time, this drought can be placed in a long-term historical perspective because of the great lengths of tree-ring chronologies developed for this project. Following this drought, rainfall since *ca.* 1976 has been above-average, but does not show the unprecedented rainfall believed to have occurred since *ca.* 1976 seen in other, more northerly precipitation reconstructions.

A remarkable feature of the 1,373-year long reconstruction is the changing variability of year-to-year precipitation over time, a feature also observed in other tree-ring chronologies in the southern portion of the Southwest (*e.g.*, Mount Graham in the Pinaleño Mountains of southeastern Arizona). The period between AD 900-1300 was marked by unusual swings between extremely wet periods and very dry periods, each often lasting well over one hundred years. This pattern changed beginning AD 1300, when such wide long-term swings diminished in their frequency and magnitude. Analysis of the variance of precipitation at a shorter time scale (25 years) revealed trends not observable in both the mean and variance at longer time scales. For example, a rapid increase in variance in the early 1400s marks a major change in precipitation not found when analyzing simple changes in short-term or long-term average rainfall. A major change in climate is also suggested *ca.* 1825 when variance began to drop to its lowest levels in the entire 1,373 year record, corroborated by a near-simultaneous and major change in annual rainfall at El Malpais. The change at El Malpais, however, suggested rainfall *increased* with a similar increase in variance as opposed to the lower variance and *decreased* rainfall seen in the southern portion of the Southwest.

INTRODUCTION

The paleoenvironment of the Southwest has been intensively studied, especially for the last two millennia, due in part to increased knowledge gained from archeological studies of extensive cultures that once thrived in a semiarid environment believed too hostile to support such large populations. Detailed paleoenvironmental reconstructions for northern portions of the Southwest (*i.e.*, the Four Corners area) have been developed based on geomorphic, stratigraphic, palynological, dendrochronological, and archeological evidence (Euler *et al.* 1979; Dean *et al.* 1985; Karlstrom 1988). However, the southern portions of the Southwest have received less attention from researchers than the northern portions, despite the existence of extensive cultural branches that collectively make up the southern Mogollon culture area (*e.g.*, the Mimbres of southwestern New Mexico, and the San Simon of southeastern Arizona) (LeBlanc 1989). Paleoenvironmental reconstructions in southern New Mexico and northern Chihuahua have largely been limited to vegetation reconstructions based on palynological studies and studies on packrat middens (Elias 1987; Van Devender and Toolin 1983; Van Devender *et al.* 1984). The temporal scales represented by the majority of these reconstructions range from 2,000-75,000 years BP (Before Present). Unfortunately, these temporal resolutions are too coarse for understanding environmental changes that occurred during the last 2,000 years that may have impacted local populations of the Mogollon culture of southern New Mexico.

The need for an understanding between environment and culture for the southern New Mexico area is great. Ceramics, permanent villages, and agriculture first appear in the southern Mogollon area *ca.* AD 250, suggesting a marked shift in adaptation over the entire area between AD 200-300 (LeBlanc 1989). Was this change in adaptive strategies by the Mogollon populations in response to changing environmental conditions? A climate reconstruction for El Malpais National Monument in northwestern New Mexico revealed a major shift in climate to below normal rainfall *ca.* AD 250 (Grissino-Mayer 1996). Could shifts in atmospheric circulation patterns changed seasonal rainfall amounts, necessitating changes in adaptive strategies? Between AD 1150-1300, the southern Mogollon interacted with the Casas Grandes culture of northern Chihuahua (LeBlanc 1989). Trade links are established and terminated depending on food supply which, in turn, is influenced by the stability of climate (Plog *et al.* 1988). Did changes in past climate necessitate interactions with the Casas Grandes populations? Between AD 1425-1450, the Mogollon area of southern New Mexico was completely abandoned

(Blake *et al.* 1986; LeBlanc 1989). What contribution did changes in climate, if any, have to this widespread abandonment? Reconstructions of the paleoclimate for southern New Mexico could shed light on these important archeological questions.

Paleoenvironmental reconstructions are also crucial to our understanding the relationship between climatic fluctuations and episodic cycles of erosion and sedimentation (Eddy 1974; Hall 1977). Two general hypotheses have been proposed to explain episodic arroyo formation in the Southwest (Cooke and Reeves 1976). Huntington (1914) proposed that increased rainfall would lead to increased erosion and arroyo cutting. In areas where dry-farming was practiced, the increased erosion could have prompted abandonment of settlements. A recent analog to erosion events in lowland farming areas occurred during the interval AD 1880-1910, when severe rainfall events caused downcutting and entrenchment of many Southwestern streams and washes (Bryan 1925; Leopold 1976; Hall 1977; Hereford 1986). Dean (1988) observed that "The idea that arroyo cutting is associated with high precipitation...currently enjoys widespread acceptance among archeologists." In contrast, some researchers believe that a shift to drier conditions would initiate arroyo cutting (Bryan 1928a, 1928b; Judson 1952). This hypothesis is favored primarily by geomorphologists and hydrologists who have studied the stratigraphy of the Southwest (Hack 1942; Cooley 1962; Karlstrom 1988). Whether or not arroyo cutting occurs during cyclical increases and decreases in rainfall, such episodic shifts in climate should be manifested within the long-term tree-ring record of Southwestern conifers. Furthermore, changes in the amounts, variability, and intensity of precipitation could be related to an increase or decrease in rainfall probable with spatial and/or temporal changes in summer monsoonal precipitation. Tree-ring studies that analyze long-term, century-scale trends in past rainfall could help resolve which climate scenario is most responsible for arroyo cutting, although various models could eventually explain this phenomenon (Cooke and Reeves 1976; Dean 1988).

Reconstructions of Southwestern paleoenvironments are also important for understanding the short-term (generally < 25 years) and long-term (generally > 50 years) relationships between fire occurrence and climate. Previous studies have documented that fire occurrence is significantly influenced by rainfall prior to the year of fire because this rainfall affects fuel types. amounts. and moisture which may greatly increase the chances of fire in the following year (Baisan and Swetnam 1990; Grissino-Mayer *et al.* 1995; Swetnam and Baisan 1996). Recent research has also revealed a significant relationship between long-term changes in climate and long-term changes in fire occurrence (Swetnam 1993; Grissino-Mayer 1995). At El Malpais National Monument, a tree-ring based reconstruction of past fires derived from over 200 fire-scarred trees revealed that centuries-long periods of increased rainfall saw a reduction in fire frequency (Grissino-Mayer 1995). In contrast, periods of reduced rainfall (such as the "Little Ice Age" between AD 1400-1800) saw an increase in fire frequency. Currently, the long-term relationship between fire and climate for southern/central New Mexico is unknown. Reconstructions of precipitation for southern New Mexico could provide agencies with information concerning this relationship, helping to establish guidelines for future fire management.

Tree-ring based climate reconstructions offer high-resolution (*i.e.*, annual) information on past environmental changes, and have been used extensively in the Four Corners area of the Southwest to better understand interactions between cultures and their environments (Dean 1969; Rose *et al.* 1981; Dean *et al.* 1985; Dean 1988; Cordell and Gumerman 1989; D'Arrigo and Jacoby 1991; Grissino-Mayer 1996). In southern New Mexico, however, no major paleoecological sites exist where tree-ring based climate reconstructions have been developed (Betancourt *et al.* 1993). A literature search of published climate studies based on tree rings (whether or not reconstructions were developed or simply the climate-tree growth relationship was assessed) revealed 41 such studies were conducted in New Mexico, but none pertained to southern New Mexico. Fritts (1991), however, developed reconstructions of temperature and precipitation for the western United States based on a grid of 65 tree-ring collection sites, three of which were located in southern New Mexico (Sacramento Mountains, Cloudcroft, and Tularosa Divide; see Drew 1972). Unfortunately, the spatial resolution of these reconstructions limits interpretations at the sub-regional scale of interest to this study. Grissino-Mayer *et al.*

(1991) developed a reconstruction of winter precipitation (previous year's October to current year's February) spanning 1687 to 1990 based on tree-ring widths of Colorado pinyon (*Pinus edulis* Engelm.) collected on Salinas Peak in the San Andres Mountains of south-central New Mexico. However, long-term trends were not apparent in this short reconstruction. Shaw (1993) investigated responses of Mogollon populations at the Pinedale and Reserve archeological sites to changes in past climate and environment. These few studies mark the full extent of tree-ring based paleoenvironmental studies in southern New Mexico.

PURPOSE OF THIS STUDY

The purpose of this study was to develop a detailed, high-resolution regional reconstruction of precipitation based on a network of tree-ring sites developed in the southern New Mexico/Rio Grande Basin area, with particular reference to Fort Bliss, White Sands Missile Range, and Holloman Air Force Base. These reconstructions are to be used by natural and cultural resources managers of these and other agencies to: (1) document changes in settlement and subsistence patterns of local prehistoric populations possibly due to changes in the past environment; (2) interpret past physical changes in the environment (*e.g.* arroyo cutting, channel entrenchment, soil erosion, and desertification) in light of possible past changes in climate; and (3) better understand the relationship between past climate and fire patterns, and help develop fire management strategies and policies.

DATA SYNTHESIS

The development of a regional reconstruction of precipitation required the development and synthesis of a regional network of tree-ring sites. We began our investigation by first synthesizing previously developed chronologies for New Mexico, Arizona, western

Texas, and Chihuahua currently available from (1) the databases of the Laboratory of Tree-Ring Research (LTRR), The University of Arizona, in Tucson, Arizona, and (2) the International Tree-Ring Data Bank (ITRDB) at the National Geophysical Data Center in Boulder, Colorado. Additional unpublished tree-ring data sets were gathered based on information from Drew (1972, 1976), Bannister *et al.* (1970), Dean and Robinson (1978), and Robinson and Cameron (1991). In addition, information on tree-ring data sets that were currently being developed for the Southwest were solicited from dendrochronologists participating on the ITRDB Dendrochronology Internet discussion group.

In addition to the actual tree-ring chronologies, this synthesis revealed significant holdings of archeological tree-ring samples in the archives of the LTRR collected from numerous sites throughout the southern portion of the Southwest. These collections were made between *ca.* 1930-1990, and were composed of well-preserved pinyon samples that were primarily charcoal. These samples were dated to help determine the construction dates of various Mimbres culture pithouses and above-ground dwellings. Unfortunately, climate reconstructions were not the primary purpose of these collections, and only very few of the charcoal samples were ever measured. We therefore synthesized which sites were relevant to our study, located the archeological samples within the vast holdings of the LTRR, re-dated all previously dated samples to ensure their accuracy, then measured the widths of over 18,000 tree rings from 244 series from 12 archeological sites. This process resulted in the longest tree-ring chronology yet developed for the southern portion of the Southwest, dating back continuously to AD 532.

To conduct the reconstruction, climate data were synthesized as well, utilizing the comprehensive holdings of climatic data sets archived at the Laboratory of Tree-Ring Research. While the goal of this study particularly targeted a reconstruction of precipitation, we believed an analysis of other climate variables would be useful for examining the potential for additional reconstructions for future research. Numerous weather stations exist for the western Texas/southern New Mexico area. Unfortunately, data from nearby weather stations in Mexico were too short and/or unreliable to be useful for effective climate reconstructions. In this study, climate data from both individual stations (in the U.S.

Historical Climate Network) and National Oceanic and Atmospheric Administration regional climate divisions. both obtained from the National Climatic Data Center in Asheville, North Carolina. were investigated.

STUDY SITES

The synthesis revealed that major gaps existed in the current network of tree-ring sites throughout the southern New Mexico study area. To better represent regional climate, it was required to fill these gaps with additional field collections. We targeted specific sites from strategic locations in southern and central New Mexico that we believed would yield material that would eventually extend the final precipitation reconstruction back in time. We were particularly interested in the mountains to the west and east of the Rio Grande for three reasons. First, these mountain ranges have received little attention from dendrochronologists in the past to develop millennial-length tree-ring chronologies despite their relatively easily-accessible locations. Several tree-ring chronologies have previously been developed in these mountain ranges, but these extended back only to *ca.* AD 1600. Second, field reports from members of the Department of Biology at the University of New Mexico suggested that long-lived Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and southwestern white pine (*Pinus strobiformis* Engelm.) trees may be living in these mountains. Third, recent success with extending tree-ring chronologies based on living trees using remnant wood (*e.g.*, Grissino-Mayer 1995, 1996) suggested that millennial-length tree-ring chronologies were possible from these locations. We believed that similar environments could exist at these locations where abundant remnant wood could be found to extend the information obtained from the living trees.

The network of archeological pinyon chronologies was ideally situated and provided a wide spatial coverage for southern New Mexico. We realized that the gaps in the network required additional field collections, and we specifically targeted sites in (1) the Magdalena Mountains, (2) the San Mateo Mountains, and (3) the Organ Mountains (Figure 1).

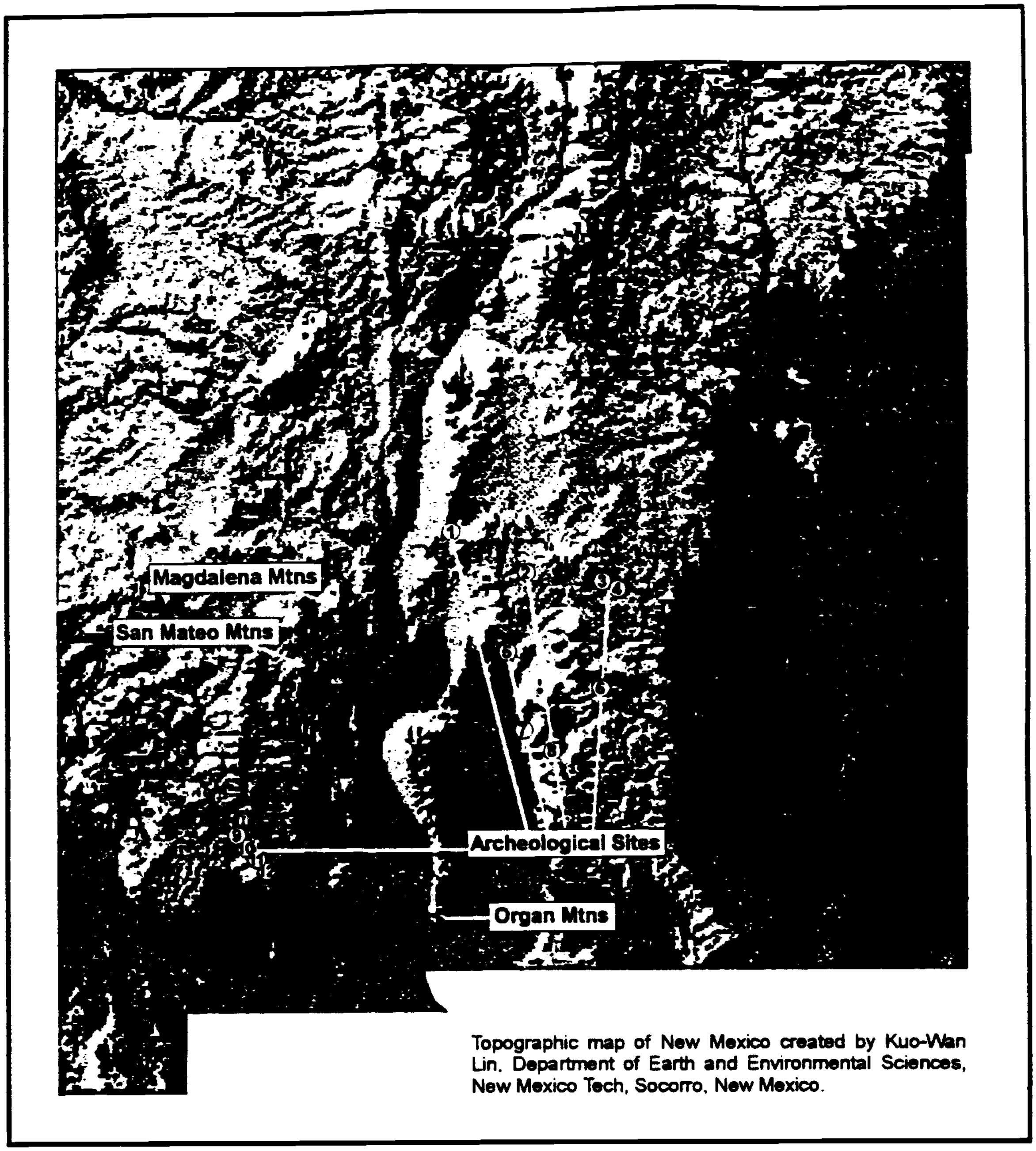

Figure 1. Locations of tree-ring samples collected and/or measured for this study. Samples from living trees were collected from the Organ, San Mateo, and Magdalena Mountains. Archeological pinyon samples came from Tenabo (1), Gran Quivira (2), Armstrong Ruin (3), LA 2945 (4), Taylor Draw (5), Ft. Stanton (6), Three Rivers (7) LA 30949 (8), Harris Village (9), Nan Ranch (10), Galaz Ruin (11), and Mattocks Ruin (12).

The Magdalena Mountains

This mountain range is located west of Socorro, New Mexico, and is administered by the Magdalena District of the USDA Forest Service. Surprisingly, no tree-ring data had been collected from this mountain range despite its ease of access. A well-graded and maintained Forest Service road extends from the base of the range all the way to the summit. Near the summit lies Longmuir Lightning Observatory and several astrophysical complexes, as well as a campground. The Magdalena Mountains rise to nearly 11,000 feet, and exhibit characteristics of being near altitudinal treeline. For example, the mountains are topped by alpine meadows, interspersed with isolated forests of Douglas-fir and limber pine trees growing in several growth forms: the characteristic erect form, windswept (or "flagged") form, and krummholz (short, scrubby, mat-like growth). The latter growth form is unusual in that Douglas-fir normally does not exhibit the krummholz form. Even more surprising were the numerous krummholz mats of pinyon. We found many examples of pinyons growing at elevations above 10,000 feet, a rare habitat for this species (Little 1953; Kearney and Peebles 1960). One specimen collected was approximately 12 inches high, yet contained over 250 annual rings.

We sampled two locations near the summit of the Magdalena Mountains near South Baldy. The South Baldy Ridge (SBR) site is located along a ridge extending at a maximum of one mile to the northwest from the peak of South Baldy along a Forest Service trail (Figure 2). The trail eventually ends at North Baldy approximately 4.5 miles to the north. The ridge is steep-sided on its northern face, and contained numerous Douglas-fir trees that exhibited basic characteristics of being long-lived (Schulman 1937; LaMarche 1982). We sampled over 60 trees at this site over the course of two days. Samples included increment cores as well as numerous cross sections cut from dead and downed samples.

The South Baldy (SBD) site (Figure 3) is located approximately one mile to the northeast of the SBR site, no more than 100 feet west and just off the main Forest Service

Figure 2. The steep slopes of the South Baldy Ridge site in the Magdalena Mountains.

Figure 3. Rocky scree slopes at the South Baldy site in the Magdalena Mountains. The South Baldy Ridge site lies in the background.

road at a sharp bend prior to reaching the locked gate that leads to the observatories. In fact, the trail head to the SBR site is 100 meters to the north. This site is also exceptional in that the Douglas-fir trees growing on the western flank of this small knob are no more than 10 feet in height, yet are perhaps as old as the trees at the SBR site (Figure 2). The SBD site is characterized by a rocky substrate with little soil except on the eastern face. We collected approximately 60 trees from this site as well, both increment cores as well as cross sections from remnant material.

The San Mateo Mountains

This mountain range is located north-northwest of Truth or Consequences, New Mexico, and is administered by the USDA Forest Service, Magdalena District. We sampled at two locations in these mountains. The Vicks Peak (VPK) site is located at the extreme southern end of the mountain range, easily visible from Interstate-25 traveling north. The site is very rugged, composed of loose scree and rock, at a very steep and dangerous angle. We encamped at an abandoned mine at approximately 8,100 feet elevation. We ascended the steep slope to an elevation of 9,800 feet and sampled both living and dead trees along the way. At our highest ascent, we were located on a ridge that extended northwest-to-southeast overlooking the Rio Grande Valley. This ridge contained numerous specimens, mostly of Douglas-fir, that appeared very old. We eventually collected samples from 20 living and dead trees at this site.

The Indian Point (IPT) site is located lower in elevation approximately two miles north of the Vicks Peak site, about one-half mile before the turnoff to a local campground. From the Forest Service road, this site looked promising; the site was steep and rocky, and contained ponderosa pine and Douglas-fir trees with contorted crowns. The ascent to this site was also steep and very dangerous. The Indian Point site consisted of a ridge that trended north-south that ended in a steep cliff, easily seen from the Forest Service road. We sampled 20 living and dead trees from this site; however, dead and downed material was limited at this site, and the living trees did not appear as old as first seen from the road. Most of this forest appeared to be regrowth after a major forest fire within the last 200 years: the old trees observed from the road were obviously survivors of this fire. and were not very numerous.

The two sites sampled in the San Mateo Mountains have one central problem: accessibility. Both are located at the tops of steep. dangerous gradients with loose scree and boulders. The Vicks Peak site should eventually be sampled more thoroughly for tree-ring material; however, we do not recommend the arduous and dangerous route taken during our field trip. Rather. the Vicks Peak site can perhaps be more easily accessed from the north along trails that wind through the Apache Kid Wilderness. Such a sampling effort would require backpacking and overnight camping, and would also require the use of pack animals to help ferry out the heavy cross sections.

The Organ Mountains

The Organ Mountains are central to this project because of their proximity to the project study area. We were fortunate in that tree-ring collections had been made in Fillmore Canyon on the west side of the mountains in 1992 and 1994 (Morino 1996). Another collection was obtained in the fall of 1995 specifically for this project near the Rabbit Ears, a prominent topographic features of the Organ Mountains. This collection consisted mainly of remnant ponderosa pine material which we hoped would extend the living-tree chronology obtained previously from Fillmore Canyon. Both the Fillmore Canyon and Rabbit Ears data sets considerably extended the original chronology for the Organ Mountains collected in 1965, which then only dated back to the 1500s. More importantly, the Rabbit Ears collection increased considerably the sample depth prior to AD 1500, where the Fillmore Canyon collection was particularly weak. Because of their close proximity, we combined both the Fillmore Canyon and Rabbit Ears sites from the Organ Mountains into one chronology.

FIELD METHODS

Field sampling used standard and well-established guidelines for collecting tree-ring material suitable for crossdating and climate reconstruction purposes (Stoke and Smiley 1968; Fritts 1976; Swetnam *et al.* 1985; Schweingruber *et al.* 1990). Each site was preliminarily surveyed to identify appropriate locations where exceptionally old living trees and remnant sections of wood were located that would likely contain tree-ring patterns that were "sensitive" to one primary limiting environmental factor, such as rainfall (Fritts 1971, 1976). Site information (geological descriptions, location, vegetation associations, and disturbance history, if any was apparent) was recorded on a standard form. At least two increment cores were extracted from the opposite sides of selected individual living trees to minimize the effects of reaction wood caused by trees growing on a slope (Shroder 1980; Butler 1987). Cross sections were cut from logs and samples of remnant wood with both a chain saw and bow saw (during periods when chain saw use was restricted). Increment cores were placed in paper straws for increased stability and safety during transport, while cross sections were wrapped in plastic wrap to prevent breakage and to facilitate reassembly back in the laboratory. All relevant information (microsite conditions, location, diameter at breast height, crown condition, lean degree, lean direction) about each sample was recorded on a standard specimen form. Photographs were taken of selected individual samples to document our collections.

LABORATORY METHODS

Chronology Development

In the laboratory, all surfaces were sanded beginning with a coarse grit size (40 grit) to plane the surface flat, then progressively finer sandpaper was used until eventually a

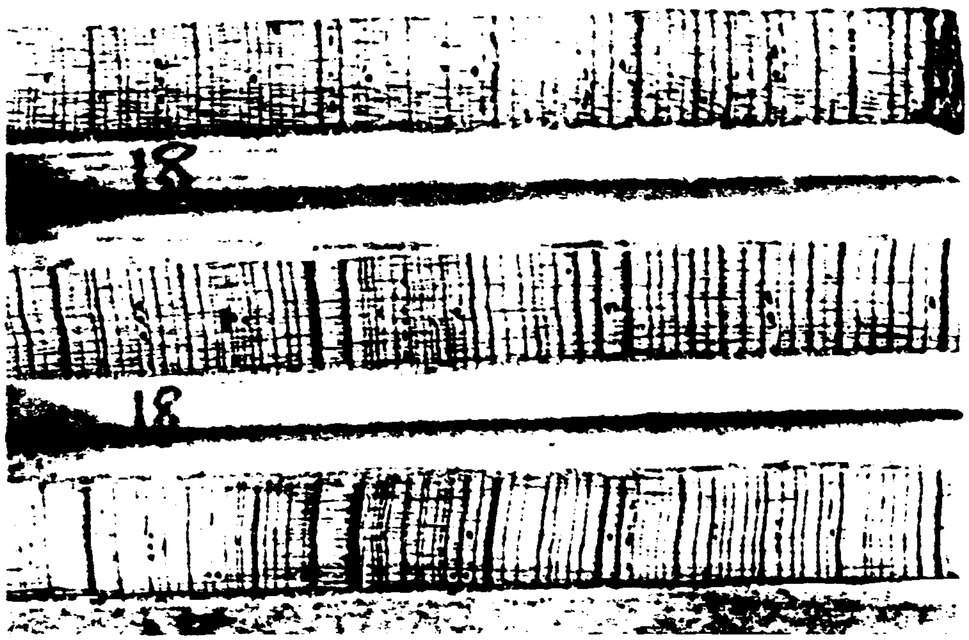

Figure 4. The ring structure of Douglas-fir trees collected in New Mexico. The ring-width patterns are highly variable from one year to the next, indicating trees sensitive to environmental fluctuations.

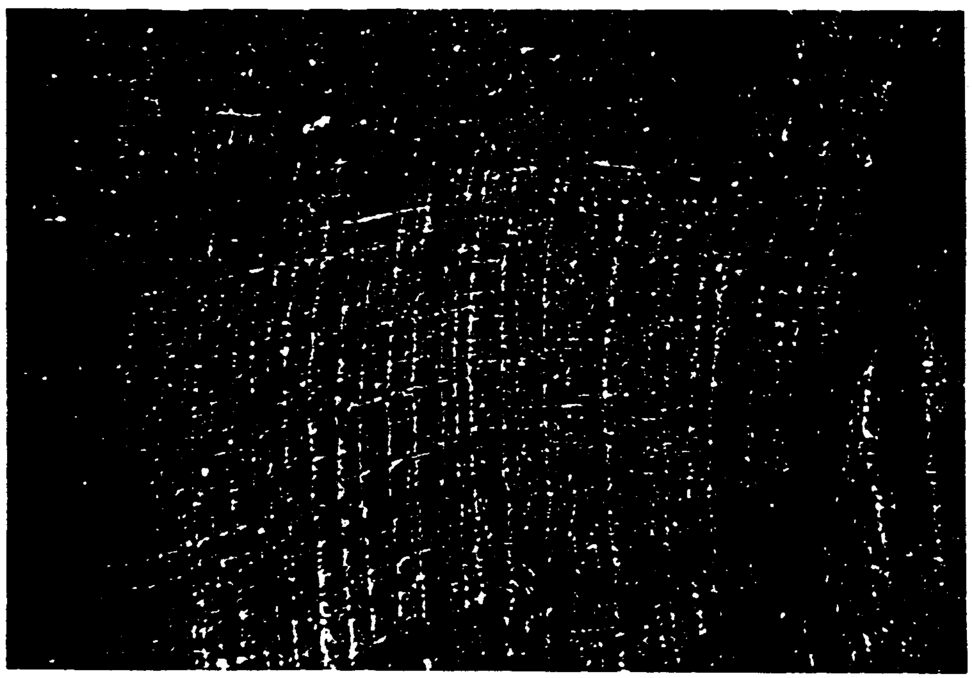

Figure 5. Tree rings on an archeological pinyon charcoal specimen, surfaced with a razor. Growth is from right to left.

400 grit was used. This process is usually sufficient for revealing the cellular structure of wood under low magnification (Figure 4). Surfaces on the archeological pinyon charcoal samples were prepared by either (1) using a razor to cut a fine surface, or (2) breaking the sample to reveal a fresh surface (Figure 5) (Stokes and Smiley 1968). Each cross-section and increment core was then crossdated (Figure 6) by creating skeleton plots for each sample, matching these against local master plots (Figure 7), and assigning each tree ring its exact year of formation (Stokes and Smiley 1968). Once all samples were crossdated, all dated rings were measured to the nearest 0.01 mm (Figures 8 and 9) (Robinson and Evans 1980). During measurement, real-time checks of measurement accuracy were performed using program VERIFY5 to ensure measurement errors were kept to a minimum (Grissino-Mayer 1997).

We then used the quality control program COFECHA to ensure the accuracy of measurements and crossdating (Holmes 1983). COFECHA performed statistical checks on crossdating by taking overlapping and successive 50-year segments of a particular measurement series and correlated these segments with a master chronology developed from the remaining series. Any segments flagged by COFECHA were inspected to determine the source of the error. If crossdating could not be ensured with 100% accuracy, or if a segment was flagged because of anomalous growth patterns, the series was excluded from further analyses. Finally, we used program CRONOL (Holmes 1992) to remove growth trends due to normal physiological aging processes not related to climate. The standardization routines in CRONOL are identical to those found in program ARSTAN, a program developed specifically to provide maximum capabilities for standardization of tree-ring time series (Cook 1985, 1987). Finally, an index of tree growth for any year was obtained by dividing the actual ring width by that predicted from the regression equation that modeled tree growth as a function of age (Graybill 1982; Fritts 1976).

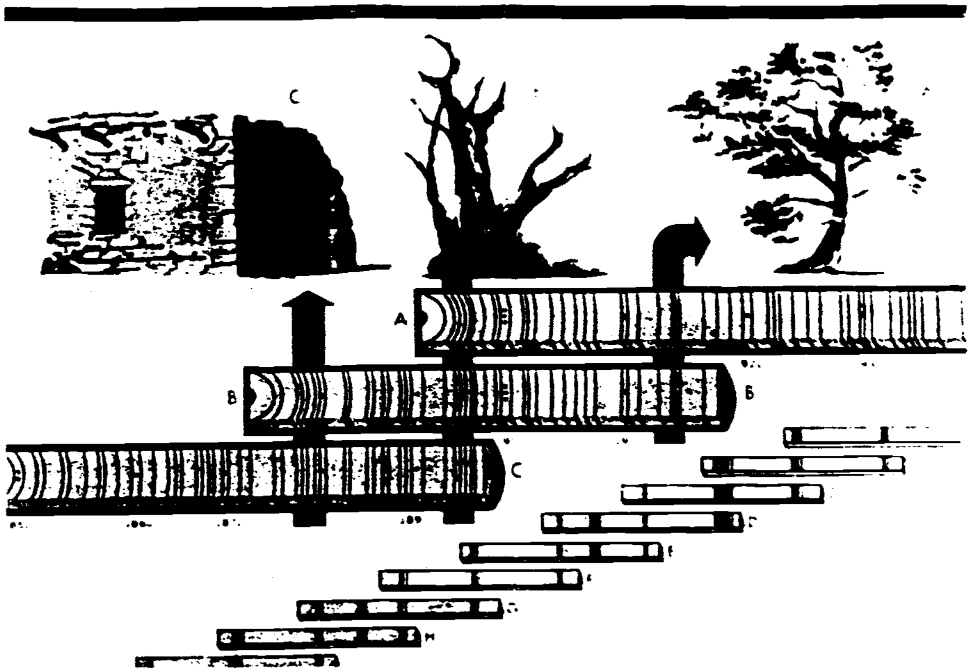

Figure 6. Crossdating allows the extension of tree-ring chronologies further back in time by matching tree-ring patterns on outer portions of samples with patterns on inner portions of younger samples.

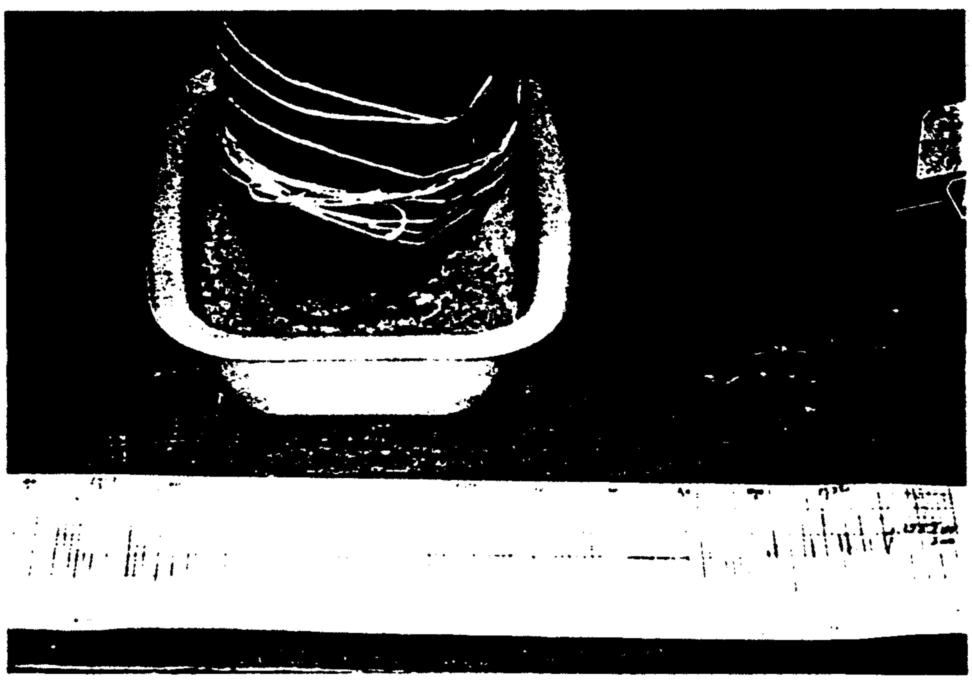

Figure 7. Crossdating between two or more samples is first conducted visually using skeleton plots. The plot for the sample being dated (upper graph) is slid over the plot for the master chronology (bottom graph) until a match is found.

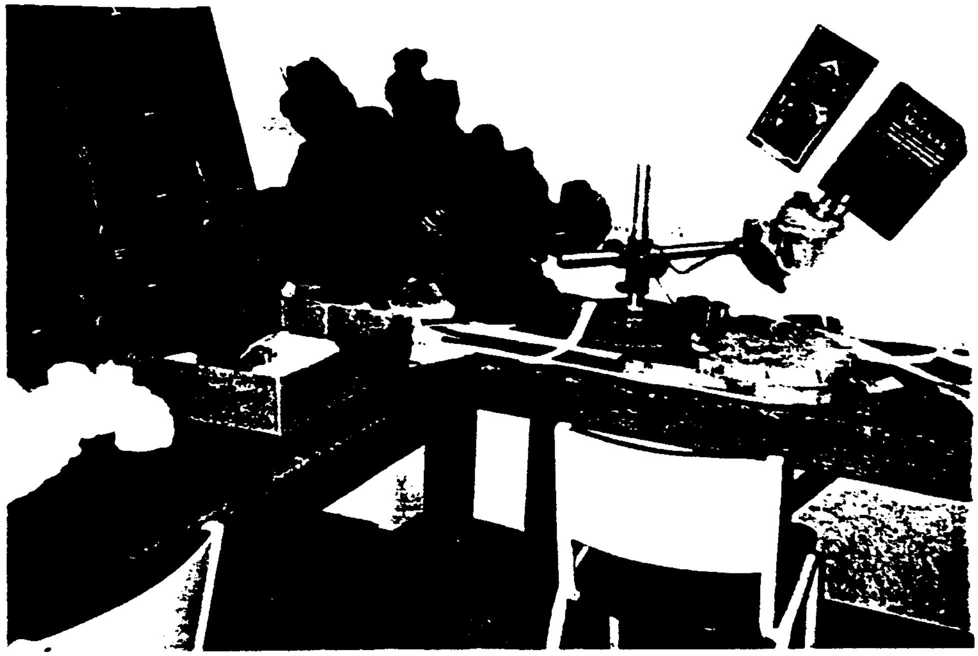

Figure 8. The crossdating station used to prepare all tree-ring samples for measurement. Bundles of cotton to the left hold archeological pinyon tree-ring samples.

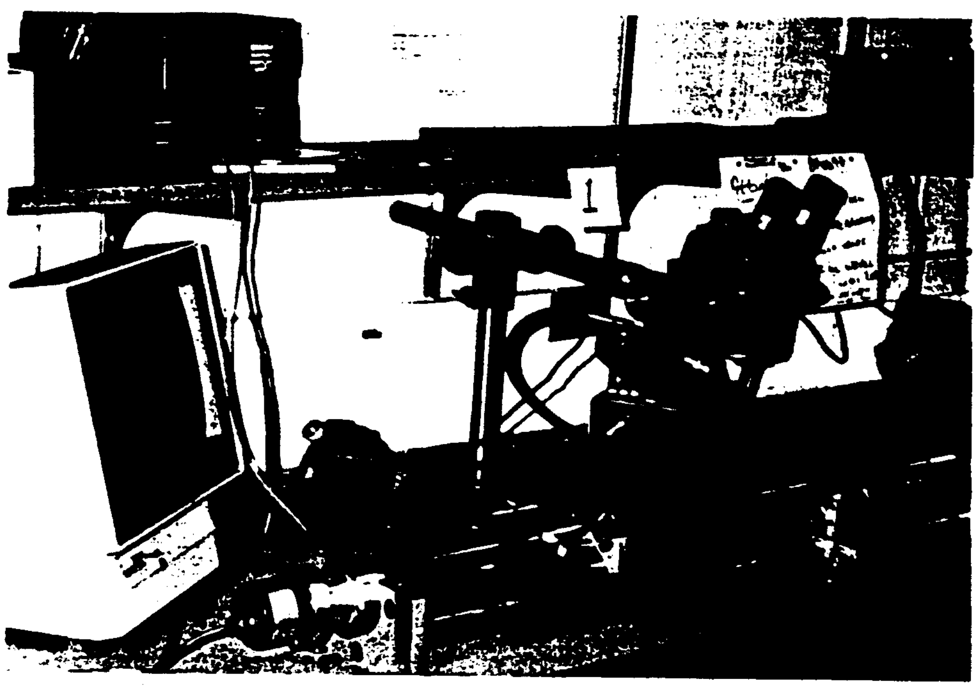

Figure 9 Measurement of tree-ring samples is conducted on a moving stage micrometer (foreground) under a microscope. The micrometer is hooked to a rotary encoder (on left end of measuring stage), a digital display (upper left), and eventually to a personal computer

Selecting Sites to Include in the Final Analyses

Despite the large number of tree-ring sites synthesized for this project in the southern New Mexico network, not all be used in the final reconstruction of climate. for several reasons. First, tree-ring data from some sites will have a poorer relationship with climate than data from other sites. Tree-ring data within a region are often collected from sites with varying topography, disturbance history, and elevation, creating data sets with different responses to climate that are dependent on these factors. Second. most chronologies developed prior to 1990 are short by comparison to more recently collected tree-ring chronologies. The reconstruction of long-term, century-scale climate trends was not the primary purpose of these earlier collections, and therefore these data sets would not retain the longer-term trends we required for this study. Third, we could not simply combine all living-tree chronologies into one master chronology because they did not have counterpart archeological chronologies or tree-ring data that extended prior to AD 1600. Hence, the climate reconstruction prior to AD 1600 could not have been interpreted in the same way as the post-1600 reconstruction, simply because the chronologies for each part would have been composed of different, discontinuous data.

We therefore decided to develop criteria that allowed a reduction of the number of data sets kept for further analyses. First, all chronologies synthesized for this study were correlated against each other to isolate those chronologies with poor agreements with the majority of other regional chronologies. Any chronology with poor correlations with the other data sets was excluded from further analyses. Second, because the purpose of this study was to develop a millennium-length reconstruction of precipitation, the length of the chronology was a primary consideration for retaining a chronology in the final analyses. All chronologies deemed too short to be useful for this project were excluded from further analysis. Third, we assessed the relationship between climate and tree growth on a site-by-site basis to select those sites where the climate/tree growth relationship was strongest. Sites that demonstrated weak relationships with climate were excluded from further analyses. Finally, we wished to isolate a suitable tree-ring chronology that could extend the archeological pinyon chronology out to the present to ensure calibration with historical climate was possible. Ideally, this living tree extension chronology would also be composed of pinyon, but any species would be suitable as long as statistical parameters (variance, skewness, and kurtosis) were similar between the two data sets.

Analyzing the Climate/Tree Growth Relationship

The climate-tree growth relationship was investigated using PRECONK (Fritts *et al.* 1991; Fritts and Shashkin 1995) and the SAS statistical package (Schlotzhauer and Littell 1987) to isolate those months in which temperature and precipitation had significant effects upon tree growth. The analyses included both response function and correlation analyses between the tree-ring index chronology and monthly climate values (Fritts 1976; Grissino-Mayer and Butler 1993). Response function analysis is commonly used in dendroclimatic studies to remove the correlation that exists among the independent monthly climate variables used to determine which variables significantly affect tree growth (Fritts *et al.* 1971; Fritts 1976). While response function analysis is considered more robust, results from correlation analyses are considered simpler to interpret, and can be used to provide a preliminary assessment of the strength of the climate/tree growth relationship.

Climate variables analyzed included total monthly precipitation, average monthly temperature, and the average monthly Palmer Drought Severity Index (PDSI). The PDSI is a measure of meteorological drought which incorporates precipitation, temperature, soil conditions, and global geographic location (Palmer 1965), and often demonstrates higher monthly correlations with tree growth than either rainfall or temperature (Grissino-Mayer 1988; Buckley 1989; Stockton 1990; Cleaveland and Duvick 1992). Because trees often allocate carbon and food reserves for use during the following year's growing season (Fritts 1966, 1971, 1976), all analyses included monthly values lagged by one year to investigate the effects of previous year's climate upon current year's tree growth. Because trees respond to climate over a period often extending to the previous growing season, various seasonal variables were constructed for correlation analyses by averaging or grouping monthly values (Grissino-Mayer and Butler 1993; Grissino-Mayer 1995).

Developing the Climate Reconstruction

We chose the climate variable, monthly or seasonal, with the most significant response function weights and correlation coefficients for reconstruction when compared with the site chronologies retained. Calibration equations were developed that predicted annual values for the selected climate variable from the tree-ring index chronologies on half-sample subsets (*i.e.*, a calibration period and a separate verification period) of the full period using ordinary least squares analysis. Statistical outliers that adversely affected the calibration (*i.e.*, reduced the model sum of squares and the resulting *F*-value) were identified using studentized residuals and Cook's *d* values (Schlotzhauer and Littell 1987). The model was then re-specified with the outlier removed and re-inspected for additional outliers in the new model. Each model was verified by comparing the actual values for the verification period against the values predicted from the calibration equation. Verification tests included correlation analyses, reduction of error tests, the product means test, and the sign-products test (Fritts *et al.* 1990; Fritts 1991). If the comparison proved the calibration equation was a robust estimator of climate, the calibration equation was verified as the climate/tree growth relationship was considered strong throughout the historical period. We then used the entire period to develop a new transfer function equation to reconstruct the selected precipitation variable for the entire length of the tree-ring chronology (Briffa *et al.* 1990; Grissino-Mayer 1995).

Analyzing Trends in Past Rainfall

A major goal of this research was to analyze both short-term, decadal trends as well as long-term, century scale trends in past climate. To partition decadal and century-length climate episodes from the original reconstruction, we fit both 10-year and 100-year smoothing splines (Cook and Peters 1981) through the reconstructed precipitation series. To standardize and quantify the magnitude of past climatic fluctuations. we converted all yearly reconstructed rainfall totals to standard deviation units (z-scores) by subtracting the series mean and dividing by the standard deviation of the overall series (Schlotzhauer and Littell 1987; Barber 1988). In this study, a significant departure from mean climate was determined by noting years when reconstructed climate was predominantly below (drought) or above (wet period) the ±1.1 standard deviation (sd) levels. These levels delimit the 25% most extreme climate episodes (12.5% above and 12.5% below the mean) considered potentially significant to the physical environment and to native populations (Dean 1988; Grissino-Mayer 1995).

To identify a specific short-term (decadal) or long-term period when climate deviated significantly from the average, we first isolated those drought or wet periods that had at least five consecutive years when the standard deviation levels from the 10-year spline fell below the -1.1 sd level (for dry years) or above the +1.1 sd level (for wet years). The beginning and ending year for each period was determined by noting the first or last year when the reconstructed climate variable fell below the -0.5 sd level (for dry years) or above the +0.5 sd level (for wet years). Because effects of climate can be exacerbated by the length of the drought or wet period, each period was also weighted by its duration, using a modification of the formulae used by Grissino-Mayer (1995). To rank the most severe dry periods, an index was calculated by first standardizing (mean subtracted, then divided by the standard deviation) both the average precipitation per year and the duration for each period. The absolute value of the lowest (negative) standard value in either data set was then added to all values to ensure only positive indices. The index for ppt/yr was then combined with the index for duration to derive the index, *i.e.*, the magnitude of the drought was "penalized" if the drought was of short duration. Rankings for the wettest periods were calculated similarly, *i.e.*, the magnitude of the wet period was "rewarded" the longer the period.

Previous studies have shown that changes in the variability of climate are strong indicators of long-term climate change, and may be as important as changes in mean climate

(Katz and Brown 1992). Furthermore. changes in climate variability have been used to explain certain behavioral responses by the Anasazi. High temporal variability likely produced differences in resource availability that caused interactions among groups within the Four Corners area (Plog *et al.* 1988) and favored long-term food storage to prevent starvation during frequent and intense drought periods (Dean *et al.* 1994). Low temporal variability meant stable climatic conditions and perhaps less interaction among groups. We analyzed changes in variance of reconstructed precipitation by computing the running variance for overlapping 25 year periods (Grissino-Mayer 1995). We then compared these changes in variability with changes in long-term climate as determined by the 100-year spline fit through the reconstructed precipitation series.

RESULTS

Tree-Ring Chronologies Chosen for this Study

Our data synthesis revealed that numerous tree-ring chronologies had been developed for the southern portion of the Southwest and northern Mexico in recent years (Table 1). However, none of these living tree chronologies was considered useful to this project primarily because (1) these chronologies were too short, often only extending back to *ca.* AD 1600, and (2) most chronologies ended in the mid-1960s to early 1970s, and therefore lacked critical years during recent decades needed for high-quality calibrations with climate data. The earliest dates on these data sets likely reflect the pulse of re-establishment that occurred following a severe and prolonged drought known to have impacted the majority of the Southwest around *ca.* AD 1580-1600 (Swetnam and Brown 1992). These data sets nonetheless proved valuable by providing the necessary dating control for establishing the crossdating of samples collected specifically for this project, including latter portions of the archeological pinyon samples. Skeleton plots from these data sets were generated and often used to date the more troublesome samples when visual crossdating was uncertain.

Table 1. Previous tree-ring chronologies developed in southern New Mexico and northern Mexico screened for use in this study. The lengths of these chronologies were considered too short to be useful for this project, although these chronologies helped by establishing the dating patterns used to crossdate the samples collected specifically for this study, especially since AD 1500.

Site Name	**Latitude**	**Longitude**	**Length**
Organ Mountains, NM	32°21'	106°33'	1597 - 1971
Wofford Lookout, NM	32°59'	105°42'	1663 - 1965
Cloudcroft Low, NM	32°57'	105°49'	1670 - 1965
Cloudcroft High, NM	32°57'	105°40'	1515 - 1960
Silver Springs Canyon, NM	33°00'	105°40'	1542 - 1965
Mimbres Junction, NM	32°56'	108°01'	1655 - 1982
Oscura Peak, NM	33°33'	106°40'	1644 - 1981
Salinas Peak, NM	33°15'	106°45'	1687 - 1990
Spring Canyon, NM	32°43'	106°22'	1751 - 1990
Elk Canyon, NM	33°03'	106°32'	1799 - 1990
Hoosier Canyon, NM	32°42'	106°21'	1659 - 1990
Black Mountain, NM	33°23'	108°14'	1470 - 1987
McDonald Observatory, TX	30°41'	104°01'	1748 - 1965
Sierra del Nido, Mexico	29°31'	106°49'	1569 - 1970
Sierra del Madre, Mexico	30°20'	108°30'	1636 - 1965
Rancho Escondido "A", Mexico	30°10'	108°15'	1720 - 1965
Rancho Escondido "B", Mexico	30°08'	108°15'	1630 - 1965

We had greater success in establishing long chronologies from the field collections made specifically for this project, however. The crossdated increment cores from the South Baldy site in the Magdalena Mountains confirmed that the Douglas-fir trees here are exceptionally old, some of the oldest living trees yet discovered in the American Southwest. One sample, SBR026, is a living Douglas-fir tree with an inside ring of AD 1151, making this the third oldest Douglas-fir ever found in New Mexico, and the oldest found outside El Malpais National Monument (Grissino-Mayer 1995). Numerous living

Douglas-fir trees and one southwestern white pine were located that extended back into the 1200-1300s. The tree-ring chronology from these living trees was successfully extended well prior to AD 1000 using remnant wood samples found lying in and around the steep talus slopes that characterize the Magdalena Mountains. Subfossil wood samples from South Baldy and nearby Timber Peak yielded eight trees that predated AD 1000, the oldest being an exceptional Douglas-fir log with an inside ring date of AD 622.

We also had success breaking the AD 1000 boundary with samples collected from the San Mateo Mountains. However, the limited number of samples collected meant fewer older tree-ring dates. Several trees extended back to the AD 1300-1400s, while the tree rings from one Douglas-fir remnant, VPK014, extended back to AD 910. We consider the San Mateo Mountains one of the most promising tree-ring sites in the American Southwest, largely because the mountain range is spatially extensive and is characterized by steep talus slopes and rock glaciers (Blagbrough 1986) that provide ideal environments for harboring long-lived trees and remnant subfossil wood. For the purpose of this study, the samples collected from the San Mateo Mountains were combined with those from the Magdalena Mountains because tree-ring patterns from both ranges were basically similar due to their close proximity. This also helped strengthen the sample depth prior to AD 1200. The combined Magdalena/San Mateo Mountains chronology forms one of two primary, millennial-length tree-ring chronologies used in this study to reconstruct past precipitation (Figure 10).

The Organ Mountains collections at the Rabbit Ears and Fillmore Canyon sites yielded numerous samples that extended well prior to AD 1500, with the oldest ponderosa pine sample dating back to AD 1306. The collection of tree-ring samples from the Organ Mountains made in the mid-1960s extended back only to AD 1597 – we therefore extended the tree-ring chronology from this area by nearly 300 years. More importantly, the Rabbit Ears collection considerably increased the sample depth prior to AD 1500, a period when the Fillmore Canyon collection had few samples. For this study, we combined these two sites into one collection because of their close proximity and similar tree-ring patterns. We consider the Organ Mountains, like the Magdalena and San Mateo Mountains,

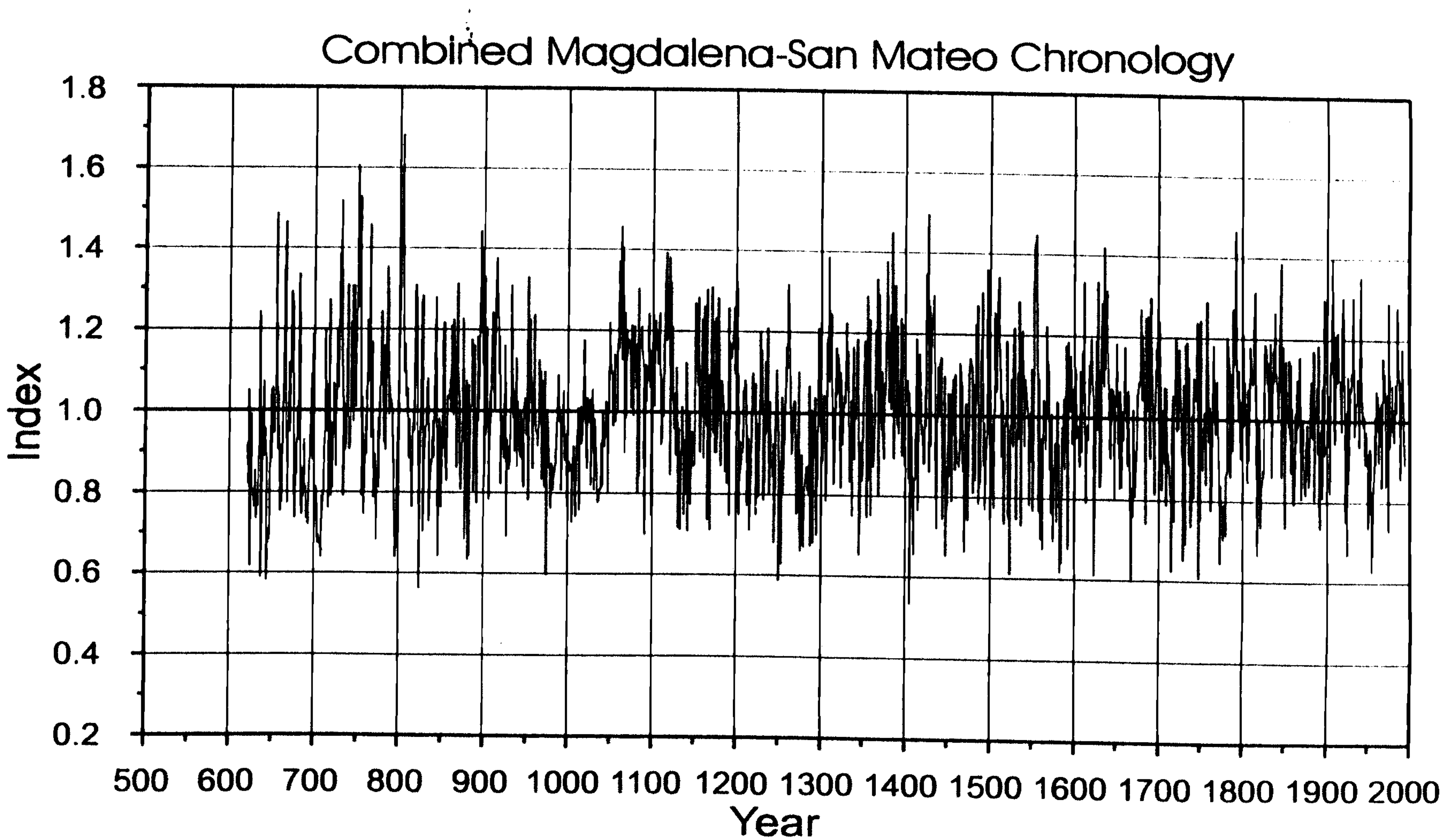

Figure 10. The final tree-ring chronology for the combined data from both the Magdalena and nearby San Mateo Mountains in south-central New Mexico. Variance tends to increase prior to AD 800 due to decreasing sample size.

an important site for future tree-ring collections because the site is likely to contain remnant ponderosa pine samples that extend prior to AD 1000. Additional collections should help date the few samples from the Rabbit Ears site that remain undated, samples that are perhaps older than any samples yet collected from the Organ Mountains.

Table 2 lists archeological sites in southern New Mexico where tree-ring material had been collected and deposited in the archives of the Laboratory of Tree-Ring Research. Most of these data sets contained at least one dated sample, while some sites, such as the Galaz Ruin and Mattocks Ruin sites, contained 50-100 or more dated samples. Occasionally, the dated tree-ring samples extended well prior to AD 1000. Few samples from any of these sites had ever been measured, however. We first screened these sites based on (1) the number of samples collected, (2) the age of the oldest samples at each site, (3) the internal (*i.e.*, within-site) continuity of the tree-ring record at each site, (4) the continuity of the site with tree-ring samples from nearby sites, and (5) whether the location of the site was suitable to fill in gaps in the network of tree-ring sites for the study area. Based on these criteria, we identified 12 sites (denoted by asterisks in Table 2) with suitable tree-ring data. At a few sites (*e.g.*, Nan Ranch, Mattocks Ruin, and Galaz Ruin), the number of dated samples exceeded the amount we considered adequate to obtain a strong climate signal. We therefore further screened the samples at these sites by choosing only those samples with the longest tree-ring record, in the hope these would retain some longer-term decadal climate trends as opposed to the shorter (*e.g.*, 30-35 years) samples. In general, any archeological tree-ring sample greater than 50 years length was considered suitable for inclusion to the final chronology. The 244 charcoal samples selected to be measured for this project yielded a continuous archeological pinyon tree-ring chronology from AD 1607 back to AD 532, the longest archeological tree-ring chronology yet developed for southern New Mexico.

Next, we used cross-correlations between various tree-ring chronologies throughout the Southwest to help determine which possible data sets to include in the final analyses (Table 3). The two long Douglas-fir and southwestern white pine tree-ring chronologies

Table 2. Summary of archeological sites located in southern New Mexico screened for use in this project (data from Robinson and Cameron 1991). Asterisks indicate sites used in this project. Published inside dates (Bannister *et al.* 1970) are given in parentheses. Most sites contained very few dated samples, and were not considered useful for our study. The SU Site contained the oldest dated samples, but was not continuous with the next oldest dated site, Harris Village.

Site Name	UTM Easting	UTM Northing	(Inner) Outer Dates
Gran Quivira, NM (*)	399480	3791290	1607
Tenabo, NM (*)	369200	3808100	1466
Huning Ruin, NM	317000	3852000	1183
Armstrong Ruin, NM (*)	461220	3776230	1366
LA 2945, NM (*)	457840	3777490	1268
Mogollon Village, NM	692720	3700460	(645) 898
Gila Cliff Dwellings, NM	754670	3679600	(1157) 1287
Bat Cave, NM	758400	3740430	(577) 821
Duck Creek Ruin, NM	705000	705000	(1155) 1243
SU Site, NM	698400	3730420	(295) 497
Twin Bridges Site, NM	697000	3727000	(629) 783
Turkey Foot Site, NM	696000	3725000	(664) 788
Wheatley LA 4424, NM	705240	3735820	(683) 899
Starkweather Ruin, NM	704000	3734250	(598) 769
LA 2948, NM	718250	3745080	(443) 517
Harris Village, NM (*)	221550	3639350	(531) 877
Higgins Flat, NM	707640	3737430	1281
WS Ranch LA 3099, NM	694390	3697610	1267
LA 5936, NM	716240	3756580	420
Three Rivers, NM (*)	401600	3687723	1347

Table 2. (Continued).

Site Name	UTM Easting	UTM Northing	(Inner) Outer Dates
Taylor Draw, NM (*)	390790	3741220	979
Ft. Stanton Ruin, NM (*)	452000	3705000	1363
LA 30949, NM (*)	423444	3669548	875
Ormand Village, NM	723460	3647780	1342
Kwilleylekia, NM	727000	3652620	1380
NM Y:4:35 (ASM), NM	778600	3639800	996
LA 5421, NM	724075	3650550	1126
Defausell Site, NM	726200	3649460	1108
Mattocks Ruin, NM (*)	222500	3637700	1117
Galaz Ruin, NM (*)	226675	3632575	893
Mitchell LA 12076, NM	219600	3643800	1065
NM Z:5:17 (ASM), NM	230000	3625000	1104
NM Z:5:85 (ASM), NM	233000	3614900	1099
NM Y:4:5, NM	779600	3650700	1098
NM Z:5:20, NM	779600	3650700	1063
Jans's Site, NM	220100	3642800	1381
Wheaton-Smith, NM	230375	3629900	964
Berrenda Creek, NM	249098	3629471	1105
Nan Ranch, NM (*)	233675	3616875	1128
Martin Site, NM	224050	3637175	1043
Nan 15 LA 73824, NM	240950	3621330	1116

Table 3. Correlation coefficients (r-values) among sites in the core study area, p > r-value, and number of observations used to calculate the r-value. NA indicates insufficient or no overlap occurred between the two data sets being tested.

	Malpais	Magdalena /San Mateo	Sevilleta	Organ Mtns.	Sacramento Mtns.	Salinas Pk.	Oscura Pk.	Animas Mtns.	Black Mt.	Graham Doug-fir	Graham white pine	Manzano Mtns.	Sierra Blanca	Cloudcroft	Bear Trap
Pinyon	.50 .0001 1075	.47 .0001 985	.64 .064 9	.46 .0001 301	.28 .047 65	NA	NA	.29 .0007 134	.50 .0001 411	.21 .0001 503	.26 .0001 731	.24 .059 63	-0.03 .8194 53	.13 .209 92	NA
Malpais		.53 .0001 1371	.54 .0001 394	.46 .0001 687	.41 .0001 451	.46 .0001 304	.44 .0001 338	.54 .0001 519	.55 .0001 793	.21 .0001 887	.34 .0001 1117	.63 .0001 449	.09 .062 430	.40 .0001 446	.48 .0001 309
Magdalena/ San Mateo			.57 .0001 394	.60 .0001 689	.50 .0001 454	.62 .0001 304	.59 .0001 338	.58 .0001 519	.63 .0001 793	.33 .0001 887	.38 .0001 1120	.58 .0001 449	.40 .0001 430	.53 .0001 446	.57 .0001 309
Sevilleta				.49 .0001 394	.49 .0001 394	.60 .0001 304	.59 .0001 338	.49 .0001 394	.54 .0001 391	.34 .0001 393	.24 .0001 394	.60 .0001 394	.23 .0001 386	.46 .0001 363	.56 .0001 309
Organ Mtns					.61 .0001 453	.59 .0001 304	.56 .0001 338	.59 .0001 519	.54 .0001 683	.40 .0001 685	.41 .0001 689	.52 .0001 449	.27 .0001 430	.54 .0001 446	.46 .0001 309
Sacramento Mtns						.59 .0001 304	.62 .0001 338	.47 .0001 450	.55 .0001 447	.35 .0001 449	.33 .0001 454	.50 .0001 449	.13 .006 430	.53 .0001 419	.45 .0001 309
Salinas Pk.							.73 .0001 295	.49 .0001 304	.58 .0001 302	.42 .0001 304	.26 .0001 304	.54 .0001 304	.41 .0001 297	.57 .0001 274	.46 .0001 288
Oscura Pk.								.49 .0001 338	.56 .0001 338	.43 .0001 338	.33 .0001 338	.56 .0001 338	.38 .0001 338	.50 .0001 317	.48 .0001 309

Table 3. (Continued)

	Malpais	Magdalena /San Mateo	Sevilleta	Organ Mtns.	Sacramento Mtns.	Salinas Pk.	Oscura Pk.	Animas Mtns.	Black Mt.	Graham Doug-fir	Graham white pine	Manzano Mtns.	Sierra Blanca	Cloudcroft	Bear Trap
Animas Mtns									.62 .0001 516	.55 .0001 518	.51 .0001 519	.54 .0001 448	.24 .0001 430	.42 .0001 446	.47 .0001 309
Black Mt.										.32 .0001 793	.37 .0001 793	.60 .0001 445	.15 .002 430	.52 .0001 446	.55 .0001 309
Graham Doug-fir											.39 .0001 887	.37 .0001 447	.41 .0001 430	.30 .0001 446	.37 .0001 309
Graham white pine												.40 .0001 449	.13 .006 430	.33 .0001 446	.28 .0001 309
Manzano Mtns													.14 .005 430	.55 .0001 417	.49 .0001 309
Sierra Blanca														.31 .0001 407	.24 .0001 309
Cloudcroft															.50 .0001 295

from the Pinaleño Mountains of southeastern Arizona were considered for inclusion because of their high-quality, sensitive (*i.e.*, variable ring width patterns indicating a probable climate signal) series. However, these chronologies had low correlations with the majority of sites, likely due to their geographic position outside the core study area. A Douglas-fir site in the Sacramento Mountains, Sierra Blanca, had been collected by two European investigators and submitted to the ITRDB. However, this chronology also had poor correlations with nearly all data sets, which may indicate that problems exist with the internal crossdating of series from this location. Some sites had very high correlations with other sites, but lay outside the core study area (*e.g.*, the Animas Mountains and Black Mountain Douglas-fir collections). Still other sites (*e.g.*, Bear Trap, Cloudcroft, Salinas Peak, and Oscura Peak) were again too short to be particularly useful for this project.

Our next step was to isolate a tree-ring data set within the region that eventually could be used to extend the archeological pinyon chronology to the present. Because the outside date for the pinyon chronology was AD 1607, it would otherwise not be possible to calibrate this valuable data set with historical climate. We first sought candidate pinyon data sets from the region, but soon realized that no modern pinyon data sets extended far enough back in time with a sufficient number of samples to overlap with this archeological chronology. We then sought a data set within the region from a different species with perhaps similar statistical properties that would overlap with the archeological pinyon data set. The ponderosa pine tree-ring data set from the Organ Mountains satisfied these criteria – the data set was long enough for sufficient overlap (back to AD 1306), was also a highly sensitive data set (*i.e.*, the ring widths showed considerable year-to-year variation), and the two chronologies eventually developed from these data sets exhibited a statistically significant correlation during the period of overlap ($r = 0.47$, $p < .0001$, $n = 301$).

We were surprised to learn that the Organ Mountains ponderosa pine tree-ring data were *more* variable than the archeological pinyon tree-ring data. Pinyon tree-ring data, especially from lower elevations, are usually highly variable with up to 5% of the rings missing (see Grissino-Mayer *et al.* 1991). Ponderosa pine tree-ring data, usually collected from higher elevations, are usually not as variable as pinyon tree-ring data. However, the Organ Mountains tree-ring sites are extreme in their topographic position (*i.e.*, very steep, with little ground cover to retain runoff), which may have induced a greater sensitivity to rainfall than sites at lower elevations. We eventually stabilized the variance of the Organ Mountains tree-ring chronology to simulate that from the archeological pinyon. Variance stabilization is a common statistical technique (Draper and Smith 1981) that facilitates the combining or comparing of two time series with heterogeneous or temporally unstable statistical properties (see, *e.g.*, Cook *et al.* 1988 and Grissino-Mayer *et al.* 1989). Once stabilized, the two data sets showed consistent synchroneity during the overlapping period (*i.e.*, AD 1306-1550) (Figure 11). The stabilization of variance was the only transformation necessary. The final result yielded a continuous tree-ring chronology from AD 532-1995 (Figure 12).

In summary, a total of 18 sites (the Timber Peak and South Baldy sites in the Magdalenas, the Vicks Peak and Indian Point sites in the San Mateos, the Fillmore Canyon and Rabbit Ears sites in the Organs, and the 12 archeological pinyon sites) comprise the two primary data sets, and provided the necessary spatial coverage in the southern-central New Mexico area required for this project. We developed additional data sets that we thought could eventually be used for this project (*e.g.*, pinyon and southwestern white pine data sets from the Sacramento Mountains) which required the crossdating and measurement of several thousand additional tree rings from several hundred more samples. However, we excluded these data sets from this analysis because (1) the data sets were much shorter than the two primary data sets and therefore may have concealed any long-term trends, and (2) correlations with nearby data sets showed weaker relationships. We succeeded, however, in building many new tree-ring chronologies for the Southwest, thus creating a much denser network of sites that extend at least back to AD 1500 (and earlier) which future researchers may find useful for evaluating past climate.

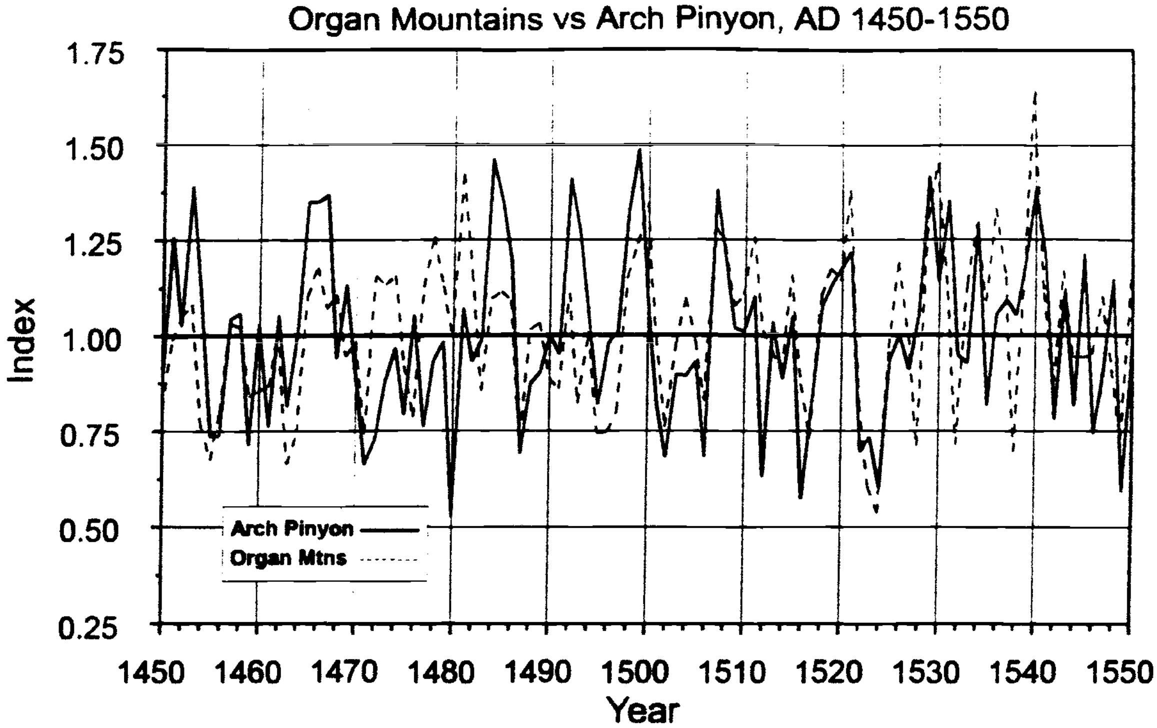

Figure 11. The period AD 1450-1550 for the Organ Mountains living tree ponderosa pine chronology and the archeological pinyon chronology, demonstrating acceptable synchroneity ($r = .47$, $p < .0001$, $n = 301$ total) to justify combining the two chronologies into one.

Quality Control of the Primary Data Sets

A total of 279 tree-ring samples were crossdated and measured from the combined Magdalena/San Mateo Mountains data sets, representing 87,419 measured rings. Results from the quality control checks on crossdating and measurement accuracy performed by the computer program COFECHA revealed that only eleven 50-year segments of 3,430 segments tested (0.32%) were flagged as being potential problem segments. Reinspection of these segments revealed anomalous ring patterns perhaps due to local disturbances affecting individual trees. However, these segments contribute only a minute amount of noise that was all but canceled by the large number of samples throughout the

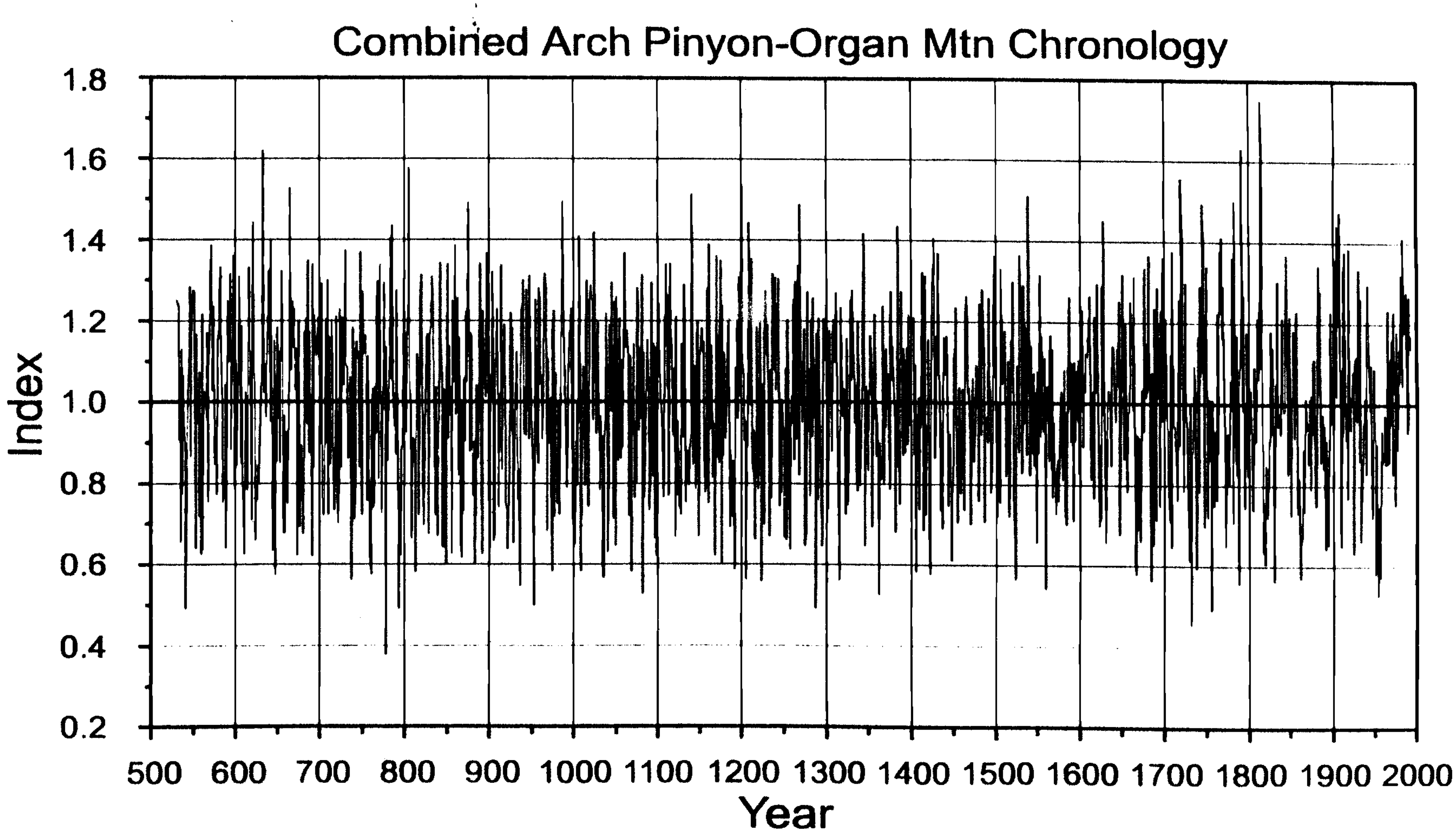

Figure 12. The final tree-ring chronology for the combined tree-ring data from the Organ Mountains and the archeological pinyon data from south-central New Mexico.

particular flagged segment. It was deemed necessary to include these segments to prevent splitting one measurement series into two, which could have reduced the probability of examining long-term trends. The mean interseries correlation (which measures the strength of the signal in common among all samples) was high by Southwestern standards at 0.75, while the average mean sensitivity (a standard measure of variability in tree-ring series) was 0.41, an unusually high value considering the elevation of the trees sampled at these two mountain ranges (between 8,500-9,250 feet in the San Mateo Mountains, and between 9,500-10,000 feet in the Magdalena Mountains).

In the archeological pinyon data set, 244 tree-ring samples from the 12 sites, representing 18,811 individual tree rings, were measured. Only thirteen 30-year segments of a total 905 segments tested for accuracy (1.44%) were flagged as being potentially errant. Again, re-inspection of the charcoal samples confirmed that no crossdating errors were evident, and that the flagged segments arose because of anomalous ring patterns, perhaps due to local disturbance factors. The mean interseries correlation was again high at 0.72, while the average mean sensitivity was very high at 0.54. This latter value far exceeds the average mean sensitivity reported for 25 archeological data sets in northwestern New Mexico (Dean and Robinson 1978), including the data set developed for El Malpais National Monument (Grissino-Mayer 1995).

A total of 64 samples from the Fillmore Canyon and Rabbit Ears sites comprise the Organ Mountains ponderosa pine chronology, representing 13,874 measured tree rings. Of 549 50-year segments tested for crossdating and measurement accuracy, only one was flagged as being a potential problem segment (0.18%). The average interseries correlation was again high at 0.78, while the average mean sensitivity was extremely high at 0.58, one of the highest mean sensitivity values yet attained for any Southwestern tree-ring data set. In summary, the development of the two primary data sets for this project required the measurement of 120,104 tree rings from 587 samples representing the four primary tree species found throughout the core study area (Colorado pinyon, ponderosa pine, Douglas-fir, and southwestern white pine).

Generating the Final Tree-Ring Chronology

Once the individual series had been standardized and combined using a mean-value function to form a standard tree-ring chronology, the final step in generating the final tree-ring data set to be used in the regional reconstruction was to combine these two primary data sets into one in such a manner that would retain the short-term and long-term trends. For this process, we used principal components analysis (PCA) available in SAS (SAS 1985) to concentrate the common variance from these two data sets into one data set (known as an *eigenvector*). The results showed that 76% of the variance in both data sets could be captured in the first eigenvector. The scores from this data set (mean of zero and standard deviation of 1.0) were then output to a separate file and represented the final (transformed) tree-ring data set used in all further analyses. Because PCA can only be conducted over the common period represented by the data sets, this final tree-ring chronology extends back to AD 622 rather than AD 532. The number of samples that comprised this final data set was exceptionally high with a maximum of 190 samples in the late 1700s (Figure 13). The data set contained at least 100 samples from AD 1400 to the present, while the data set had a maximum of 60 samples prior to AD 1000 (*ca.* AD 815).

In summary, we eventually generated for this project two tree-ring data sets each greater than 1,300 years in length with which to eventually reconstruct past climate. The first primary data set is the combined Magdalena/San Mateo Mountains tree-ring chronology that extends back to AD 622. Both Douglas-fir and southwestern white pine were included in this data set. The second primary data set contains the combined archeological pinyon/Organ Mountains ponderosa pine tree-ring data that extend back to AD 532. As shown in Figure 1, these two data sets actually represent data throughout the core study area in the central and southern portions of New Mexico in very close proximity to Fort Bliss, White Sands Missile Range, and Holloman Air Force Base. Although we collected and synthesized numerous tree-ring sites for this project, the two primary data sets stood out as being the highest quality and longest tree-ring data sets that would satisfy the

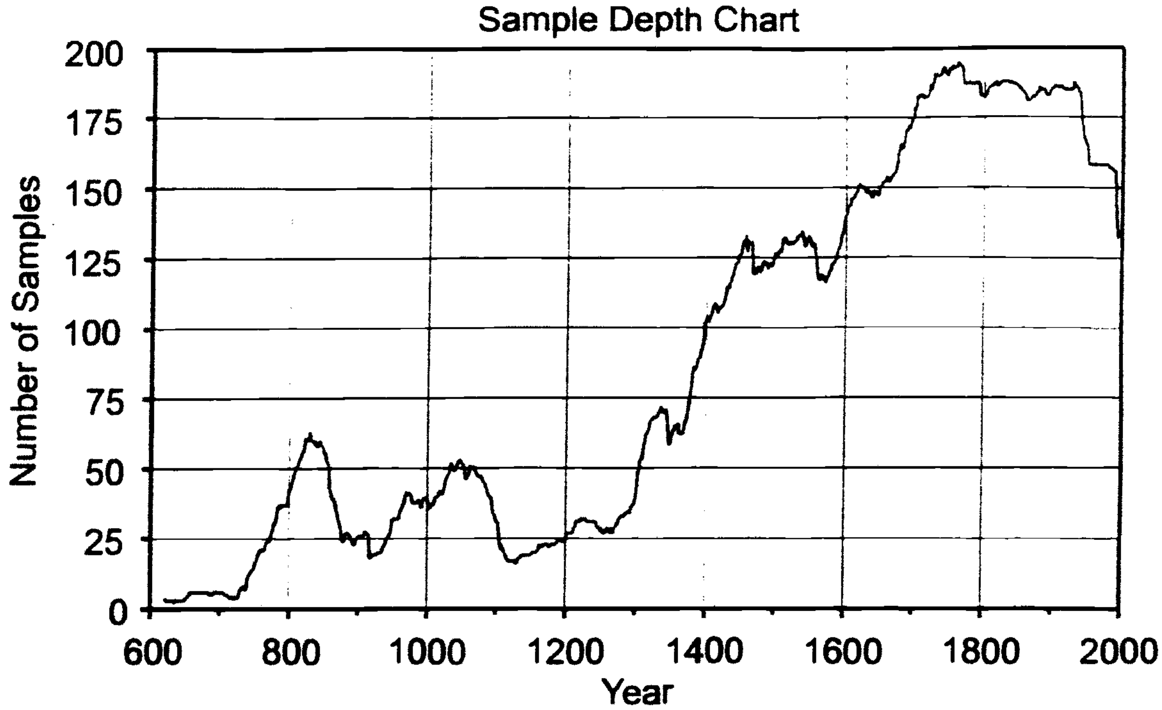

Figure 13. Number of tree-ring samples for each year through the full length of the final data sets used. Sample depth increases during certain periods prior to AD 1200 due to the contribution of individual archeological sites.

goals of this study. Furthermore, as we will demonstrate in the next section, these tree-ring data have an exceptionally strong relationship with precipitation for the region, a relationship that otherwise could have been weakened by inclusion of other data sets.

The Climate/Tree-Growth Relationship

We tested the climate/tree growth relationship using both regional (NOAA Climate Division Five, Central Valley) and single station climate data (Historical Climate Network). Correlation analyses revealed stronger relationships using regional climate data, perhaps because these data represent the combined information of weather stations across a region, thereby eliminating or reducing local effects to which the trees may not respond. While we found an adequate relationship between climate and tree growth when the calibrations were conducted over the full period represented by the regional climate data

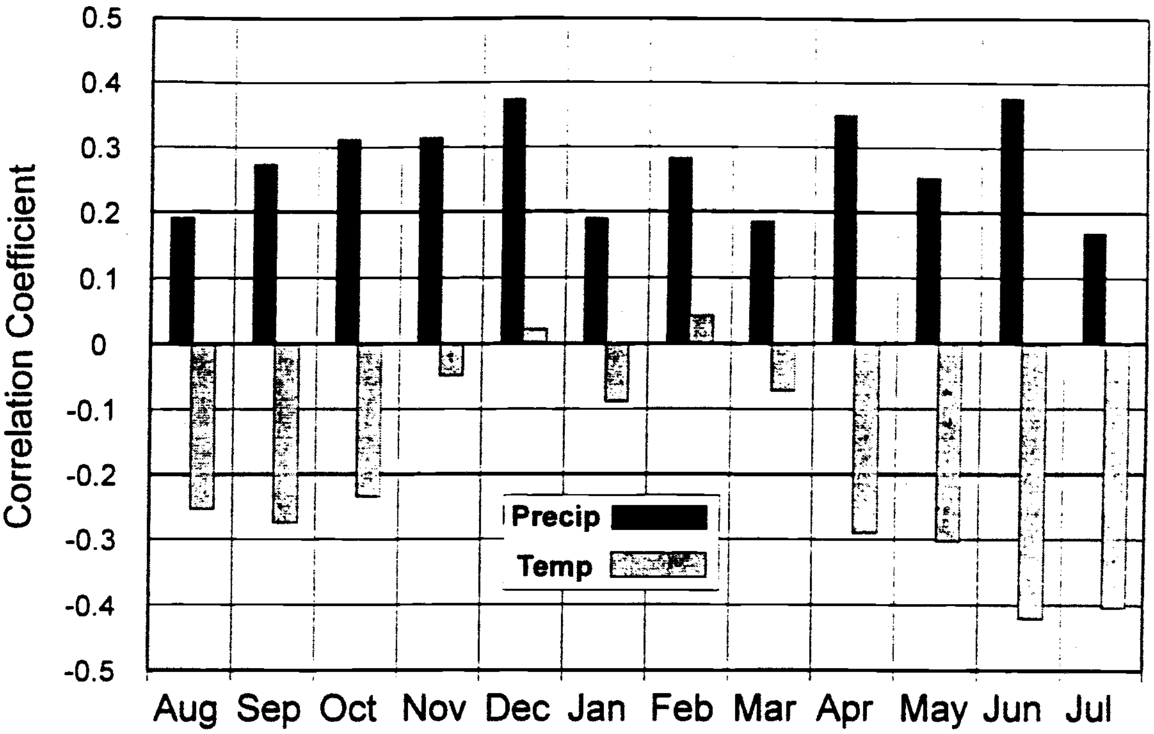

Figure 14. Correlation coefficients between climate (the average monthly temperature and total monthly precipitation), and tree growth over the period 1931-1994. Values for the coefficients greater than 0.20 or less than -0.20 are statistically significant at the .05 level.

(1895-1995), the relationship was generally weak between 1895-1930. Inspection of the climate data for the central Rio Grande area revealed that the weather station for Socorro, New Mexico, did not begin recording weather observations until 1931. The Socorro weather station is centrally located among the study sites, and its absence prior to 1931 obviously reduced the strength of the climate/tree growth relationship. We therefore conducted the calibrations on the period 1931-1995.

We also tested the effects when using more than one species to develop a chronology and found that the correlations increased slightly when the southwestern white pine tree-ring data were combined with the Douglas-fir tree-ring data. We also found that correlations between climate and tree growth again increased slightly when the tree-ring data from the San Mateo Mountains were combined with the data from the Magdalena Moun-

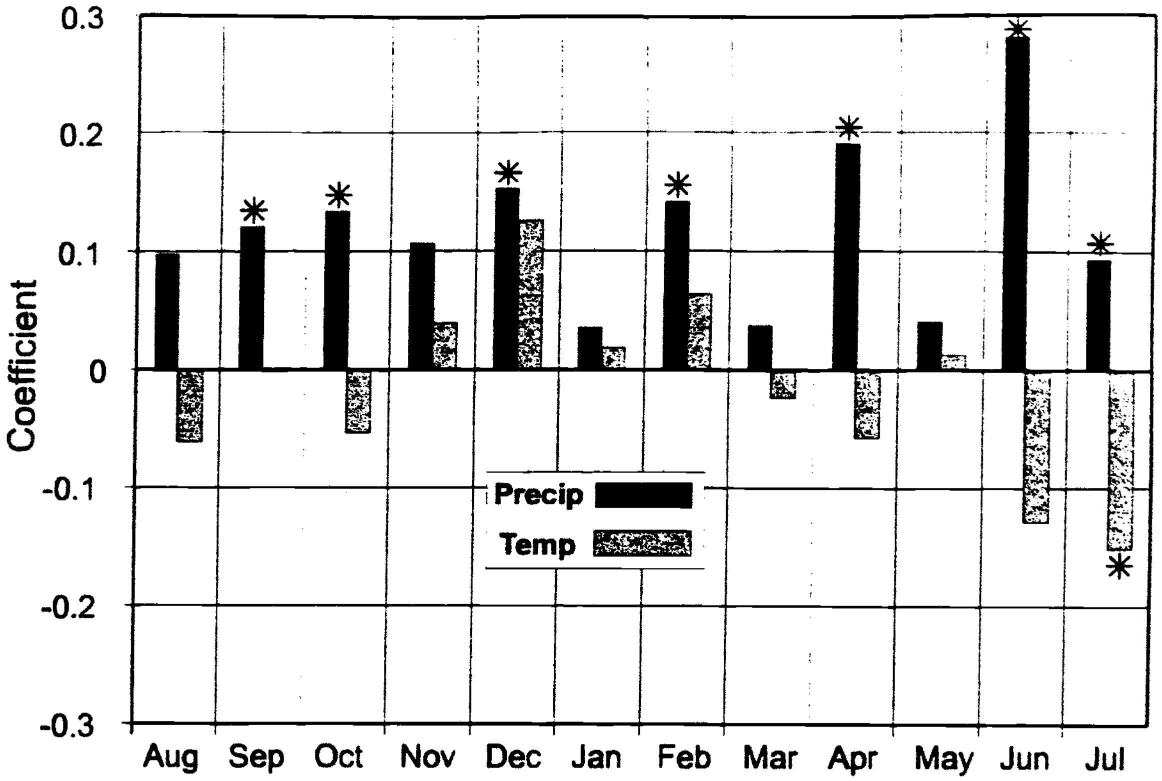

Figure 15. Relationships between monthly climate and tree growth using the final chronology developed for this project. Asterisks indicate significant ($p < .05$) associations.

tains. These results confirmed earlier studies that suggested the climate signal within tree-ring data could be enhanced and provide a more valid depiction of past climate by using multiple species (Graumlich 1989; Grissino-Mayer and Fritts 1995) and multiple sites within a region (*e.g.*, see Fritts and Shatz 1975; Fritts 1991; Fritts and Shao 1992).

The correlation analysis revealed statistically significant ($p < .05$) coefficients between tree growth and monthly rainfall from the previous growing season's September (thus reflecting the effects of climate preconditioning growth during the following year) to the current growing season's June (Figure 14). The trees of southern-central New Mexico appear conditioned by rainfall during the previous fall and the current spring and summer, while winter rainfall (January through March) appears to have little effect. This analysis also revealed a surprisingly strong relationship with average monthly temperature (Figure 14) that simulated the temporal pattern with precipitation. Coefficients were significant during the previous growing season's August through October and during the current growing season's April through July. Response function analysis, however, which uses PCA to provide a more biologically accurate depiction of the climate/tree growth relationship, does not show such a strong relationship with temperature, while precipitation once again shows significant coefficients between the previous summer and current summer (Figure 15).

Table 4. Results from the calibrations between climate and tree growth (represented by the first eigenvector) for the periods 1931-1962, 1963-1994, and 1931-1994.

Period	Parameter Estimate	Constant	F-Value	Adj. r^2 #	Residual Autocorr.	Outliers
1931-1962	2.03 *	9.57 *	191.18 *	0.88	0.19	1932,1945,1946
1963-1994	2.57 *	9.07 *	82.36 *	0.75	0.33	1973,1984, 1989,1992
1931-1994	2.14 *	9.34 *	224.69 *	0.79	0.44	1932,1973,1984, 1989,1992

r-squared adjusted for loss of degrees of freedom
* $p < .0001$

Based on these analyses, it became clear that the trees of southern-central New Mexico respond to a *hydrologic* cycle, *i.e.*, annual precipitation during a *water year* that ranges between the previous year's August and the current year's July. When various combinations of monthly precipitation were totaled and correlated with the tree-ring data set, the strongest relationship occurred using the August through July precipitation total ($r = .72$, $p < .05$, $n = 99$), thus indicating that precipitation could account for greater than 50% of the variance in the tree-ring data set (explained variance is equivalent to the correlation coefficient squared). We therefore decided to reconstruct total annual water year (previous August-current July) precipitation for south-central New Mexico, similar to

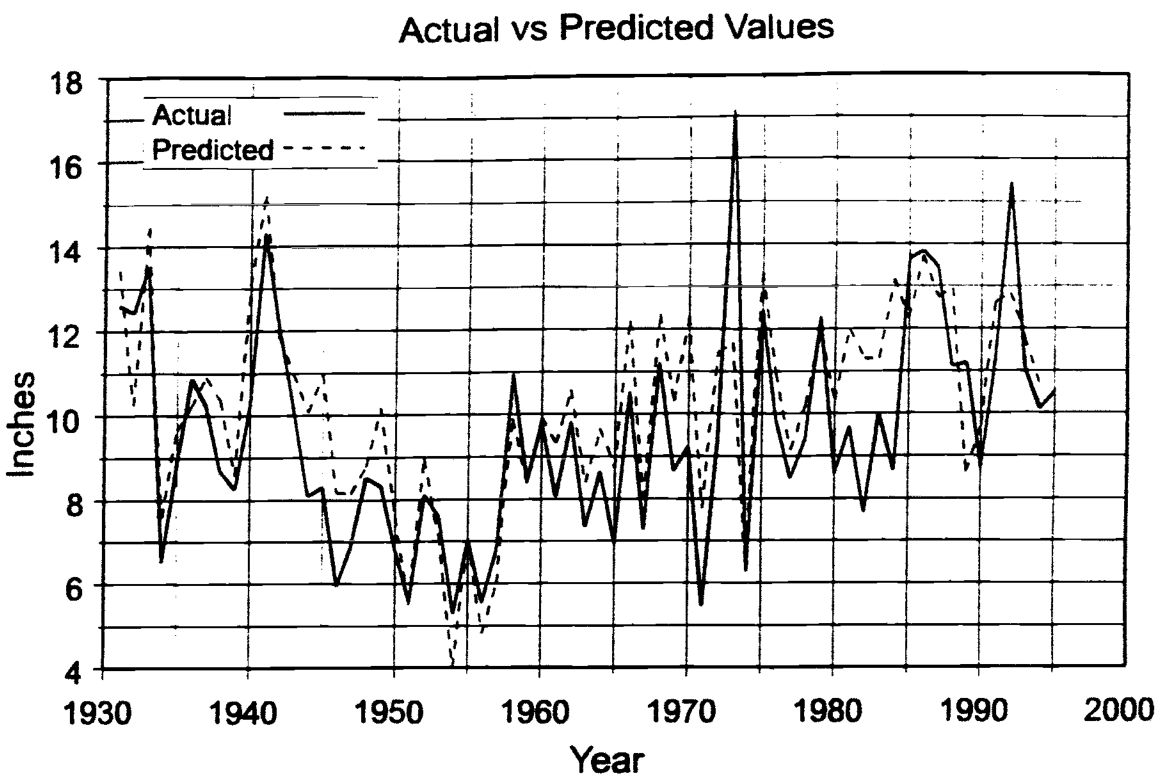

Figure 16. The relationship between tree growth and water year rainfall over the period 1931-1994, demonstrating acceptable synchroneity in both the high (year to year) and low (decadal) frequencies. Rainfall during the water year 1973 (August 1972 to July 1973) was exceptional, likely due to an enhanced El Niño event.

water year reconstructions conducted in northern New Mexico for El Malpais National Monument (Grissino-Mayer 1995, 1996) and for Arroyo Hondo near Santa Fe, New Mexico (Rose *et al.* 1981).

A 1,373 Year Reconstruction of Precipitation

The calibrations between climate and tree growth revealed exceptionally strong associations for both subset periods (1931-1962 and 1963-1994) (Table 4 and Figure 16). The initial model (all observations kept) that predicted water year rainfall total from tree growth for the period 1931-1962 yielded an adjusted r^2 (adjusted to account for loss of degrees of freedom) of 0.80, indicating that tree growth could explain 80% of the variance in the climate data over this period. This value ranks as one of the highest attained in dendroclimatic reconstructions worldwide, but can be partially explained by the fewer observations in the initial data set (32). The final model (three outlier observations – 1932, 1945, and 1946 – removed) yielded an adjusted r^2 of 0.88. The initial model developed for the period 1963-1994 was somewhat weaker with an adjusted r^2 of 0.49. However, we noted that rainfall for the period beginning in the early to mid-1970s appeared somewhat erratic, as exemplified by rainfall during the period August, 1972 to July, 1973. Late summer and early fall of 1972 saw unusually high amounts of rainfall, perhaps due to an unusually strong El Niño event (Quinn and Neal 1992) that may have enhanced rainfall during the fall and winter seasons. Most of this rainfall obviously occurred as runoff in southern-central New Mexico, and was not made readily available for tree growth. Hence, the tree rings for this year show an otherwise average width (Figure 16), providing a climatically reasonable explanation for removal of this yearly observation from the calibrations equation. Removal of the one observation for 1973 caused the adjusted r^2 to jump from 0.49 to 0.58. Other extreme outliers occurred during 1984, 1989, and 1992, and were removed, causing the adjusted r^2 for the final model for this period to reach 0.76.

Verification statistics were all statistically significant (Table 5). The equation developed for the 1931-1962 calibration period generated predicted values for the period 1963-1994 that had a very strong correlation with the actual annual values ($r = 0.70$), well above the value of 0.30 needed for statistical significance. The calibration equation developed for the 1963-1994 generated predicted values for the 1931-1962 period that had an even stronger correlation with the actual values ($r = 0.90$), this despite the fact that all observations, including the statistical outliers, were retained in the verification period. The close association of the predicted and actual values during the full period 1931-1994 can be visually inspected in Figure 16. A significant amount of undesirable autocorrelation remained in the residuals from both calibration models and the final model (Table 4), indicating that one or more additional explanatory variables were needed. We believe this additional autocorrelation arose because of the strong influence of temperature on tree growth (Figure 14), which was *not* being accounted for in any of our models. However, we also believe that an accurate depiction of the tree growth/precipitation relationship was modeled in our analyses.

Table 5. Verification statistics for both calibration periods confirming the ability of both models to simulate the actual annual rainfall totals.

Calibration Period	Verification Period	Correlation Coeff. [a]	Reduction of Error [b]	t-value [c]	Sign Products [d]	Negative First Diff. [e]
1931-1962	1963-1994	0.70	0.57	4.38	7	6
1963-1994	1931-1962	0.90	0.74	4.47	5	3

Values needed for statistical significance ($p < .05$): a: ≥0.30; b: ≥0.09; c: ≥1.7; d: ≤10; e: ≤10. All values are highly significant.

The final statistical model took the form:

$$(\text{Predicted water year ppt total})_t = [2.03 * (\text{tree-ring data}_t)] + 9.57$$

interpreted as "the total amount of rainfall for any particular water year (t) can be predicted by multiplying the tree-ring index for the same year by 2.03 and adding a constant of 9.57." The calibration equation was able to capture both high-frequency (year-to-year) and low frequency (decadal and longer) trends in the actual climate data (Figure 16). This equation was then used to predict water year rainfall totals for each year back to AD 622 (Figure 17), although the reconstruction is less reliable prior to AD 800 because of a reduced sample size.

Trends in Past Rainfall since AD 622

Tables 6 and 7 list interannual to decadal-length dry and wet periods based on the 10-year spline that occurred for extended durations above or below the ±1.1 sd level (Figure 17). These dry and wet periods should be compared to the long-term average of 9.34 inches of rain per year between AD 622-1994. The most severe short-term (< 25 years)

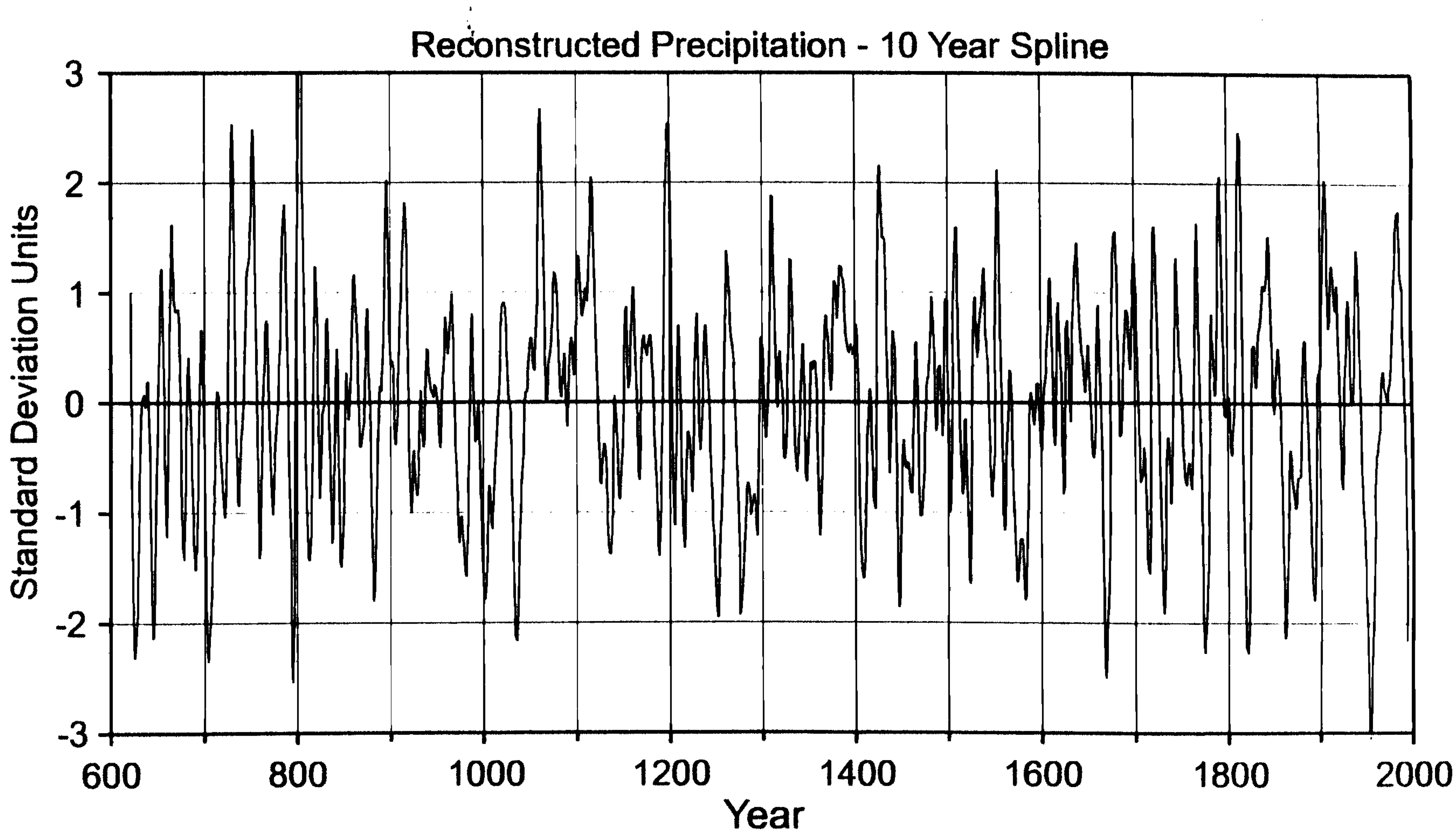

Figure 17. Reconstructed annual water year (previous August to current July) rainfall, AD 622-1994, filtered with a 10-year smoothing spline to show decadal trends. Actual reconstructed values for each year are provided in Appendix 1.

drought, based on both magnitude (average precipitation per year) and duration, occurred between AD 1272-1296. Known as the "Great Drought" in the Four Corners area of the Southwest (Douglass 1929; Baldwin 1935), this drought was unusual in its length (25 years), and is clearly visible as an extended period of below average rainfall in Figure 17. The second most severe drought occurred recently during this century, between AD 1946-1961. Known locally as the "50s Drought," this drought is hypothesized to have caused widespread mortality in stands throughout the southern portion of the Southwest (Betancourt *et al.* 1993). Interestingly, this drought did not appear to be as severe in the northern portion of the Southwest (Grissino-Mayer 1995).

These two periods can be compared with two of the most extreme short-term wet periods during the last 1,373 years. The wettest period occurred between AD 1100-1120, when rainfall averaged nearly 11 inches per year for the entire period. As we will point out later, this period immediately preceded the collapse of the Mimbres culture in southwestern New Mexico *ca.* AD 1150, and may have contributed to the collapse by stimulating increased population growth during periods of successful farming and abundant provisions. These increased populations simply could not be sustained during the subsequent drought that followed between AD 1125-1140. Another major wet period occurred again during this century between AD 1903-1921 and is strikingly similar to the short-term wet period between AD 1100-1120. Both periods were similar in duration and average rainfall per year. The wet period early in the 20th century may have contributed to successful establishment of ponderosa pine stands in much of the Southwest, first reported by Pearson (1923). Today, these relatively unhealthy stands of dense "doghair" pine thickets (slow-growing, stagnant stands of pines where effects of competition on growth outweigh effects of natural thinning processes) proliferate throughout much of the Southwest.

Table 6. The most severe interannual to decadal-length droughts since AD 800, weighted by both magnitude and duration.

Rank	Period	Magnitude [a]	Duration [b]
1	1272-1296	7.88	25
2	1946-1961	7.21	16
3	1666-1674	6.95	9
4	1571-1587	7.60	17
5	881-885	6.75	5
6	1817-1826	7.16	10
7	1772-1782	7.31	11
8	1445-1450	6.93	6
9	998-1014	7.84	17
10	1246-1258	7.54	13
11	1031-1042	7.53	12
12	1859-1867	7.34	9
13	972-985	7.79	14
14	1125-1140	8.18	16
15	1728-1735	7.64	8
16	1889-1896	7.65	8
17	1405-1415	7.90	10

[a] magnitude measures the average precipitation per year for the specified period. These values can be compared to the average of 9.34 inches total precipitation per year between AD 622-1994.

[b] duration in years.

Table 7. The wettest interannual to decadal-length periods since AD 800, weighted by both magnitude and duration.

Rank	Period	Magnitude [a]	Duration [b]
1	1100-1120	10.97	21
2	800-808	12.36	9
3	1903-1921	10.83	19
4	1810-1816	12.24	7
5	1425-1435	11.54	11
6	1193-1203	11.51	11
7	1833-1850	10.54	18
8	1057-1066	11.47	10
9	1377-1393	10.55	17
10	1309-1314	11.94	6
11	1790-1795	11.89	6
12	1979-1994	10.65	15
13	893-899	11.63	7
14	908-920	10.80	13
15	1766-1771	11.45	6
16	1677-1683	11.27	7
17	1634-1641	11.03	8
18	1720-1727	10.85	8

[a] magnitude measures the average precipitation per year for the specified period. These values can be compared to the average of 9.34 inches total precipitation per year between AD 622-1994.

[b] duration in years.

Long-term trends in past rainfall, often lasting 100 years or longer, are evident in the 100-year spline fit to the reconstructed precipitation values (Figure 18). In general, several periods occurred when rainfall exceeded the ± 1.1 sd level for extended durations. For example, the most severe and longest-lasting long-term drought period occurred between AD 940-1040. Between AD 970-1030, rainfall was well below the -1.1 sd level, and briefly surpassed the -2.0 sd level between AD 995-1005 (Figures 17 and 18), the only period (when sample depth is adequate) that surpassed this extremely low level. This dry period was interrupted only by a brief period of rainfall in the AD 980s that was only slightly above average (Figure 17).

This long-term dry period was immediately followed by the most extreme long-term wet period in the entire 1,373 year reconstruction. Between AD 1040-1125, rainfall was generally well above average, exceeding the +1.1 sd level between AD 1050-1120, and exceeding the +2.0 sd level between AD 1065-1105 (Figure 18). The duration of this wet period is easily seen in the 10-year spline fit to the reconstructed data as well (Figure 17), interrupted only by a brief period of average rainfall in the early 1090s. Between AD 1125-1140, a short-term, but very severe, drought occurred that interrupted this period of favorable rainfall. After this 16-year drought, rainfall again returned to above-average conditions which lasted until *ca.* AD 1210. As we will demonstrate later, we believe the long-term wet period between AD 1040-1125 and the short-term wet period between AD 1100-1120 both contributed to the collapse of the Mimbres culture by allowing changes to develop in Mimbres settlement (*e.g.*, riparian farming) and demographic (*e.g.*, population increases) patterns from which they could not recuperate once the long period of drought that followed was underway.

The long-term drought that followed between AD 1210-1305 was similar in duration to the drought between AD 940-1040, but never surpassed the -2.0 sd level. Nonetheless, this drought was severe and long-lasting, and must have had an impact on the ancient Native Americans that populated southwestern New Mexico at the time. Interestingly, the southern Mogollon began an interaction phase with the cultural center at Casas Grandes further to the south after the collapse of the Mimbres culture *ca.* AD 1150 (LeBlanc

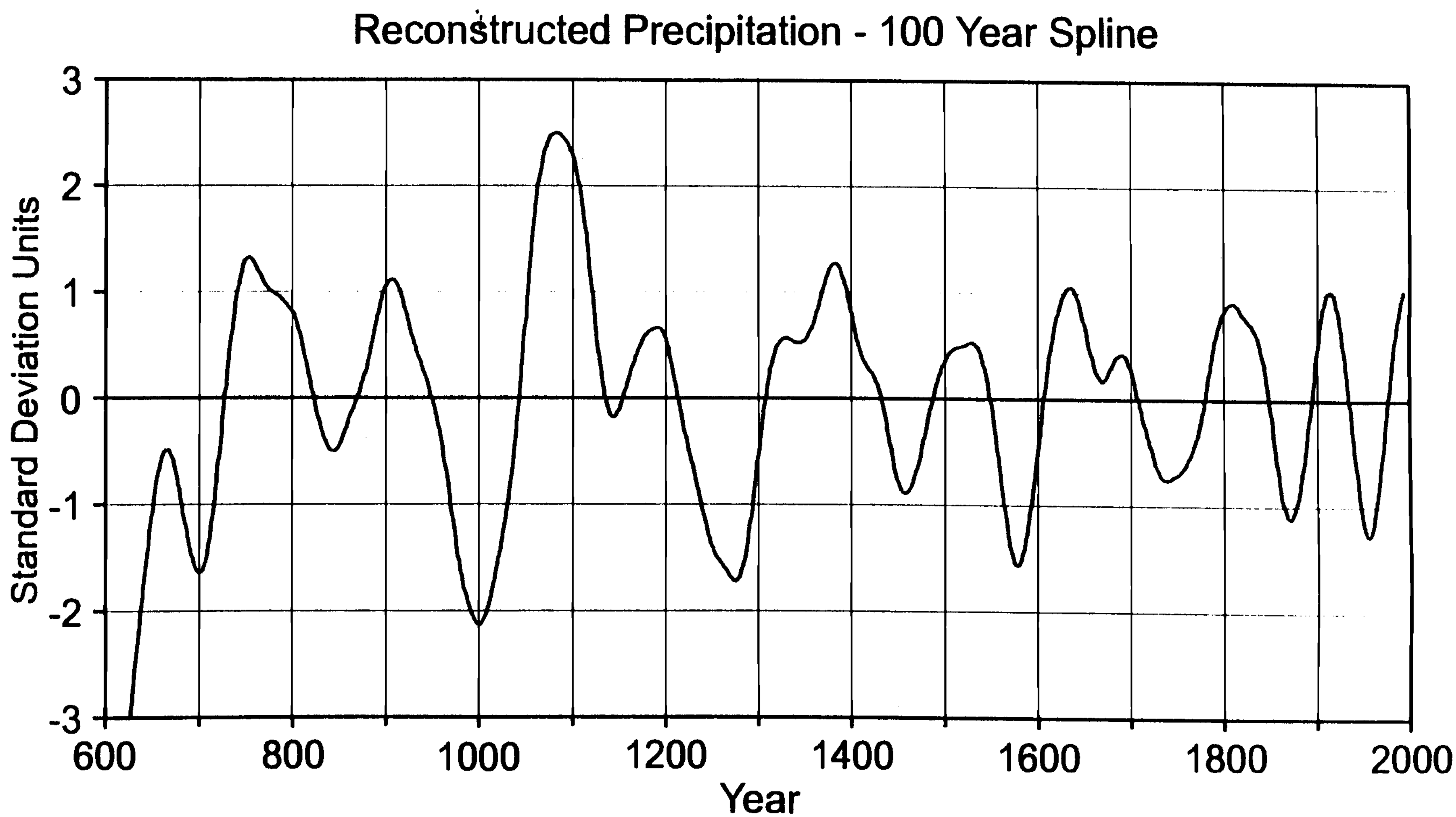

Figure 18. Reconstructed annual water year (previous August to current July) rainfall, AD 622-1994, filtered with a 100-year smoothing spline to show long-term (> 50 years) trends.

1989). This interaction phase lasted until *ca.* AD 1300, after which the Mogollon peoples largely abandoned southwestern New Mexico and/or were subsumed into the Casas Grandes culture.

After AD 1300, the severity of long-term wet and dry periods diminishes (Figure 18), as few periods exceeded the ±1.1 sd level, and no period approached the ±2.0 sd level. In fact, *long-term* precipitation patterns after AD 1300 could be classified as benign, interrupted only by several short-term drought or wet periods (Tables 6 and 7). A major short-term drought occurred between AD 1571-1587 within a decades-long drought period between AD 1550-1605, a drought also reconstructed for northern New Mexico (D'Arrigo and Jacoby 1991; Grissino-Mayer 1995, 1996). However, this drought does not appear to be as severe in southern-central New Mexico as it had been for the Four Corners region.

The most remarkable feature of long-term climate after AD 1300, however, does not concern changes in *average* rainfall, but rather concerns changes in climate *variability*. As shown in Figure 18, the long-term variance about the long-term average actually decreases over time. The period between AD 900-1300 was marked by unusual swings between extremely wet periods and very dry periods, each often lasting well over one hundred years. This pattern changed beginning AD 1300, when such wide long-term swings diminished in their frequency and magnitude. Furthermore, this feature can not be an artifact of changing sample depth over time because the number of samples increases to a peak in the 1700s; the two graphs (Figures 13 and 18) are not associated whatsoever. Nor is this feature unique to tree-ring reconstructions in southwestern New Mexico. A decrease in long-term variance over time has also been observed in other tree-ring chronologies and reconstructions in the southern portion of the Southwest (*e.g.*, Mount Graham in the Pinaleño Mountains of southeastern Arizona) (Grissino-Mayer, *unpublished data*), suggesting that the decrease in precipitation variability over time is a real feature of Southwestern climate.

When we investigate changing variability in rainfall at a shorter time scale (25 year running periods), the long-term pattern disappears, but instead emphasizes decadal trends in past rainfall variability not seen in the 100-year spline (Figure 19). For example, a

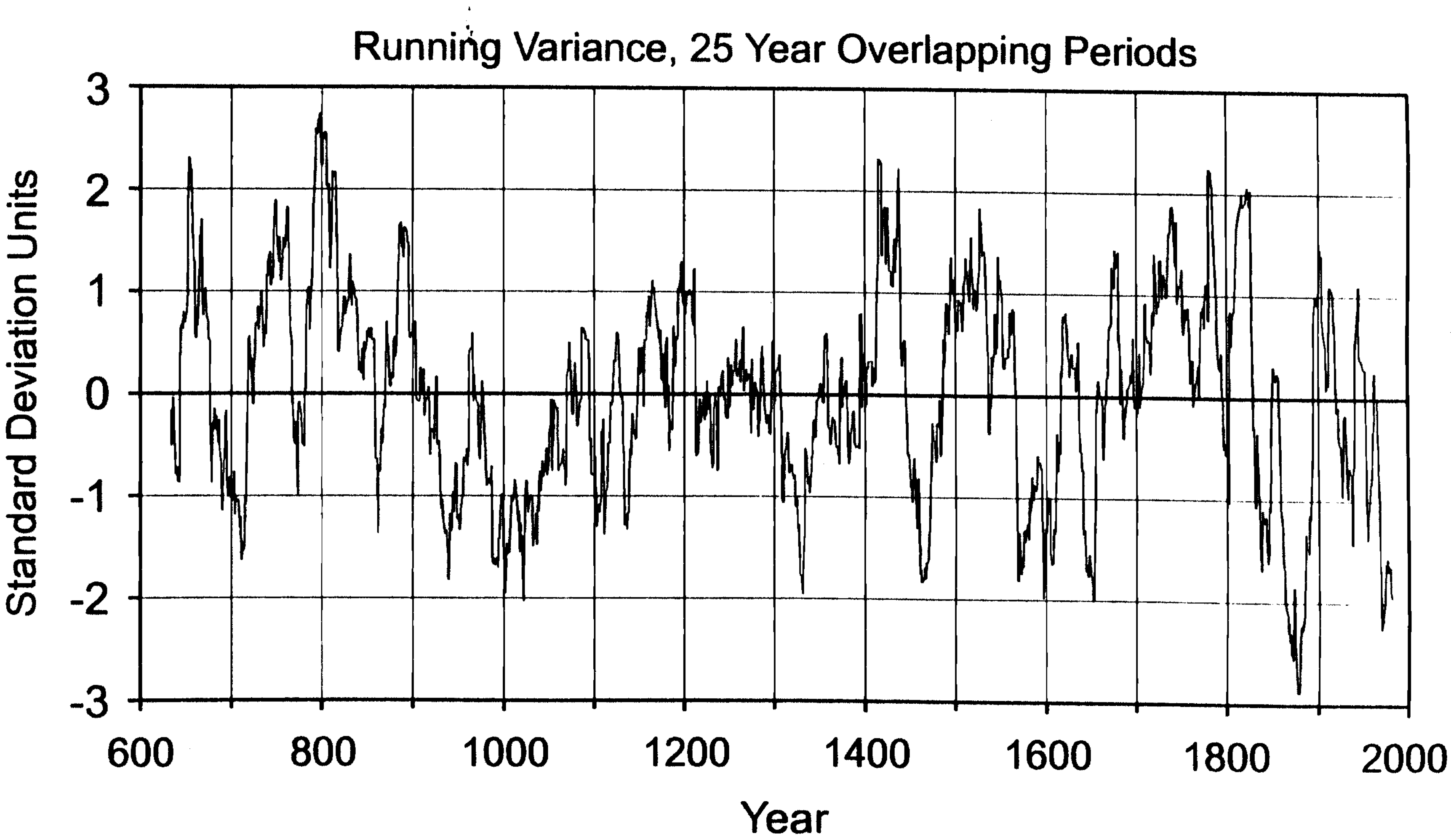

Figure 19. The variance of the reconstructed precipitation calculated for 25 year overlapping periods lagged by one year. This graph shows periods of high variability (*e.g.*, AD 1415-1435) and low variability (*e.g.*, AD 1860-1890). Transitions between the two may signify major changes in overall climate for south-central New Mexico.

rapid increase in variance in the early 1400s marks a major change in precipitation not found when analyzing simple changes in short-term or long-term average rainfall. Interestingly, this increase in variance was concurrent with a major change in rainfall as observed in a reconstruction of precipitation developed for El Malpais National Monument to the north of the study area (Grissino-Mayer 1995). The variability of precipitation then swings between short-term periods of high and low variance, eventually culminating in another major change in precipitation patterns that began *ca.* 1825. Again, this change in precipitation patterns is not visible when analyzing only changes in mean climate. The period between AD 1825-1895 was marked by the lowest levels of variance in the entire 1,373 year record (Figure 19). Interestingly, this change in precipitation is nearly concurrent with a major change in annual rainfall at El Malpais National Monument (Grissino-Mayer 1996). The change at El Malpais, however, suggested rainfall *increased* with a similar increase in variance as opposed to the lower variance and *decreased* rainfall seen in the southern portion of the Southwest.

DISCUSSION

Effects of Climate on the Southern Mogollon, AD 900-1300

The reconstruction revealed that the most severe long-term drought during the last 1,373 years occurred between AD 940-1040 (Figure 17), and may have impacted, to some degree, the demographic, settlement, and interaction patterns of the Mogollon culture. Periods of stress and deteriorating environmental conditions are believed to have prompted regional interactions between ancient Native American groups to help overcome shortages of food and supplies (Plog *et al.* 1988). Between AD 750-1000, the Mimbres interacted with the Hohokam of southern Arizona at unprecedented levels (LeBlanc 1989), perhaps in response to the generally unfavorable climate conditions that existed during this period. Furthermore, the population for the region as a whole was well below its effective carrying capacity (LeBlanc 1989), indicating some factor, such as hydrologic drought, may have contributed to keeping population densities low.

Between AD 1040-1120, rainfall was abundant, representing a portion of the wettest long-term (> 50 years) period in the entire 1,373 year reconstruction (between AD 1040-1210). Within this long-term favorable period, the first two decades of the 1100s represented the wettest short-term (< 25 years) period in the entire reconstruction (Table 7 and Figure 17). Rainfall was also very reliable as indicated by the low variability that occurred during this period (Figure 19), indicating rainfall did not vary greatly from year to year. Basically, not only was rainfall abundant, but the climate system was stable. These unique environmental conditions may have contributed to the cultural advances made by the Mogollon during this time, *e.g.*, a shift from pithouse to above-surface structures (LeBlanc 1986, 1989), and a dramatic increase in population (Anyon *et al.* 1981; LeBlanc 1986).

Climatically, the Classic Mimbres period between AD 1000-1150 occurred during very favorable long-term climate conditions, beginning with an increase in annual rainfall *ca.* AD 1000, after a long period of below average conditions (Figure 17). Rainfall occurred at unprecedented levels based on the 1,373 year reconstruction, which may have contributed to a change in architecture from semisubterranean pithouses to above-ground dwellings. Although speculative, would increased rainfall have contributed to this change, given the change in soil conditions that may have occurred due to increased soil moisture? Changes in farming practices are evident that the Mogollon took advantage of increased runoff by building checkdams, and, perhaps, irrigation systems (LeBlanc 1989). For the first time, rooms solely dedicated to food storage were constructed, indicating successful farming and an abundance of provisions. Minnis (1985) was one of the first to suggest that the favorable responses and advances made by the Mogollon during this period likely resulted from favorable rainfall patterns, which allowed marginal areas to be utilized for farming.

Beginning *ca.* AD 1125, however, a major change in climate occurred as rainfall dropped to unprecedented low annual totals. Furthermore, this rather rapid decrease in rainfall was concurrent with a shift in variance from low (below the -1.1 sd level) to high (above the +1.1 sd level) levels (Figure 19), indicating a relatively rapid change from a stable climate regime to a more erratic one. Rainfall totals were well below the long-term average enjoyed by the Mogollon previously, while rainfall patterns from one year to the next were no longer as predictable as they once had been. During this 16-year long period, some of the driest years in the entire 1,373 year reconstruction occurred (see Appendix 1 for a full listing of the reconstructed values): only 6.94 inches of rainfall during the AD 1128 water year, 6.79 inches in 1131, only 5.86 inches in 1134, and only 6.43 inches in 1138 (compared to the long-term average of 9.34 inches per year). Only three years during this 16 year period – AD 1129 (10.92 inches), AD 1130 (9.67 inches), and AD 1132 (10.75 inches) – exceeded the average of 9.34 inches of rainfall. In the northern portion of the Southwest, this drought is believed to have contributed to the collapse of the Chaco system and cultural centers in the Virgin Branch area, the Grand Canyon, Black Mesa, and Red Rock Valley (Dean *et al.* 1985).

A central question in any paleoenvironmental study of southern New Mexico concerns the impact these deteriorating rainfall conditions may have had on the Mogollon culture. LeBlanc (1989) asks, "Did an environmental shift, even a minor one, lead to the collapse of the Mimbres culture?" He goes on to ask, "Was the development of the Casas Grandes interaction sphere itself triggered by an environmental shift?" We believe our study provides new insights that eventually may help answer these questions, because we feel the severity and duration of the drought between AD 1125-1140 at least *contributed* to the collapse of the Mimbres culture by prompting migration to outlying areas or by assimilation of the Mogollon into a more prosperous and stable community such as Casas Grandes further to the south. We emphasize that direct causality between changes in the environment of the Mogollon peoples and changes in cultural patterns would be difficult to prove. Rather, we see changes in the environment as *contributing* or *allowing* changes in culture to occur.

Interactions with other societies would be expected during periods of environmental stress. Based on probable behavioral characteristics of cultures experiencing environmental change (Plog *et al.* 1988), this drought could have prompted native populations in the southern Mogollon area to interact with the Casas Grandes center to help alleviate impacts due to this and other droughts that followed. Trade is believed to increase in response to an environment that is less predictable. LeBlanc (1989) cautions, however, that "environmental change would not automatically cause a cultural collapse," and that the collapse of the Mimbres culture around *ca.* AD 1150 was more likely due to assimilation into the Casas Grandes interaction sphere. Nelson (1993), however, provides an alternative hypothesis that states the Mimbres were not assimilated into the Casas Grandes sphere, but rather shifted land-use patterns further east to the eastern slopes of the Black Range. This shift in land-use patterns would be consistent with an increase in the severity of hydrologic drought. A move further east would position the Mimbres closer to a reliable supply of water at the Rio Grande. Unfortunately, neither LeBlanc nor Nelson had the benefit of a long-term reconstruction of precipitation with which to help evaluate changes in Mimbres cultural patterns. Our study reveals that deleterious environmental conditions, previously undocumented for this portion of the Southwest, may at least have *contributed* to the Mimbres collapse, whether from depopulation by migration to outlying areas or assimilation into the Casas Grandes culture.

The Casas Grandes interaction phase lasted between AD 1150-1300, marked by the sociopolitical influence of the Casas Grandes center in northern Chihuahua, Mexico, on a sphere of sites extending well into southern New Mexico and Arizona (LeBlanc 1989). This phase terminated nearly simultaneously with the most severe of any drought in the entire 1,373-year reconstruction. The drought between AD 1272-1296 (Figure 17), also known as the "Great Drought," is a common feature in precipitation reconstructions of northern New Mexico and Arizona (Douglass 1929; Baldwin 1935; Dean and Robinson 1979; Euler *et al.* 1979; Rose *et al.* 1981; D'Arrigo and Jacoby 1991; Dean and Funkhouser 1995; Grissino-Mayer 1995, 1996), and is hypothesized to have had considerable influence on the environments of the ancient Anasazi of northern New Mexico (Dean *et al.* 1985). Our study has reliably reconstructed this drought for the southern-central portions of New Mexico. Average annual precipitation during this drought was only 7.88

inches, compared to 9.34 inches over the entire 1,373 year length of the reconstruction, representing an average 16% reduction in rainfall for *each* of the 25 years in the drought. This drought was punctuated by the fourth lowest rainfall total in the entire reconstruction: only 4.06 inches during the AD 1288 water year (Appendix 1).

The impact of the "Great Drought" was made all the more severe because it culminated a century-long drought between AD 1210-1305, one of the longest and most severe periods of below-average precipitation in the entire reconstruction, and followed closely another decade-long drought between AD 1246-1258, itself listed as one of the ten most severe (Table 6). These decaying environmental conditions were perhaps too difficult for the southern Mogollon (although the concept of "Mogollon" may no longer apply to the post-1150 period) who could not adjust as rapidly as the environment was changing, despite the interactions with Casas Grandes. This may have set the stage for the cultural disintegration that no doubt followed due to the much-reduced precipitation, similar to the scenario hypothesized for northwestern New Mexico (Grissino-Mayer 1995). However, unlike the "Great Drought" in northwestern New Mexico, the variability of precipitation during this period was inconsequential and relatively stable (Figure 19). Interestingly, Cordell and Gumerman (1989) term the period between AD 1150-1300 the Reorganization Period, and note that it was a time of "apparent instability."

In the end, LeBlanc (1989) does acknowledge the probable effect of climate change on the southern Mogollon: "Environmental factors may have been involved in some of the changes, for example, favorable rainfall regimes may have resulted in population growth in the A.D. 1000s, or drought in the late 1200s affecting the Casas Grandes collapse." He further warns that "one must be careful not to assume that all culture change derives from cultural factors, ignoring the effects of environmental change." Unfortunately, archaeologists working in southwestern New Mexico had few reliable proxies for past climate with which to infer past environmental changes. Tree-ring data were no exception. Prior to our study, a well-replicated, millennial-length tree-ring chronology from southern New Mexico did not extend back prior to the Classic Mimbres period. Furthermore, previously developed tree-ring chronologies often lacked a long-term climate signal. This latter problem arises because (1) tree-ring data derived from archeological contexts are usually short, and (2) any long-term signal contained therein may be removed by the transformations commonly used in tree-ring research (Rose *et al.* 1981; Dean 1988; Grissino-Mayer 1995, 1996).

Our study addressed these shortcomings, and have provided tree-ring data that we believe *do* show major fluctuations in the environment between AD 900-1300 at decadal and century time scales that may have contributed to cultural changes in the Mogollon culture. In summary, four climatic events eventually contributed to the collapse of this culture:

(1) A long-term period of below average rainfall between AD 940-1040, unprecedented in its severity, may have contributed to keeping population densities low in the Mogollon region.

(2) A period of above average rainfall that followed between AD 1040-1125 may have contributed to population increases and changes in settlement patterns that reflected greater use of peripheral areas. Food provisions were therefore plentiful.

(3) This long-term period of above average rainfall culminated with the wettest short-term period in the entire 1,373 year reconstruction between AD 1100-1120. Rainfall was abundant and stable from year-to-year.

(4) Abruptly, a 16-year period of unprecedented below average rainfall occurred between AD 1125-1140 for which the Mimbres were unprepared. By AD 1150, the Mimbres culture had collapsed completely, initiating the Casas Grandes interaction phase.

We agree that changes in the environment *allow* for change, rather than directly causing it (LeBlanc 1989). Based on the new findings presented in this report, however, we conclude that *environmental change in southwestern New Mexico between AD 900-1300 must have had a greater impact on the Mogollon peoples than previously believed.*

Climate in Southwestern New Mexico, AD 1300-present

Precipitation during the 1300s increased considerably over that experienced during the last century-long drought period between AD 1210-1305. In fact, rainfall was especially abundant between AD 1355-1400 (Figure 17), when levels exceeded the 1.1 sd level. Inexplicably, however, native populations in southwestern New Mexico continued to decrease from the low levels experienced during the Great Drought, despite the favorable rainfall patterns that once again may have favored successful farming. LeBlanc (1989) points out that "Given the availability of good farm land, it is hard to see how this population could have been under nutritional stress." Instead, the Mogollon may have simply turned to new adaptive strategies. Cordell and Gumerman (1989) term the period following AD 1300 the Aggregation period, noting that areas that continued to be occupied following the Great Drought consisted of very large sites, and were often in closer proximity to reliable water sources. Unfortunately, events in the southern Mogollon region during the Aggregation period are poorly known, owing in part to the lack of such large sites (LeBlanc 1989).

One possibility that is little considered (but rapidly gaining acceptance) is that the *intra-annual* distribution of rainfall may have shifted considerably from its previous state, and could not have supported the traditional farming practices formerly possible. Grissino-Mayer (1995) hypothesized that the Little Ice Age period (*ca.* AD 1400-1800) in northern New Mexico could have witnessed a decrease in summer monsoonal rainfall patterns. He based his hypothesis on the fact that past fire activity, as reconstructed using the dendrochronologically dated fire-scar record, occurred all through the growing season because of the proliferance of late-season fire scars. Such late season fires would be possible only under a precipitation regime no longer dominated by summer monsoonal rainfall as it had been prior to the Little Ice Age. It seems plausible that the decrease in summer rainfall was earlier in the southern portion of the Southwest, which would have contributed to keeping population densities low despite the overall favorable rainfall conditions that apparently prevailed following AD 1300. Furthermore, the increase in rainfall after AD 1300 itself may be misleading because the cooler temperatures that occurred during the Little Ice Age would have meant less evapotranspiration from trees, greater water use efficiency, and increased growth, despite the decrease in summer rainfall. This situation is hypothesized to have later occurred in the Southwest during 1816 – the "Year without a Summer" – when trees throughout the Southwest produced a ring that was incredibly wide, due primarily to the cooler temperatures that occurred throughout 1815-1816 (Cleaveland 1992).

The 1400s were a century of below average rainfall during (Figures 17 and 18) which two of the worst short-term (< 25 years) droughts occurred during the entire 1,373 year reconstruction. A major drought occurred between AD 1405-1410 during which rainfall averaged only 7.90 inches per year over the 11 year period (Table 6). Only two years during this interval – AD 1406 with 10.6 inches and AD 1414 with 12.5 inches – exceeded the long-term average of 9.34 inches (see Appendix 1 for all reconstructed annual precipitation totals). In fact, the narrowest tree ring formed in any year since AD 622 occurred during this interval in 1407, and indicated a mere 3.6 inches of rain fell during this year. Another major short-term drought occurred between AD 1445-1450 (Table 6) when each year averaged only 6.9 inches of rainfall. No short-term wet period of any consequence occurred during this century.

In contrast, the first 50 years of the 1500s saw generally above average rainfall conditions, especially between AD 1526-1543 (Figure 17), although this period did not qualify as an exceptional period of above average rainfall because the wet years were interspersed with numerous dry years. This wet period was followed by another drought of ecological and archeological significance that occurred between AD 1571-1587 (Figure 17), a drought not only severe and long-lasting, but also widespread throughout New Mexico. First mentioned by Douglass (1929), this drought was also documented by Rose *et al.* (1981), D'Arrigo and Jacoby (1991), Betancourt *et al.* (1993), and Grissino-Mayer (1995, 1996). This drought was perhaps more severe and longer lasting in northwestern New Mexico, beginning *ca.* 1565 and lasting until 1608 (Grissino-Mayer 1995). Native populations had, by this time, aggregated to central locations with more reliable sources of water, such as the Zuni Pueblo and areas near the Rio Grande (Cordell and Gumerman 1989; Ahlstrom *et al.* 1995), thus lessening the impact by this drought. However, this long dry period may have contributed to hardships on both the Native American and Spanish populations at the time, and may have led to events that precipitated the brutal encounter between the Spanish and Acoma Puebloans in AD 1599 (Forbes 1960; Spicer 1962). Swetnam and Brown (1992) suggested this drought may be responsible for the proliferance of tree-ring chronologies throughout the Southwest that extend back only to AD 1600, similar to the assertion by Betancourt *et al.* (1993) that the 1666-1674 drought may also have impacted conifer populations resulting in few pinyon chronologies for south-central New Mexico that extend beyond AD 1700.

A major drought also occurred between AD 1666-1674 (Figure 17) which had one of the lowest averages for total precipitation per year (6.95 inches) of any of the major droughts. This drought has particular significance to archeology because it is believed to have prompted the abandonment of Gran Quivira (Betancourt *et al.* 1993), one of the 12 archeological sites used in this study. Gran Quivira was a large pueblo at the foot of Chupadera Mesa in central New Mexico (Figure 1) occupied from the 13th to the 17th centuries, and is believed to have served as a hub for regional activity. Crop failures and widespread starvation attributable to this drought are well documented (Vivian 1975). Betancourt *et al.* (1993) further suggested that this drought may have induced the Pueblo Revolt of 1680, although other factors, such as the declining political relationship between the Puebloans and Spanish and the influx and rise of the Apachean culture, surely contributed to this uprising. We agree with Betancourt *et al.* (1993), however, that this drought may have caused widespread mortality of conifers in southern-central New Mexico that would explain the difficulty in locating living-tree sites with which to bridge the tree-ring material collected from archeological sites. This drought could explain why many tree-ring sites in southern-central New Mexico extend only to the mid-1600s, *e.g.*, Wofford Lookout, Cloudcroft, Mimbres Junction, Salinas Peak, Oscura Peak, and Hoosier Canyon (Table 1).

The second most severe short-term drought in the entire 1,373 year reconstruction occurred between AD 1946-1961 (Figure 17), and is known popularly throughout the Southwest as the "50s drought." This drought also has the distinction of having some of the lowest precipitation totals for any individual years in the entire 1,373 year long reconstruction (Figure 17). Based on magnitude alone, this drought would be considered the most severe of any since AD 622. Tree growth indicated only 5.29 inches of rainfall occurred for the 1951 water year (actual total was 5.56 inches), only 6.68 inches in 1953 (actual was 7.59 inches), 4.02 inches in the 1954 water year (actual was 5.28 inches), 6.63 inches in 1955 (actual of 7.08 inches), only 4.70 inches in 1956 (actual of 5.55 inches), and only 5.72 inches in the 1957 water year (actual of 6.73 inches) (see Appendix 1). The 4.02 inches in 1954 rank this as the third worst drought year of any year between AD 622-1994. These values represent 28-57% reductions in precipitation when compared to the long-term average of 9.34 inches of rainfall per year, and are considerably greater in magnitude when compared to the 20th century average of 9.58 inches.

The extensive dieback in the pinyon-juniper woodlands of central New Mexico and elsewhere that occurred due to this drought was studied and documented by Betancourt *et al.* (1993) who found that 90% of pinyons living in 1940 at the Sevilleta Long-Term Ecological Research Station had died by 1956. The significance of this drought to the study of disturbance ecology, as suggested by Betancourt *et al.* (1993), is that the drought can be used as a "tracer" for tracking the impacts of (and recovery from) a catastrophic drought, providing necessary background information for assessing the ability of ecosystems to recover from natural catastrophes that occur only on century time scales. For the first time, the 1950s drought can be placed in historical perspective – this drought was as severe and nearly as long lasting of any drought during the past 1,373 years, equaled in its severity only by the "Great Drought" between AD 1272-1296.

Other droughts listed in Table 6 may have had similar impacts on forested areas of the Southwest. However, one prominent drought listed in the historical record as being particularly severe does not show up in the tree-ring record for the sites used in this study. The drought between AD 1899-1904 is well documented in the climate data; for this

NOAA climate division, only 6.66 inches of rainfall fell in the 1899 water, 6.11 inches in 1900, 8.7 inches in 1901, 7.3 inches in 1902, 7.73 inches in 1903, and only 4.46 inches in 1904, all of these total values far less than the long-term mean of 9.34 inches. Yet the trees in the Organ, Magdalena, and San Mateo Mountains indicated only average to above-average rainfall fell in these years (Figure 17) as predicted by the calibration equation(see Appendix 1): 8.5 inches in the 1899 water year, 9.39 inches in 1900, 9.32 inches in 1901, 8.78 inches in 1902, 11.86 inches in 1903, and 8.2 inches in 1904, values hardly similar to the actual values. We offer three possible explanations for this discrepancy.

First, we previously showed the strong correlation between the trees used in this study and monthly average temperature (Figures 14 and 15). While precipitation may have been well below average for these years, below average temperatures may have mitigated the effects of the hydrologic drought by reducing water loss due to evapotranspiration, thus reducing the severity of the water shortage on tree growth. Second, this drought may have been more pronounced at elevations lower than the sites from where the living trees were collected and used in this study. All weather stations in the central-southern Rio Grande Valley used in the estimation of regional climate data are located at much lower elevations than the sites from where we collected living tree samples. Third, the number of weather stations that existed at the turn of the century in this portion of the Southwest was very small, and even then many annual data were missing. It is well-known that the regional data developed by NOAA are suspect prior to 1930 because of the fewer stations active at the time, and because of the abundance of missing data that had to be estimated. Had additional stations been recording weather observations at the time with regularity throughout the entire study area, the records may have revealed this drought was not as severe as previously believed for this portion of New Mexico. We would also suggest that this drought may not have had the devastating effects on grassland and forested ecosystem as did previous droughts, simply because this drought was comparatively short-lived (six years). This is corroborated by the fact that dendrochronologists working in the Southwest have rarely had difficulty finding trees that survived the 1899-1904 drought, at any elevation, unlike previous droughts when significant changes in ecosystems occurred (*e.g.*, 1946-1961) or were likely to have occurred (*e.g.*, AD 1270-1295, 1571-1584, and 1666-1674).

Swetnam and Betancourt (in press) also document a dramatic change in tree growth rates beginning *ca.* 1976-1977 in many Southwestern tree-ring chronologies concurrent with an increase in annual area burned in Canada and the western United States. Both events are believed to be related – an increase in the frequency of El Niño-Southern Oscillation events is hypothesized to trigger a change in the amount and seasonal distribution of rainfall. Rainfall is shifted more towards the winter and spring months while summer rainfall is much reduced. The increase in annual rainfall may cause increased growth rates of Southwestern trees, while also causing an increase in fine fuels necessary for fire spread. Not only were tree growth rates enhanced, but the rates of growth after 1976-1977 were unprecedented for at least the last 2,129 years at El Malpais National Monument (Grissino-Mayer 1995). However, our study revealed no such increases in growth rates for any trees sampled for this study. Three possibilities exist for this lack of increase:

[1] First, the increase in post-1976 precipitation may have been more pronounced in the northern portions of the Southwest than in southern areas. However, similar unprecedented increases have been noted for nearby sites in the Animas Mountains of southwestern New Mexico and the Pinaleño Mountains of southeastern Arizona. Therefore, this hypothesis alone may not be tenable.

[2] Second, we previously demonstrated the strong relationship that exists between trees used in our study and average monthly temperature (Figures 14 and 15). The lack of increased growth may exist because the influence of temperature may have masked any precipitation effects that would have increased tree growth. Had the increased precipitation that occurred at these higher elevations been accompanied by higher temperatures, water use efficiency would have decreased, resulting in rings of only average width. Only a detailed examination of both temperature and precipitation trends since AD 1976 would confirm this hypothesis.

[3] Third, the living trees used in this study were all collected on exceptionally steep

slopes in the San Mateo, Magdalena, and Organ Mountains, predominantly characterized by rocky scree and talus. Although rainfall may have increased, runoff from these slopes would be expected to be higher than in other areas. Hence, although precipitation had increased to unprecedented annual totals since 1976, trees growing on certain sites, like those used for our study, simply may not show its effects a strongly as other sites where runoff is less.

[4] Finally, we certainly must consider the fact that precipitation in the southern Rio Grande Valley simply may not have occurred at unprecedented levels since AD 1976 as it may have at other sites. Although the actual precipitation values for the post-1976 period are somewhat higher than any extended period since 1930, the indices of tree growth clearly kept pace with the precipitation totals (Figure 16). The trees had indeed accurately recorded the amount of rainfall that fell per year since AD 1976, and these annual totals simply did not occur at such unprecedented levels as recorded elsewhere (*e.g.*, El Malpais National Monument and the Jemez Mountains of northern New Mexico).

Another climatic factor that has certainly impacted Southwestern environments and tree growth over millennial time scales is the El Niño-Southern Oscillation (ENSO). Swetnam and Betancourt (1990, 1992) documented the strong relationship that exists between decadal and longer patterns of wildfire occurrence and ENSO activity, and found that annual area burned increased during high ENSO activity as measured by the Southern Oscillation Index. Based on century-scale fire–climate relationships observed at El Malpais National Monument, Grissino-Mayer and Swetnam (1997) proposed a climate scenario for the Southwest where long-term periods of decreased annual rainfall were characterized by (1) winter–spring rains that are enhanced by increased El Niño-Southern Oscillation activity, and (2) summer monsoonal rainfall that is much reduced. This pattern would increase the likelihood of wildfires occurring later into the growing season as was observed prior to *ca.* AD 1800 (Grissino-Mayer 1995). These relationships suggest long-term changes in the intra-annual distribution of precipitation (winter-spring dominant versus summer dominant rainfall) for the Southwest may be influenced by increased/decreased ENSO activity over century time scales.

While our study could not reconstruct changes in the seasonal distribution of rainfall, we envision that the tree-ring data collected for this study can one day be used to develop seasonal reconstructions of rainfall using intra-ring and density properties (*e.g.*, latewood densities and/or latewood widths as a proxy for late season rainfall). For this project, total ring width was the only tree-ring variable analyzed. Other variables that can potentially be used to analyze intra-annual climate are latewood and earlywood widths, latewood percentage, and maximum latewood and minimum earlywood densities (Hughes 1992; Filion and Cournoyer 1995; Sheppard *et al.* 1996; Briffa *et al.* 1996). Furthermore, studies on the isotopic composition of tree rings from Southwestern samples may eventually lead to the identification of important source regions for moisture in the Southwest. Such studies can be used to reconstruct temporal patterns of summer monsoonal circulation patterns, because summer moisture originates in different geographic locations than winter moisture, and will have different isotopic signatures (Wright *et al.* 1996).

The key for future studies will be to increase the number of tree-ring chronologies collected within the southern Rio Grande Valley to fill in holes in the network, thereby increasing the amount of paleoclimatic information extracted across a broader spatial scale. Additional sites exist in the Magdalena Mountains, Sacramento Mountains, Guadalupe Mountains, and the El Capitan Wilderness, all in southern or central New Mexico, that we believe contain long-lived trees and favorable environments for preserving remnant sections of subfossil wood many centuries old. It would be desirable to conduct research in peripheral areas to the core study area, such as southern Arizona, northern New Mexico, and northern Chihuahua and Sonora. Recently, we learned of an extraordinary site in the Maderas del Carmen highlands in northern Mexico just south of the Big Bend area. These highlands rise to 10,000 feet, and are covered by trees that should yield one or more tree-ring chronologies in excess of 1,000 years.

Finally, we would like to emphasize that the living trees in the mid- to high elevations and the remnant wood samples found lying on the mountain slopes in and around southern New Mexico and western Texas should be considered as valuable scientific resources. and should be accorded some form of protected status. Such samples are all the more valuable in areas generally closed to the public. such as the areas in and around Fort Bliss, White Sands Missile Range. and Holloman Air Force Base. because human disturbances that would remove such trees and wood (*e.g.*, collection of fuelwood. cutting for fence posts, indiscriminant logging practices) are likely minimized. In this sense. military bases may harbor sites that contain tree-ring samples of exceptional age. and should be considered prime locations for future collections by dendrochronologists.

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Appendix 1. Reconstructed precipitation for water year rainfall (in inches) for the central Rio Grande Valley in south-central New Mexico. AD 622-1994.

622	11.34	662	8.37	702	8.49	742	6.95
623	8.61	663	6.28	703	9.70	743	7.43
624	9.98	664	10.49	704	6.34	744	11.70
625	5.05	665	14.81	705	5.40	745	10.28
626	5.34	666	13.21	706	5.60	746	12.15
627	7.87	667	9.32	707	7.32	747	9.83
628	7.08	668	10.59	708	8.33	748	10.58
629	6.71	669	8.49	709	6.24	749	12.61
630	7.02	670	10.82	710	9.62	750	8.48
631	8.53	671	10.65	711	5.96	751	8.83
632	7.86	672	9.17	712	8.87	752	15.18
633	11.27	673	11.57	713	8.49	753	11.79
634	7.78	674	9.16	714	9.81	754	12.56
635	8.92	675	11.99	715	10.16	755	13.98
636	11.54	676	11.13	716	10.46	756	11.24
637	9.18	677	6.07	717	8.99	757	6.47
638	7.06	678	6.36	718	6.09	758	10.25
639	8.60	679	8.06	719	10.12	759	8.57
640	10.49	680	7.35	720	9.52	760	5.38
641	11.00	681	7.55	721	9.09	761	6.83
642	8.28	682	8.04	722	7.68	762	8.51
643	11.39	683	12.71	723	6.27	763	11.11
644	8.16	684	11.16	724	8.61	764	8.39
645	4.31	685	9.24	725	10.96	765	8.43
646	6.51	686	7.17	726	7.99	766	12.79
647	8.19	687	10.40	727	7.43	767	8.39
648	4.66	688	7.11	728	11.96	768	10.72
649	8.84	689	9.90	729	9.99	769	12.28
650	8.82	690	7.26	730	13.53	770	6.77
651	9.55	691	8.07	731	13.73	771	8.98
652	9.53	692	5.24	732	13.50	772	10.55
653	10.24	693	9.57	733	11.12	773	8.42
654	8.05	694	6.45	734	8.81	774	5.53
655	10.20	695	9.30	735	7.52	775	7.99
656	14.63	696	9.98	736	9.02	776	9.78
657	12.15	697	10.73	737	8.99	777	9.70
658	6.78	698	9.72	738	6.22	778	9.64
659	9.52	699	11.31	739	7.59	779	6.15
660	6.78	700	10.11	740	12.56	780	11.91
661	6.89	701	6.74	741	9.49	781	10.06

782	9.25	825	5.33	868	6.15	911	11.14
783	9.02	826	8.26	869	11.51	912	9.37
784	11.51	827	12.09	870	8.40	913	9.60
785	11.03	828	12.29	871	9.97	914	9.47
786	10.19	829	5.32	872	7.85	915	13.56
787	14.42	830	8.93	873	9.29	916	11.01
788	11.38	831	10.11	874	8.72	917	11.54
789	8.92	832	10.11	875	9.83	918	11.82
790	9.88	833	11.56	876	13.80	919	11.08
791	8.59	834	11.53	877	10.54	920	10.32
792	11.18	835	9.71	878	6.40	921	6.63
793	9.47	836	7.22	879	10.26	922	7.70
794	5.04	837	6.59	880	10.83	923	6.97
795	6.43	838	8.59	881	6.91	924	7.34
796	4.61	839	7.69	882	5.41	925	11.28
797	6.33	840	7.28	883	9.18	926	11.04
798	7.86	841	7.57	884	4.50	927	6.77
799	9.24	842	10.05	885	7.78	928	9.90
800	11.56	843	12.30	886	9.64	929	6.60
801	12.02	844	12.17	887	9.96	930	7.31
802	11.64	845	9.53	888	9.36	931	8.32
803	12.37	846	5.63	889	8.23	932	9.82
804	15.16	847	4.73	890	12.44	933	12.21
805	13.82	848	9.38	891	9.05	934	9.93
806	13.98	849	9.00	892	5.58	935	7.80
807	10.20	850	5.33	893	12.01	936	8.70
808	10.53	851	8.61	894	9.66	937	6.02
809	7.57	852	11.25	895	10.26	938	9.94
810	8.77	853	10.08	896	12.55	939	11.59
811	8.75	854	11.70	897	12.83	940	9.76
812	7.98	855	8.54	898	13.65	941	11.30
813	8.33	856	8.59	899	10.44	942	8.95
814	6.48	857	6.00	900	8.57	943	8.82
815	7.89	858	11.08	901	6.13	944	8.11
816	8.36	859	9.84	902	12.00	945	10.97
817	9.60	860	12.17	903	8.98	946	10.30
818	7.64	861	9.17	904	12.67	947	8.45
819	9.23	862	11.86	905	10.63	948	7.49
820	12.88	863	11.21	906	7.08	949	11.29
821	13.31	864	8.22	907	5.88	950	10.77
822	12.08	865	11.88	908	10.15	951	8.57
823	7.21	866	10.22	909	9.83	952	8.77
824	7.25	867	8.07	910	11.59	953	10.83

954	4.89	997	10.26	1040	9.31	1083	5.21
955	9.54	998	7.94	1041	5.93	1084	12.14
956	12.41	999	5.99	1042	8.06	1085	6.82
957	8.35	1000	8.29	1043	10.03	1086	9.88
958	7.49	1001	7.42	1044	8.71	1087	11.33
959	11.46	1002	6.46	1045	8.95	1088	11.32
960	12.53	1003	7.19	1046	11.30	1089	10.60
961	9.85	1004	8.43	1047	9.74	1090	6.93
962	9.40	1005	6.23	1048	6.25	1091	6.02
963	8.47	1006	8.95	1049	10.04	1092	10.88
964	8.77	1007	11.17	1050	12.34	1093	11.24
965	10.75	1008	9.21	1051	8.21	1094	9.06
966	12.11	1009	5.29	1052	11.49	1095	10.66
967	11.25	1010	6.71	1053	10.27	1096	11.89
968	10.91	1011	8.90	1054	8.25	1097	7.84
969	6.29	1012	9.73	1055	11.54	1098	11.15
970	10.54	1013	8.89	1056	8.32	1099	5.38
971	9.30	1014	6.44	1057	9.92	1100	10.81
972	7.43	1015	10.14	1058	8.70	1101	12.70
973	10.10	1016	11.16	1059	11.05	1102	11.93
974	7.04	1017	9.07	1060	12.98	1103	10.18
975	4.10	1018	7.41	1061	12.55	1104	10.95
976	10.39	1019	9.31	1062	12.55	1105	10.58
977	10.34	1020	12.05	1063	13.37	1106	10.26
978	6.73	1021	10.89	1064	11.30	1107	8.84
979	8.77	1022	9.76	1065	12.91	1108	9.63
980	6.61	1023	9.26	1066	9.39	1109	12.31
981	6.98	1024	11.58	1067	7.01	1110	11.21
982	8.36	1025	10.91	1068	11.73	1111	10.76
983	7.95	1026	9.84	1069	6.76	1112	9.08
984	6.59	1027	7.62	1070	10.22	1113	11.42
985	7.72	1028	9.18	1071	10.49	1114	7.93
986	9.36	1029	10.92	1072	11.42	1115	11.37
987	10.67	1030	9.68	1073	9.20	1116	13.56
988	12.11	1031	6.73	1074	9.39	1117	12.71
989	11.31	1032	9.03	1075	8.25	1118	11.46
990	9.25	1033	8.20	1076	12.44	1119	10.20
991	8.59	1034	7.90	1077	12.11	1120	12.47
992	6.79	1035	5.51	1078	8.86	1121	6.30
993	8.28	1036	5.30	1079	11.57	1122	12.80
994	9.74	1037	7.28	1080	10.61	1123	8.21
995	10.68	1038	7.72	1081	9.53	1124	10.52
996	9.43	1039	9.29	1082	12.34	1125	8.32

1126	7.55	1169	5.10	1212	9.76	1255	10.79
1127	8.53	1170	9.88	1213	11.17	1256	8.53
1128	6.94	1171	13.60	1214	6.86	1257	7.27
1129	10.92	1172	8.18	1215	6.97	1258	7.17
1130	9.67	1173	11.88	1216	8.51	1259	9.59
1131	6.79	1174	8.33	1217	5.33	1260	10.52
1132	10.75	1175	8.93	1218	8.48	1261	9.82
1133	9.21	1176	13.06	1219	11.08	1262	13.04
1134	5.86	1177	6.31	1220	8.76	1263	10.00
1135	7.90	1178	10.46	1221	8.50	1264	12.21
1136	8.78	1179	10.54	1222	9.63	1265	10.11
1137	7.64	1180	11.23	1223	11.00	1266	8.12
1138	6.43	1181	9.90	1224	5.03	1267	10.76
1139	8.21	1182	7.91	1225	9.49	1268	9.87
1140	7.42	1183	9.96	1226	8.29	1269	8.43
1141	11.81	1184	10.36	1227	6.13	1270	12.40
1142	12.17	1185	10.56	1228	10.54	1271	10.21
1143	6.38	1186	6.49	1229	12.37	1272	7.53
1144	8.97	1187	8.59	1230	10.26	1273	7.30
1145	9.87	1188	7.96	1231	11.10	1274	9.12
1146	6.45	1189	6.52	1232	10.66	1275	11.09
1147	7.66	1190	7.97	1233	7.41	1276	5.27
1148	9.98	1191	10.05	1234	6.23	1277	5.04
1149	9.60	1192	5.21	1235	10.72	1278	6.40
1150	6.58	1193	11.05	1236	7.59	1279	10.21
1151	7.68	1194	10.09	1237	10.02	1280	7.11
1152	11.93	1195	11.42	1238	12.67	1281	7.50
1153	11.37	1196	10.30	1239	9.99	1282	6.74
1154	10.53	1197	12.47	1240	8.41	1283	9.60
1155	12.17	1198	11.28	1241	11.36	1284	7.55
1156	8.19	1199	10.73	1242	8.61	1285	9.95
1157	7.36	1200	13.63	1243	9.60	1286	7.71
1158	8.47	1201	14.65	1244	9.62	1287	10.36
1159	11.71	1202	11.25	1245	10.66	1288	4.06
1160	11.60	1203	9.75	1246	5.59	1289	9.63
1161	7.12	1204	7.01	1247	7.43	1290	9.58
1162	13.43	1205	8.62	1248	8.06	1291	5.71
1163	11.06	1206	5.80	1249	10.17	1292	10.56
1164	8.65	1207	8.42	1250	8.54	1293	9.29
1165	12.25	1208	8.00	1251	4.55	1294	8.75
1166	6.42	1209	11.16	1252	6.23	1295	5.89
1167	8.84	1210	12.11	1253	8.97	1296	5.15
1168	9.11	1211	9.84	1254	4.77	1297	9.35

1298	12.03	1341	7.35	1384	8.48	1427	12.86
1299	10.40	1342	8.71	1385	15.05	1428	15.22
1300	9.71	1343	9.04	1386	10.71	1429	7.55
1301	10.33	1344	10.69	1387	7.12	1430	11.11
1302	10.88	1345	12.01	1388	11.94	1431	9.77
1303	6.99	1346	12.14	1389	13.21	1432	10.45
1304	7.97	1347	4.85	1390	8.75	1433	13.17
1305	10.74	1348	9.08	1391	8.38	1434	11.57
1306	9.26	1349	7.99	1392	11.64	1435	11.73
1307	8.11	1350	7.30	1393	9.63	1436	8.68
1308	8.15	1351	9.73	1394	9.13	1437	7.44
1309	11.52	1352	10.02	1395	9.57	1438	5.58
1310	11.89	1353	11.59	1396	11.83	1439	8.98
1311	12.65	1354	10.69	1397	8.06	1440	11.11
1312	10.54	1355	5.79	1398	12.23	1441	10.69
1313	12.66	1356	11.60	1399	8.49	1442	9.75
1314	12.37	1357	7.99	1400	8.33	1443	11.18
1315	9.10	1358	11.46	1401	10.30	1444	11.02
1316	5.59	1359	11.66	1402	10.86	1445	6.07
1317	8.51	1360	6.84	1403	10.87	1446	8.81
1318	10.75	1361	9.52	1404	11.19	1447	8.82
1319	11.39	1362	8.41	1405	7.47	1448	4.62
1320	9.46	1363	5.70	1406	10.28	1449	6.27
1321	10.62	1364	8.06	1407	3.61	1450	7.00
1322	10.36	1365	8.38	1408	9.24	1451	10.46
1323	7.97	1366	9.70	1409	8.05	1452	8.53
1324	6.45	1367	8.95	1410	8.14	1453	10.95
1325	10.97	1368	13.05	1411	5.45	1454	9.28
1326	8.99	1369	6.78	1412	8.35	1455	6.13
1327	7.33	1370	12.14	1413	7.87	1456	7.65
1328	9.36	1371	10.46	1414	12.53	1457	10.20
1329	10.10	1372	10.10	1415	5.93	1458	9.85
1330	11.01	1373	9.00	1416	9.26	1459	7.15
1331	11.24	1374	10.52	1417	12.04	1460	9.69
1332	11.81	1375	8.51	1418	8.76	1461	7.89
1333	11.45	1376	7.35	1419	8.74	1462	8.75
1334	9.48	1377	11.18	1420	8.64	1463	6.99
1335	7.86	1378	11.26	1421	10.06	1464	7.73
1336	9.36	1379	10.95	1422	6.52	1465	9.99
1337	8.57	1380	12.81	1423	6.06	1466	11.76
1338	6.31	1381	9.20	1424	9.11	1467	11.18
1339	10.72	1382	7.83	1425	9.77	1468	10.02
1340	10.47	1383	11.15	1426	13.71	1469	8.59

1470	8.15	1513	9.69	1556	13.19	1599	10.47
1471	5.22	1514	8.00	1557	9.70	1600	8.35
1472	9.13	1515	10.20	1558	7.73	1601	5.94
1473	9.55	1516	6.66	1559	10.61	1602	9.36
1474	9.20	1517	6.18	1560	4.57	1603	11.52
1475	6.71	1518	9.66	1561	9.08	1604	10.33
1476	8.67	1519	10.15	1562	8.76	1605	8.42
1477	9.76	1520	10.27	1563	7.27	1606	9.55
1478	10.84	1521	12.42	1564	8.81	1607	8.68
1479	10.53	1522	6.27	1565	9.98	1608	10.94
1480	6.61	1523	5.67	1566	10.47	1609	9.42
1481	11.22	1524	4.11	1567	7.85	1610	11.39
1482	10.19	1525	8.91	1568	11.64	1611	11.33
1483	7.76	1526	10.49	1569	8.98	1612	13.23
1484	12.58	1527	9.33	1570	10.02	1613	8.36
1485	11.94	1528	8.15	1571	7.44	1614	6.77
1486	12.04	1529	12.42	1572	7.83	1615	8.65
1487	6.11	1530	12.57	1573	6.09	1616	9.38
1488	8.01	1531	10.47	1574	8.48	1617	7.65
1489	7.98	1532	6.60	1575	7.69	1618	11.53
1490	9.97	1533	9.10	1576	5.78	1619	10.28
1491	10.09	1534	11.80	1577	8.75	1620	10.49
1492	12.95	1535	8.63	1578	9.10	1621	12.43
1493	8.79	1536	12.48	1579	6.77	1622	10.37
1494	9.38	1537	10.74	1580	8.51	1623	8.71
1495	6.45	1538	6.70	1581	7.58	1624	4.87
1496	7.76	1539	11.65	1582	9.39	1625	7.78
1497	8.41	1540	13.78	1583	5.05	1626	7.65
1498	13.26	1541	10.62	1584	7.62	1627	12.36
1499	13.54	1542	7.80	1585	5.08	1628	8.96
1500	10.97	1543	10.79	1586	9.73	1629	14.34
1501	7.49	1544	8.92	1587	8.39	1630	10.47
1502	6.31	1545	9.81	1588	11.21	1631	7.10
1503	7.53	1546	8.33	1589	9.13	1632	6.38
1504	9.07	1547	7.80	1590	8.54	1633	9.48
1505	9.11	1548	9.58	1591	11.18	1634	11.30
1506	6.28	1549	6.59	1592	9.24	1635	10.22
1507	13.08	1550	10.65	1593	5.42	1636	10.02
1508	12.09	1551	7.03	1594	11.25	1637	12.16
1509	10.05	1552	8.19	1595	9.03	1638	9.31
1510	11.44	1553	13.51	1596	9.76	1639	11.61
1511	12.77	1554	11.81	1597	10.86	1640	12.32
1512	9.55	1555	13.34	1598	8.62	1641	11.28

1642	8.85	1685	4.96	1728	9.19	1771	11.73
1643	8.35	1686	11.56	1729	7.49	1772	8.21
1644	10.65	1687	9.07	1730	5.09	1773	4.85
1645	10.52	1688	8.35	1731	7.70	1774	6.94
1646	10.06	1689	12.49	1732	8.22	1775	7.32
1647	10.94	1690	9.98	1733	3.97	1776	7.06
1648	6.08	1691	6.95	1734	9.97	1777	6.08
1649	9.47	1692	13.13	1735	9.48	1778	7.29
1650	10.19	1693	10.66	1736	10.32	1779	8.22
1651	12.53	1694	10.79	1737	9.10	1780	7.25
1652	9.62	1695	9.57	1738	10.43	1781	10.46
1653	8.81	1696	6.56	1739	5.07	1782	6.74
1654	7.86	1697	10.75	1740	7.09	1783	12.20
1655	11.00	1698	9.60	1741	10.40	1784	13.30
1656	8.48	1699	12.63	1742	6.73	1785	9.53
1657	6.87	1700	10.75	1743	11.73	1786	7.37
1658	9.36	1701	12.10	1744	10.38	1787	10.05
1659	8.87	1702	8.26	1745	10.15	1788	10.11
1660	9.64	1703	12.24	1746	12.81	1789	6.22
1661	11.99	1704	9.90	1747	13.52	1790	11.46
1662	10.86	1705	7.80	1748	4.87	1791	10.84
1663	10.02	1706	8.32	1749	10.63	1792	11.37
1664	8.39	1707	6.88	1750	8.87	1793	16.30
1665	11.64	1708	10.60	1751	13.00	1794	9.84
1666	8.08	1709	5.84	1752	7.01	1795	11.54
1667	5.34	1710	12.11	1753	8.49	1796	7.83
1668	4.10	1711	9.01	1754	9.08	1797	9.32
1669	7.69	1712	8.49	1755	8.32	1798	8.51
1670	5.86	1713	8.07	1756	9.54	1799	9.69
1671	8.84	1714	7.37	1757	5.25	1800	8.64
1672	7.69	1715	7.14	1758	10.38	1801	9.99
1673	6.03	1716	5.29	1759	10.96	1802	10.58
1674	8.96	1717	9.27	1760	7.47	1803	8.86
1675	9.73	1718	11.27	1761	8.33	1804	10.27
1676	9.35	1719	7.01	1762	9.20	1805	7.41
1677	11.95	1720	10.68	1763	6.40	1806	7.65
1678	10.72	1721	13.23	1764	9.50	1807	10.42
1679	10.30	1722	13.42	1765	8.15	1808	8.58
1680	12.10	1723	9.71	1766	11.39	1809	9.03
1681	9.79	1724	8.40	1767	12.81	1810	11.01
1682	12.96	1725	9.26	1768	10.75	1811	11.47
1683	11.08	1726	12.28	1769	11.45	1812	10.32
1684	8.21	1727	9.78	1770	10.55	1813	11.49

1814	10.70	1857	10.27	1900	9.39	1943	10.00
1815	15.46	1858	11.66	1901	9.32	1944	9.21
1816	15.25	1859	6.86	1902	8.78	1945	9.99
1817	9.05	1860	8.50	1903	11.86	1946	7.58
1818	4.88	1861	6.71	1904	8.20	1947	7.57
1819	7.10	1862	5.44	1905	12.95	1948	8.11
1820	7.07	1863	6.38	1906	11.29	1949	9.31
1821	8.26	1864	7.56	1907	14.41	1950	7.10
1822	5.88	1865	7.54	1908	13.81	1951	5.29
1823	6.59	1866	9.40	1909	7.31	1952	8.27
1824	7.00	1867	7.63	1910	6.88	1953	6.68
1825	7.92	1868	9.28	1911	11.33	1954	4.02
1826	7.84	1869	10.58	1912	10.05	1955	6.63
1827	11.51	1870	7.61	1913	11.89	1956	4.70
1828	10.26	1871	7.70	1914	13.09	1957	5.72
1829	11.42	1872	9.11	1915	9.87	1958	9.06
1830	9.68	1873	8.62	1916	9.52	1959	7.76
1831	7.76	1874	7.00	1917	9.76	1960	9.09
1832	7.96	1875	8.20	1918	7.79	1961	8.56
1833	10.26	1876	8.44	1919	13.22	1962	9.64
1834	10.90	1877	9.91	1920	12.08	1963	7.77
1835	11.93	1878	9.28	1921	10.53	1964	8.86
1836	8.01	1879	7.64	1922	8.91	1965	8.05
1837	10.41	1880	6.91	1923	7.65	1966	11.03
1838	9.56	1881	8.89	1924	9.95	1967	7.41
1839	11.99	1882	10.68	1925	4.88	1968	11.16
1840	11.47	1883	11.04	1926	10.69	1969	9.40
1841	9.98	1884	9.24	1927	8.99	1970	11.11
1842	9.72	1885	12.16	1928	9.04	1971	7.23
1843	9.28	1886	7.13	1929	10.60	1972	10.40
1844	10.98	1887	9.05	1930	9.60	1973	10.59
1845	13.10	1888	9.50	1931	12.10	1974	6.00
1846	13.23	1889	9.04	1932	9.36	1975	12.01
1847	7.37	1890	8.49	1933	12.95	1976	9.97
1848	10.08	1891	9.39	1934	7.08	1977	8.42
1849	11.88	1892	5.64	1935	8.86	1978	9.33
1850	9.61	1893	6.93	1936	9.34	1979	10.79
1851	5.88	1894	6.87	1937	9.94	1980	9.42
1852	10.45	1895	7.86	1938	9.46	1981	10.85
1853	9.53	1896	7.02	1939	7.93	1982	10.27
1854	10.53	1897	9.81	1940	11.80	1983	10.26
1855	8.74	1898	12.78	1941	13.61	1984	11.87
1856	10.33	1899	8.49	1942	10.74	1985	11.08

1986	12.35
1987	11.50
1988	11.67
1989	7.95
1990	8.91
1991	11.40
1992	11.59
1993	10.68
1994	9.75