PAST VEGETATION AND CLIMATE OF THE MOGOLLON RIM AREA, ARIZONA

by

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A Dissertation Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fullfilment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY
WITH A MAJOR IN GEOSCIENCES

In the Graduate College

THE UNIVERSITY OF ARIZONA

1983

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Bonnie Fine Jacobs

entitled Past Vegetation and Climate of the Mogollon Rim Area, Arizona

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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SIGNED: Bonnie June Jacobs

Dedicated to my Parents

ACKNOWLEDGEMENTS

Many people helped me with this project by providing or helping me obtain funds and by offering helpful suggestions, insightful discussion or constructive criticism. I have tried to mention all those people by name and must apologize if any were inadvertently left out.

Funding for field work was awarded by the Graduate Student Development fund and the Provost through the Dissertation Stipend Award, 1980. Grants to Vera Markgraf from the NSF and College of Earth Sciences and National Geographic Society grant number 2410-81 to P. Martin, T. R. Van Devender, and J. Betancourt provided money for ^{14}C analyses. A Hernon-Jones scholarship from the Department of Geosciences provided further funding for completion of the dissertation.

The field work could not have been accomplished without the help of the following people: Arica Rhyersbach, George Trussell, Louis Jacobs, Pat Fall, Barbara Phillips, Suzy Reils, Kathy Flanagan, Julie Jacobs, Dave Steadman, Rob Sternberg, Ben Brown, Vera Markgraf, Bob Thompson, and Pacifico Payawal. I thank Charles Robinson and Associates for the use of their motor-driven coring apparatus.

I was able to do the pollen counts at the International Laboratory for Research on animal diseases, Kabete, Kenya, with the kind permission of Dr. Don Fawcett. Access to the microscope was generously shared by Jon Larsen and Steve Doxsey. Other research was conducted a the National Museums of Kenya, Nairobi. I express my graitude to Richard Leakey, my employer, for permision to take a leave of absence from the National Museums of Kenya in order to complete this dissertation at the University of Arizona. My stay in Tucson while writing was made possible by Steve Falconer and Pat Fall and I will always be grateful for their generosity and patience.

I would like to thank the following people for reading and editing the text and/or for productive and insightful discussion of the subject mater: Louis Jacobs, Pat Fall, Bob Thompson, Julio Betancourt, Ken Cole, Tom Van Devender, Jim Mead, Ben Brown, and Mary Kay O'Rourke.

I am very graeful to Emilee Mead and Bob Erskine who were so generous with their time and always willing to help me with the illustrations.

Lastly, and importantly, I express my sincere appreciation to my academic committee members, Vera Markgraf, Owen Davis, Paul Martin, Karl Flessa, Ray Turner, and Jim Brown, whose cooperation and interest aided me greatly in the successful completion of this project.

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ABSTRACT

This study reconstructs vegetation and climate encompassing pre-full glacial and Holocene time for the Mogollon Rim region of Arizona. Implications for the southwestern United States are discussed. Pine species (some currently disjunct) or species groups are identified. Two lakes were cored, the sediments were analyzed for pollen content, and dates were obtained by radiocarbon analysis. Hay Lake (2780 m) is surrounded by mixed conifer forest in the White Mountains, Arizona (34^{o}N and $109^{o}30'$W). Jacob Lake (2285 m, $34^{o}25'$ N and $110^{o}50'$ W) is surrounded by ponderosa pine forest. Extrapolated dates for basal sediments are approximately 42,000 B.P. and 20,000 B.P. for Hay Lake and Jacob Lake respectively.

Based on pollen, local vegetation at Hay Lake between approximately 42,000 and 29,000 B.P. consisted of mixed conifer forest dominated by *Pinus aristata*, *P. flexilis* and/or *P. strobiformis* with *Picea* codominant. Of the identified pine species, 98% are haploxylon and most are pinyon pine. Pinyon pine was more widespread at lower elevations than today. The proposed Mid-Wisconsin climate has greater winter precipitation and summers cooler than today. However, the climate was warmer and probably drier than the full-glacial. Treeline was above the site. The period 29,000 to 25,000 B.P. is climatically and vegetationally transitory to the full glacial. Yellow pines

(*P. ponderosa/contorta*) are present for the first time and *Picea* pollen increases from previous levels.

The full glacial (25,000 to 13,700 B.P.) at Hay Lake is characterized by an association of *Picea* and Gramineae pollen and at Jacob Lake by *Picea* and *Artemisia* pollen. A high elevation parkland at the forest-tundra ecotone surrounded Hay Lake. Open coniferous forest surrounded Jacob Lake. A conservative estimate of treeline depression is 570 m. Winters during the full glacial were warmer and wetter and summers were cooler and drier than today.

The early and middle Holocene is characterized by an increase in open vegetation and in herbaceous pollen taxa; *Artemisia* at Hay Lake and Gramineae at Jacob Lake. The climate was cooler and wetter than today but less so than during the Pleistocene. Iron-mottled sediments and a hiatus in the pollen record at Jacob Lake (between about 11,850 and 900 B.P.) together with expansion of *Artemisia* at Hay Lake represent overall drought during the middle Holocene when compared with today although summer monsoons may have been intensified.

Modern pollen assemblages begin at Hay Lake about 1700 B.P. and are not datable at Jacob Lake. The transition to modern conditions may have resulted from increased fire frequency at Hay Lake and from fire suppression by early settlers at Jacob Lake.

CHAPTER ONE

INTRODUCTION

Past Glacial Epochs have been pondered since the time of Lyell and Agassiz (West, 1977). Though progress has been made toward understanding the physical impact of climatic change, there is no consensus about its causes or the future direction of our present climate (Lamb, 1977; Kerr, 1982). The timing, periodicity and intensity of past climatic changes can be related, albiet in a complex way, to theories of climatic change, which have predictive value (Lamb, 1977). Therefore, the better our knowledge of past climatic change, the better is our understanding of their causes. To predict climatic trends, the current climate must be interpreted in terms of patterns observed for the past. This study is a contribution to the understanding of the climatic history of the late Pleistocene and Holocene in the White Mountains - Mogollon Rim region of Arizona, at the southern edge of the Colorado Plateau (Fig. 1).

The only way to reconsruct climatic records for the prehistoric past is through proxy data from systems that are closely linked to climate. Many reconstructions have been made on the basis of paleovegetation data, especially in

Fig. 1. Colorado Plateau, study sites and other loclaities mentioned in text.

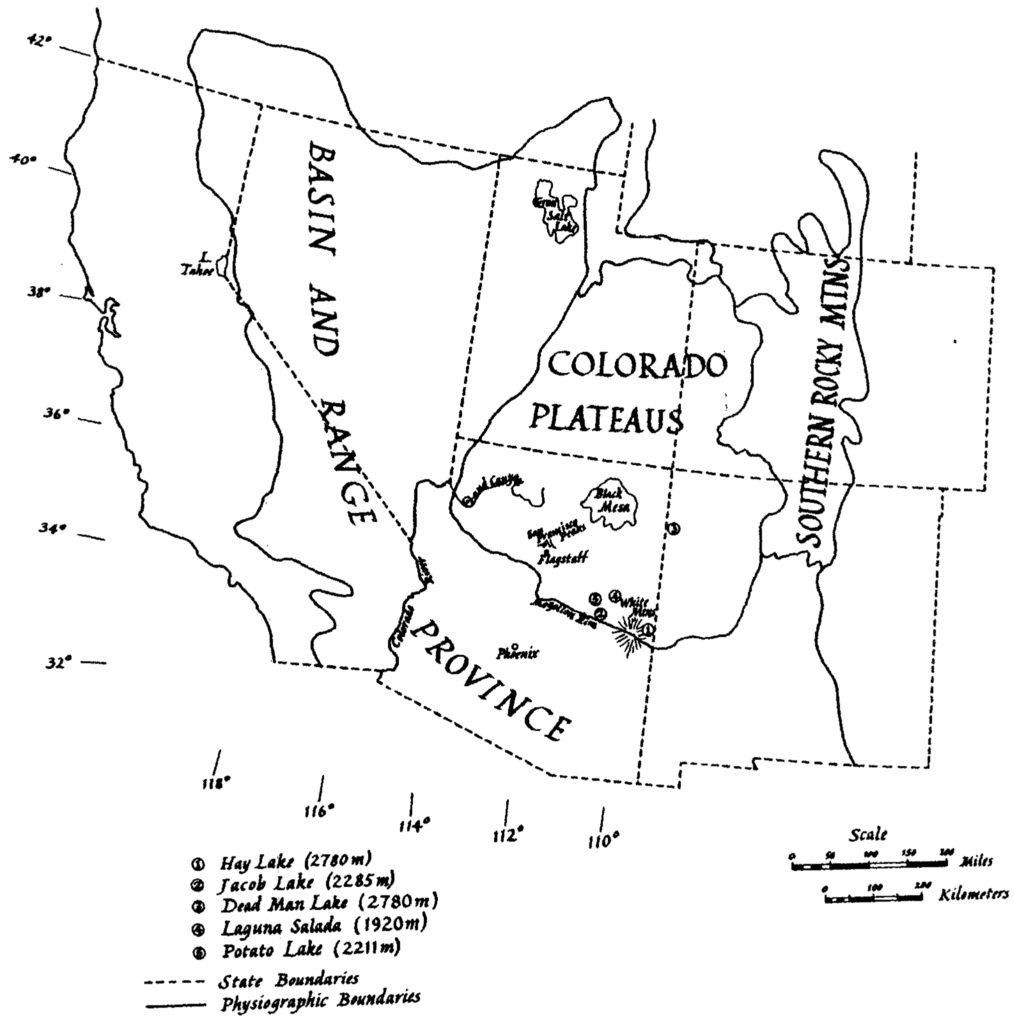

Fig. 1. Colorado Plateau, study sites and other localities.

northern hemisphere temperate regions. Recent efforts by, for example, Nicholson and Flohn (1980), Colhoun et al. (1982), and Heusser (1982) are beginning to improve the knowledge of tropical and subtropical regions. The present work will broaden the data base for vegetation and climatic reconstructions for the American southwest during the Pleistocene and Holocene, and will augment or modify reconstructions made by earlier researchers.

Some previous climatic reconstructions of the American southwest are based on plant macrofossils from ancient packrat middens (e.g., Van Devender and Spaulding, 1979), and alluvial stratigraphic sections (Haynes, 1973; Antevs, 1954). Pollen records come from large lowland playa basins (e.g., Martin, 1963a; Clisby and Sears, 1956), from alluvial sections (Mehringer and Haynes, 1965), and from smaller higher elevation lake basins (Whiteside, 1964; Wright et al., 1973). Many of these paleontological records come from sites at lower elevations and reconstructions for higher elevation vegetation in Arizona have been made mostly by extrapolation.

Plant macrofossils contained in packrat middens are assumed to be samples from communities within a radius of approximately 100 to 200 m around the site (Stones and Hayward, 1968). Each midden provides data on the past distribution of various plant species. However, problems associated with midden analysis that limit their usefulness for paleoclimatology include the following: 1) the collecting preferences of modern packrats are poorly documented 2) each midden represents an imprecise, but geologically short length of time and 3) the plant macrofossils cover a small geographic area. In addition, packrat middens are preserved only in dry environments and therefore they have not been found above approximately 1600 m in Arizona, New Mexico, or Colorado. Although they are discontinuous over time and space and are poorly understood, broadscale climatic reconsructions have been made on the basis of fossil packrat midden data (e.g., Van Devender and Spaulding, 1979; Wells, 1966; Wells and Berger, 1967). Regional and continuous paleovegetation data are needed to compliment the midden record and test theoretical vegetation and climatic reconstructions based on them.

Reconstructions based on alluvial geology and palynology (e.g., Antevs, 1954; Mehringer and Haynes, 1965) integrate information from over a much larger area, but yield less precise records of local vegetation changes in the lowland southwest. Pollen records from large playa lake basins are relatively insensitive to past distributional vegetation changes because thier pollen collecting area covers large, poorly defined regions (Jacobson and Bradshaw, 1981). These records of extralocal and possibly waterborne pollen can only be applied to long-term large-scale climatic reconstructions. Sediment cores from small lake basins with no inflowing or outflowing streams yield more sensitive pollen records that better reflect the local vegetation around the site (Jacobson and Bradshaw, 1981). Furthermore, these records are often relatively continuous and datable. A few records have been obtained from the Colorado Plateau region (Maher, 1961; Petersen and Mehringer, 1976; Andrews et al., 1975; Wright et al., 1973; Whiteside, 1964; Merrill and Pewe, 1977); they help to reveal the paleoclimatology and paleoecology of the southwestern United States.

The goal of the present study is to answer the following questions about the past vegetation, biogeography, and climate of the Mogollon Rim Region, Arizona and (more generally) of the Southwest: 1) What was the magnitude of treeline depression during cold episodes? 2) What was the vegetation at middle elevations during the late Pleistocene and Holocene? 3) What were the past distributions of some presently disjunct conifer populations such as those of the montane species *Pinus flexilis* (limber pine) and *P. aristata* (bristlecone pine)? 4) What was the seasonal distribution of rainfall and temperature during full glacial and post glacial times relative to today? and 5) What is the appropriate synoptic climatology for reconstructed rainfall and temperature regimes?

Trees reach their uper altitudinal limit in Arizona at about 3500 meters and woodlands occur as low as about 1680 meters (Lowe and Brown, 1973). The factor limiting tree growth at upper elevations is generally temperature (Daubenmire, 1974; Larsen,1974); and at lower elevations it is available moisture (Daubenmire, 1943). Pollen records from small lake basins at or near upper and lower treelines may reveal evidence of treeline fluctuations. Samples from additional sites allow more accurate regional vegetation reconstructions. Treeline fluctuations and changes in plant species composition are both used to make paleoclimatic reconstructions.

Pollen analysts identify fossil pollen by comparison with pollen from living species and assume that no evolutionary morphological changes have occurred since the pollen was deposited. Ecological tolerances for the various species are assumed to be similar during the Pleistocene to what they are today.

Paleovegetation is inferred from pollen assemblages, but pollen assemblages found in a core of lake sediment are not simple mirrors of the surrounding vegetation. The assemblages have been subject to all the events of differential pollen production, transport, deposition and preservation (Birks and Birks, 1980). A basic assumption is that these factors do not bias the sample to the extent that compensation cannot be made for their effects. These factors are overcome by comparison of the fossil pollen assemblage with modern pollen deposits in order to take into accout the effects of such things as sediment texture and depositional environment. Therefore, inherent limitations in pollen analysis do not preclude its use in reconstruction of past vegetation.

Physical Setting

Physiography and Geology

The Colorado Plateau (Fig. 1) includes parts of Arizona, New Mexico, Colorado, and Utah. In Arizona the Colorado Plateau forms the Plateau physiographic province, which is generally over a mile high, relatively mesic, and contrasts with the Basin and Range province of the generally lower elevation, more xeric southern half of the state (Peirce, Keith, and Wilt, 1970). The Mogollon Rim forms the southern edge of the Plateau, it extends through central Arizona from northwest to southeast.

Cliffs forming the Mogollon Rim are composed of resistant, Coconino Sandstone or limestones of the Toroweap or Kaibab formations. Underlying softer rocks comprise the Supai Group. The Mogollon Rim is the result of differential erosion related to the relative competency of the rock units and the regional tectonic setting. Other relatively minor modifications took place later during Late Cenozoic Basin and

Range development (Peirce, Damon, and Shafiqullah, 1979; Jacobs, 1981).

Where Coconino Sandstone is the bedrock along the Mogollon Rim, lakes and sinkholes are common. The mechanisms responsible for the formation of these basins are unknown although they may be: 1) the remains of differential erosion processes, 2) original depressions in an ancient land surface having since been exhumed by erosion of once overlying deposits, or, 3) dissolution pits in underlying dolomite or limestone deposits (e.g., the upper and middle parts of the Supai Formation; Nations and Stump,1981; Peirce et al., 1979) that caused occasional subsidence in the Coconino Sandstone.

The highest mountains in Arizona rise from the Colorado Plateau and are composed mainly of volcanic rocks. The San Francisco Mountains near Flagstaff includes the highest peak in the state, Mt. Humphreys (3850 m). The White Mountains are located in east central Arizona on the edge of the plateau. Mt. Baldy (3533 m) is the highest peak in this range and the second highest in the state. Volcanism began in the White Mountains during Oligocene-Miocene times, although the eruptions forming Mt. Baldy began about 8.6 million years ago (Merrill and Pewe, 1977).

This study is based on pollen samples from cores extracted from the sediments of two lakes. Figure 1 shows the coring localities in relation to the physical features of the region. Hay Lake is located in the White Mountains region of Arizona (34° N, 109° 30' W). It is an enclosed basin at about 2780 m (9120 ft) elevation perched on basaltic bedrock. A lava flow which may be of Pleistocene age appears to have dammed any pre-existing outlet on the northeast side of the lake. Geophysicists familiar with the basalts around Hay Lake, however, suggest they are between six and eight million years old, although, they have not been radiometrically dated (Aubele, Pers. Comm., 1983). Thus the origins of Hay Lake are unknown. The area of the basin is approximately 16 ha.

Jacob Lake is located approximately 133 km west of Hay Lake on the Mogollon Rim at about 2285 m (7500 ft) elevation and 34° 25' N, and 110 50' W. The Jacob Lake basin is more shallow and broad than the Hay lake basin and has an area of approximately 8 ha. Bedrock is Coconino sandstone (Nations and Stump, 1981). Depostion in Jacob Lake started between about 20,000 and 25,000 years ago based on extrapolation to the bottom of the sediment core collected there (see below).

Climate

Rainfall distribution in the southwestern United States is determined by the frequencey and source of moisture-bearing air masses. Figure 2 shows a simplified summary of the seasonal distribution of precipitation maxima in the western United States. Almost all of Arizona is

Fig. 2. Season of primary precipitation maximum with (+) indicating secondary maxima. From Pyke, 1972.

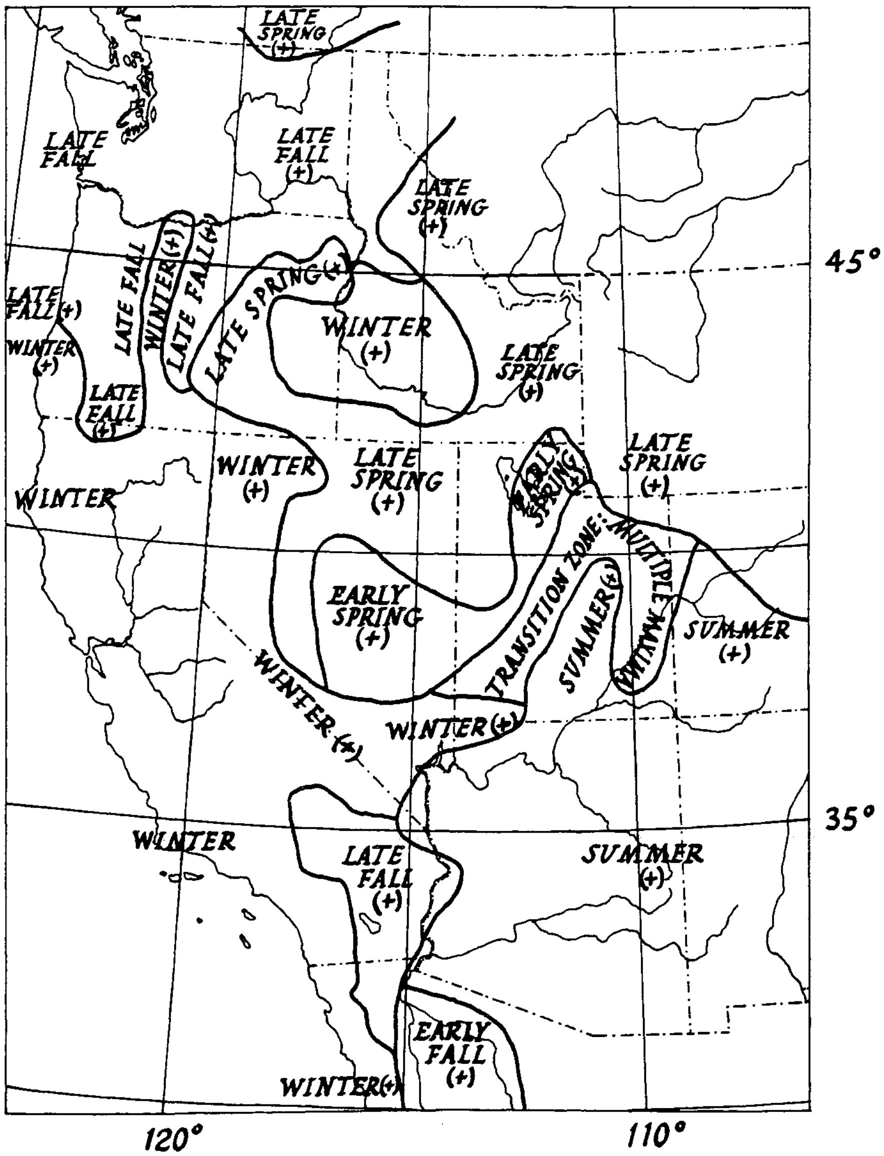

Fig. 2. Season of primary precipitation showing secondary maxima.

within the summer-dominant rainfall regime having a secondary winter maximum. Western Colorado is within the same category. Utah is divided into four sections because of its location where several airmasses interact. The extreme western and southeastern portions of Nevada, as well as the adjoining parts of California, Utah, and Arizona, are within a region of winter precipitation dominance with secondary maxima.

In most of Arizona, the secondary peak of precipitation occurs during the winter months; winter precipitation generally decreases across the state from northwest to southeast. Winter rains enter the region via Jet Stream westerlies, which are associated with the development of a low pressure cell (cyclone) off the coast of California (Bryson, 1957; Pyke, 1972; Douglas and Fritts, 1974). This low originates near the Aleutian Islands in the early fall and is associated with the circumpolar vortex. The low pressure cell migrates southward beginning in the fall and eventually brings winter and early spring rains to southern California (Efford, 1970; Douglas and Fritts, 1974). The amount of winter rainfall decreases towards the east and southeast both across Arizona and in the Great Basin to the north. Droughts in California occur when upper-level ridging along the coast keeps storms north of the normal track in Washington and Canada (Douglas and Fritts, 1974).

The moisture associated with summer maximum precipitation regimes in the southwest has been attributed to several sources. All authors (e.g., Bryson, 1957; Mitchell, 1976; Bryson and Lowry, 1955; Reitan, 1960; Hastings and Turner, 1965) agree that some of the moisture associated with the summer rains is brought into the southwest from the Gulf of Mexico. By May and June, the eastern North Pacific is no longer under the influence of the Aleutian low, which has disintegrated (Pyke, 1972) or moved north (Bryson,1957). At that time, a high pressure cell (the subtropical jet stream) is located off the coast of California and strong westerlies bring relatively dry air in over the southwest (Pyke, 1972).

Between the end of June and the first weeks of July, the high pressure cell moves rapidly north (Bryson and Lowry, 1955; Reitan, 1960; and others) or begins to dissipate (Douglas and Fritts, 1974). To the southeast a small high pressure cell breaks away from the main Bermuda High circulation (Bryson and Lowry, 1955). Thus, a moist tongue of air moves over the southwestern United States from the Gulf of Mexico bringing the onset of the summer monsoon.

Douglas and Fritts (1973) state that particularly dry Julys in Arizona result when a separate high pressure cell is centered over New Mexico. Dry air descends along the east side of the high and loses moisture it picked up in the Gulf of Mexico before it proceeds west and north to Arizona. Wetter Julys result when the high pressure cell extends continuously from the Atlantic westward into New Mexico.

Pyke (1972) and Hales (1974) suggest that the Gulf of California and the area southwest of Baja California are more important sources of summer rainfall than the Gulf of Mexico, particularly for areas to the west of the Continental Divide. Pyke (1972) states that by July and August, the source area for westerlies shifts to the south, originating south and west of Baja California, Mexico. That area is then under the influence of the warm Equatorial Current from off the coast of central Mexico, and therefore, this would be an important source of moisture for much of Arizona.

In addition, Douglas and Fritts (1973), Pyke (1972) and Hales (1974, 1972) point out that late summer and early fall storms passing the southern end of the Gulf of California are brought into Arizona via steep pressure gradients at low levels. The relatively hotter air at the surface in Arizona and Sonora causes moist, more dense, air to surge up the Gulf of California into the desert. This mechanism is responsible for some of the most intense rainstorms in Arizona history.

Sellers (1960) and Douglas and Fritts (1974) found interesting rainfall patterns for Arizona and New Mexico that have significance for climatic reconstructions. According to Sellers (1960), the precipitation characteristics for any given year are determined primarily by what happens in winter. When the jet stream is displaced southward, it brings relatively abundant winter rains. Lingering westerlies obstruct migration of the Bermuda high to the northwest resulting in relatively low midsummer rains. However, the same westerlies bring more September rain originating with tropical storms in the Pacific. Conversely, drought in the southwest is the result of a contraction of the polar vortex which decreases winter and fall rains. Midsummer rains originating with the Bermuda High are intensified, but not enough to offset decreases during the rest of the year.

Douglas and Fritts (1974) agree that southward displacement of upper-level westerlies results in retreat of the Bermuda high to the southeast. However, they discuss another phenomenon called the "cutoff low" which forms as an offshoot of the circumpolar vortex at times when it is in a state of flux (i.e., fall and spring). Areas of high relief benefit most from moisture brought in by spring and fall cutoff lows. In some cases, subsequent convective storms occur that deposit moisture brought in by advection from the intertropical convergence zone. In keeping with Sellers' (1960) results, falls or springs having numerous cutoff cyclones may be typified by a decrease in the number of extratropical lows and fronts approaching California and Oregon to the north. Well developed Aleutian lows are displaced to the southwest of their normal position.

The importance of the above-mentioned weather patterns varies from area to area in the Southwest. The White Mountains, situated in the east central part of Arizona, are probably affected most significantly by convective storms whose moisture comes from the Gulf of Mexico. September convective tropical storms, however, also probably play an important role. The Mogollon Rim region northwest of the White Mountains is more likely to receive a greater amount of its summer moisture from the Pacific off the southern coast of Baja California. September tropical storms have an important influence on the Mogollon Rim as well. Figure 3 shows the distribution of mean annual precipitation in the study area. Figure 4, shows climatic parameters for the White Mountains area. The weather station closest to Hay Lake is Greer, Arizona (2,444 meters) (Fig. 4), which receives approximately 68cm of precipitation per year. Although the mean annual temperature is only slightly above 5° C, most of the precipitation comes in the form of rain during summer convective thunderstorms. Hay Lake is approximately 336 meters higher than Greer and probably benefits somewhat more from orographic precipitation. The area north of the White Mountains is in a rainshadow as most summer moisture comes to the region from the souteast. Springerville, for example, about 25 km. northeast of Greer, and about 400 m lower in elevation, receives 55 cm less

Fig. 3. Distribution of mean annual precipitation on Mogollon Rim. The solid line delineates the Mogollon Rim. After Beschta, 1976.

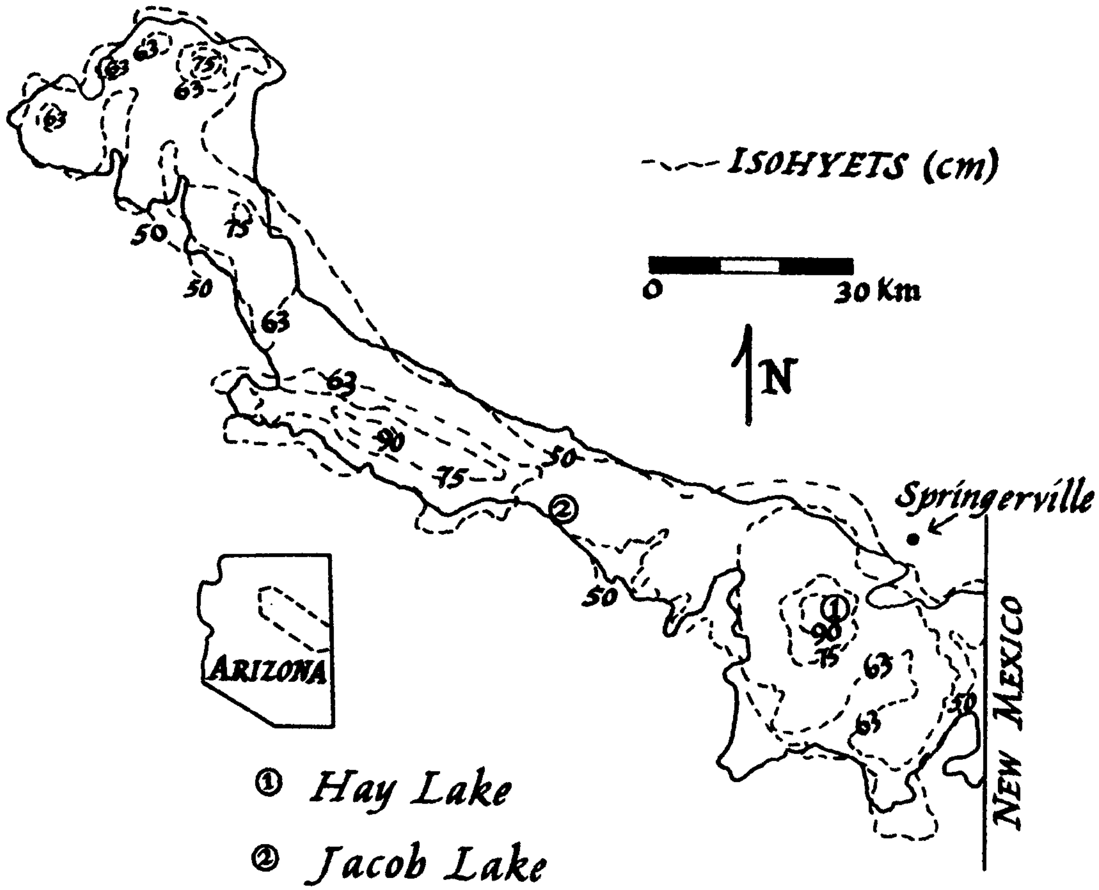

Fig. 3. Distribution of mean annual precipitation on the Mogollon Rim.

Fig. 4. Climatic parameters for the White Mountains. From Merril and Pewe, 1977.

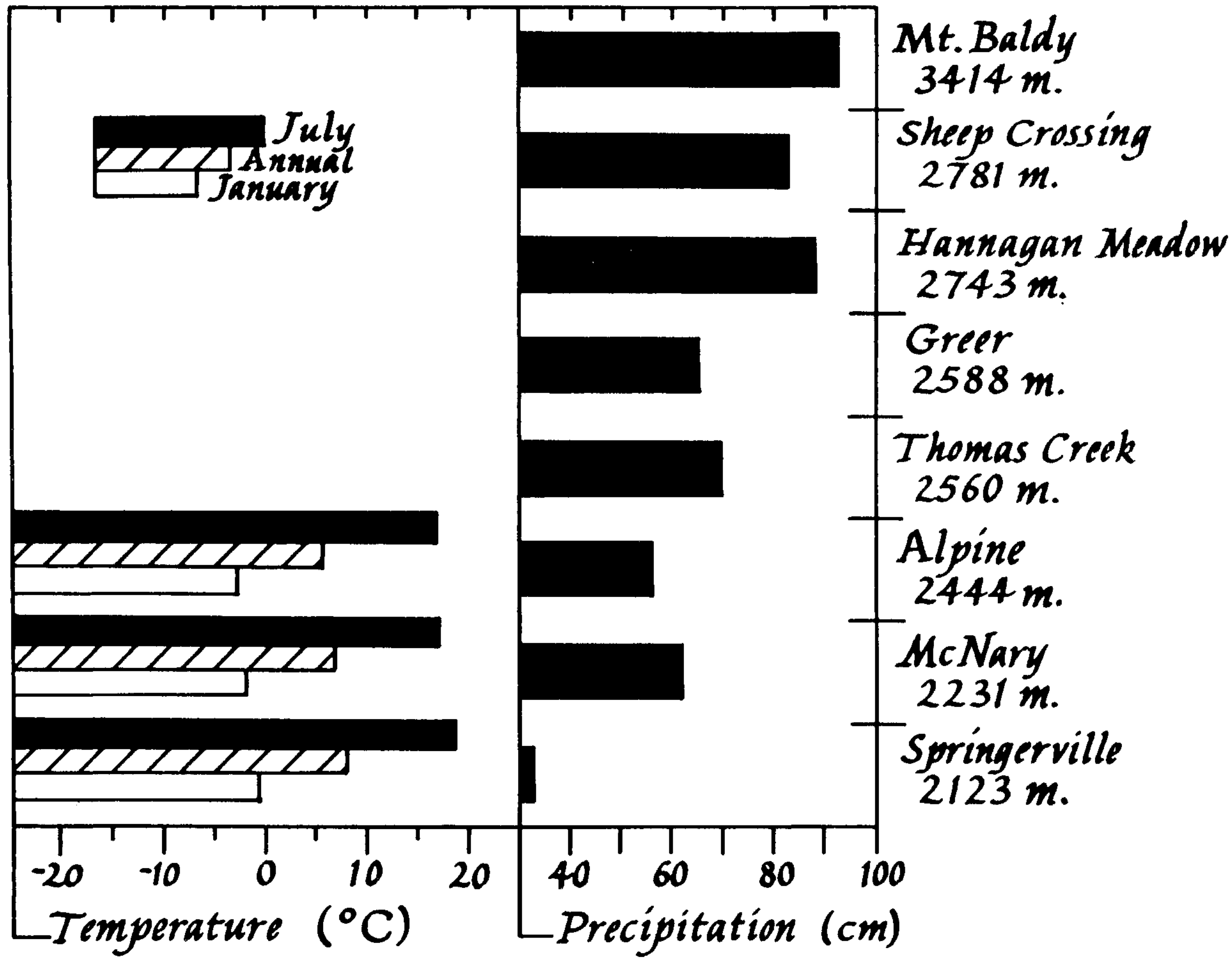

Fig. 4. Climatic parameters for the White Mountains.

precipitation (Fig 4).

Temperature variations are summarized in Figure 4. Length of the growing season at Hay Lake can be approximated by evaluating the average monthly temperatures for Greer from 1963 to 1971 (Sellers and Hill, 1974). Temperatures consistently above freezing occur between the months of April and October. Based on an average annual lapse rate of $4^{\circ}C/3048$ m, temperatures at Hay Lake should average 2.4° C less than those at Greer and the growing season at Hay Lake is also less than that at Greer.

Heber, Arizona, (2110 m) is the weather station closest to Jacob Lake but approximately 175 meters lower in elevation and 25 km to the northeast. Jacob Lake, in contrast to Heber, may intercept higher amounts of precipitation from convective winter and summer storms as it is slightly higher in elevation and is closer to the edge of the Colorado Plateau. There is probably a minor difference in the temperature regime for the two localities. Heber receives about forty-five percent of its precipitation during the summer monsoon. Winter storms originating in the Pacific make up the remainder of the year's precipitation (Sellers and Hill, 1974). Spring and fall rains are included in the winter precipitation totals for this station. These are biologically important because they overlap with the growing season, which at this relatively low elevation is long. Temperatures consistently above freezing begin in March and continue until sometime in November (Sellers and Hill, 1974).

Vegetation

The configuration of the present vegetation is a response to the modern environment as well as the result of past climatic change and plant migration. There is, therefore, an interlocking relationship between present and past vegetation and the two cannot be entirely separated. A discussion of modern vegetation of the Mogollon Rim region is important because one of the goals of this study is to reconstruct past vegetation and climate. Furthermore, interpretation of the pollen record relies heavily on modern analogue for reconstructing past plant communities and climates. A general analysis of the modern vegetation will provide a basis for later discussion of vegetation reconstructions.

The southern Colorado Plateau comprises a landscape of varied topography. Consequently, the plant communities are distributed largely according to the response of individual species to macro- and microhabitats including regional climate, substrate, slope, aspect, and associated species. The resulting complex plant communities have been classified by several authors (e.g., Moir and Ludwig, 1979; Brown, Lowe and Pase, 1979) in a variety of ways. The aim here is to incorporate these classifications by providing a concise overview of the vegetation relevant to the study area without glossing over any important variations within or among plant communities.

Figure 5 summarizes the vegetation encountered along an altitudinal transect in the study area. The Rocky Mountain alpine tundra (Brown et al., 1979) is limited to a small area on the San Francisco Peaks between timberline and an elevation of 3850 m (Lowe and Brown, 1973). Many species found there are at the southern limits of their distributions (Moore, 1965; Lowe and Brown, 1973), and the San Francisco Peaks support a relatively depauperate version of the Rocky Mountain tundra. Moore (1965) divided the flora into the predominant rock field and alpine meadow associations, recognized also by Schaack (1970).

The Engelmann spruce (*Picea engelmannii*) - subalpine fir (*Abies lasiocarpa*) forest, limited to elevations between about 2590 meters and timberline is more widespread than the alpine tundra, but still covers less than 0.5% of Arizona (Moir and Ludwig, 1979). Engelmann spruce is found at higher elevations than subalpine fir (Layser and Schubert, 1979), and occurs in the forest tundra ecotone in krummholz form. Wind-shaped Engelmann spruce is found on exposed sites on Mt. Baldy in the White Mountains (Smith and Bender, 1974) and it is the dominant tree at timberline (3350m) in the Front Range of Colorado (Wardle, 1968). Spruce-fir associations dominated by *P. engelmannii* occur in the higher elevations of

Fig. 5. Schematic representation of vegetation along an altitudinal gradient in Arizona with elevations of selected geographic features.

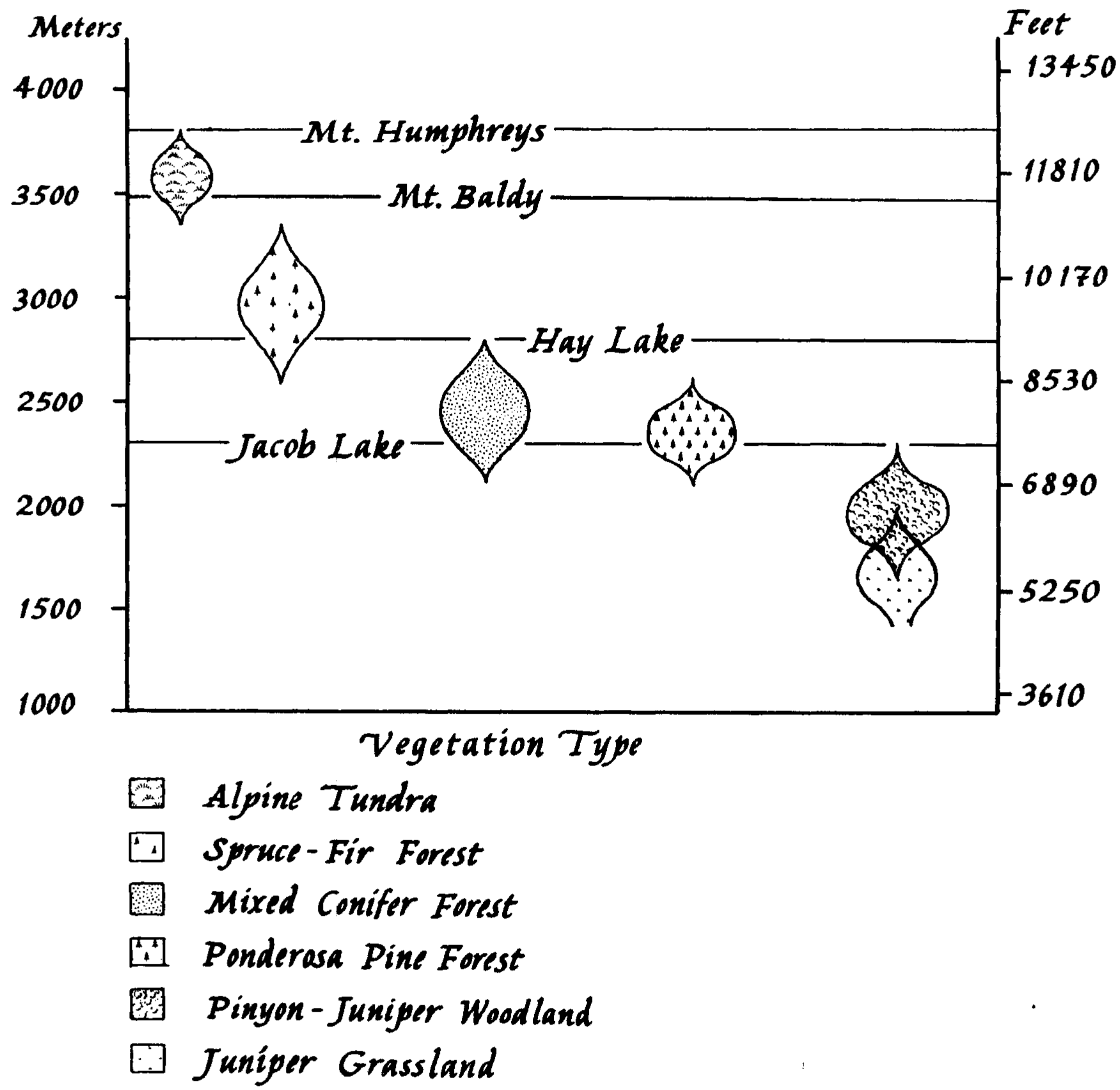

Fig. 5. Schematic diagram of vegetation in Arizona.

this community and are not associated with any other high elevation conifers such as Douglas fir [Pseudotsuga menziesii (Moir and Ludwig, 1979)]. Subalpine fir is dominant at lower elevations in the spruce-fir forest. At these and even lower elevations Douglas fir and white fir (Abies concolor) are common associates depending on site microclimate. Quaking aspen (Populus tremuloides), southwestern white pine (Pinus strobiformis), or ponderosa pine (Pinus ponderosa) may be seral near the lower limits of spruce-fir forest where sites are more favorable for these species.

Stands of bristlecone pine (P. aristata) alone or in association with limber pine [Pinus flexilis (Layser and Schubert, 1979; Brown et al., 1979)] occur on high elevation, cold, dry sites, possibly due to the lack of competition from other species (Schubert and Rietveld, 1970). This community may form an ecotone with Engelmann spruce which prefers more mesic sites. Bristlecone pine occurs in isolated pockets on the Colorado Plateau and is more continuously distributed in the Rocky Mountains along with its common associate, limber pine. In Arizona both are currently confined to the San Francisco Peaks (Little, 1971). Limber pine is considered a topoedaphic climax species associated with lithosolic situations (i.e., rocky soils) at high elevations, or, at lower elevations on southern, windswept, exposures (Layser and Schuber, 1979). Differences of opinion exist concerning the taxonomy of limber pine and the closely related *Pinus strobiformis*; however, Steinhoff and Andresen (1971) classify them separately on the basis of genetic studies. Limber pine has a more northerly distribution than *P. strobiformis* which currently does not occur north of central New Mexico (Little, 1971).

The isolation of bristlecone and limber pine in the San Francisco Mountains poses an interesting biogeographic problem that is relevent to this study. Today the closest stand of *P. aristata* to the San Francisco Mountains is 250 km, and the closest stand of *P. flexilis* is about 200 km to the north in Utah (Little, 1971). The isolated occurrence of these taxa is not necessarily due to long-distance seed dispersal because pollen and plant macrofossil records indicate their presence south of their modern main distributions during the Pleistocene (Wright et al., 1973; Cole, 1981). If they are relict from the Pleistocene, when they were distributed (continuously or in patches) from the Chuska Mountains, New Mexico across Arizona to the San Francisco Peaks (Fig. 1), pollen of these species should be present in the Pleistocene sediments from Hay Lake in the White Mountains. Specific identification of pine pollen from Hay Lake will help to resolve the following questions: 1) How widespread was the past distribution of *P. flexilis* and *P. aristata* during the Pleistocene? 2) At what time did their distributions diminish in Arizona?

Mixed conifer forest communities are widespread in the southwestern United States at elevations above about 2130 meters. Local soil and topographic features play an important role in determining the dominant coniferous species and their associates. Layser and Schubert (1979) classify mixed conifer forest in the white fir series which allows for codominance of *Pinus strobiformis* and Douglas fir. Ponderosa pine is mentioned as a long-lived seral species. Subalpine fir or Engelmann spruce may occur occasionally where the white fir forest type forms an ecotone at its upper limits with spruce-fir forests. Blue spruce (*Picea pungens*) is considered by Layser and Schubert (1979) as a topoedaphic climax species bordering meadows and stream banks.

In the White Mountains region, codominants with blue spruce are Engelmann spruce or Douglas fir and dwarf juniper (*Juniperus communis*). *Rubus parviflorus* may be important in the shrub layer depending on the site. In the White Mountains study area, important associates of white fir are Douglas fir and maple (*Acer grandidentatum*) (Moir and Ludwig, 1979). New Mexican locust (*Robinia neomexicana*), dwarf juniper, and barberry (*Berberis repens*) may also figure significantly in the shrub and herb layer.

Ponderosa pine forest is distributed widely throughout the western United States and into Mexico (Little, 1971). Ponderosa pine stands usually have a grass understory or are associated with pinyon pine, juniper, oaks or shrubs such as big sagebrush (*Artemisia tridentata*) (Merkle, 1962; Layser and Schubert, 1979; Brown et al., 1979). In Arizona, it forms extensive stands along the southern edge of the Colorado Plateau between about 2130 and 2590 meters. At least in some areas where ponderosa pine is the only dominant conifer species, fire suppression results in excessive regeneration along with changes the composition and quantity of herbaceous cover (Cooper, 1960; Weaver, 1967). Dense thickets of ponderosa pine seedlings form the understory. In the Mogollon Rim region today, controlled burns prevent the buildup of undergrowth and reduce the threat of larger, more destructive, fires (Weaver, 1967). Frequency and intensity of natural and man-made fires are important factors to consider relative to modern and past vegetation communities.

The juniper-pinyon pine woodland occupies plateaus and mesas between 1675 and 2290 meters, though pinyon pine is often not present below 1890-1980 meters (Lowe and Brown, 1973). Utah juniper (*Juniperus osteosperma*) and single-leaf pinyon (*Pinus monophylla*) are usually associated together in the Great Basin. Utah juniper can be found associated with the more widespread Colorado pinyon, *P. edulis* (Layser and Schubert, 1979). One-seed juniper (*Juniperus monosperma*) and Rocky Mountain juniper (*J. scopulorum*) are most commonly found with Colorado pinyon in northeastern and central Arizona (Layser and Schubert, 1979; Little, 1971). Alligator juniper (*Juniperus deppeana*) occurs primarily to the south in association with encinal and Mexican oak-pine woodland species (Lowe and Brown, 1973). Outlying populations occur in the White Mountains and San Francisco Peaks (Little, 1971).

The four juniper species discussed here occur sympatrically only in the Flagstaff area (Layser and Schubert, 1979) and their centers of distribution lie in surrounding regions to the north and east (Little, 1971). Thus, from modern distributional evidence the flora of the southern Colorado Plateau has its origins in the physiographic regions which surround it (Lowe and Brown, 1973).

High elevation meadows are common in the White Mountains and Grand Canyon areas generally at elevations between 2290 and 3050 meters (Lowe and Brown, 1973). In the Grand Canyon region, Merkle (1962) found that trees were excluded from meadows because of two factors: 1) seeds did not germinate and seedlings were stressed because the soils were too wet in June after snowmelt and 2) scalding near the soil surface of tree seedlings established in the spring. An alternative hypothesis (Lowe and Brown, 1973) is that lower temperatures and drier soils exclude trees from meadows. These explanations suggest edaphic reasons for the maintenance of alpine and subalpine meadowlands. Merkle

(1960) noted stunted trees at meadow edges. This supports the idea that meadows are unfavorable for tree growth and that trees are not excluded due to fire frequency or other non-edaphic factors.

Much of the area surrounding the White Mountains and to the north of the Mogollon Rim is treeless vegetation. Extensive grasslands occur between about 1525 and 2130 meters (Lowe and Brown, 1973; Brown et al., 1979; Brown and Lowe, 1980). They are classified as tall-grass, short-grass or buffalo-grass series, but, are essentially an extension of the Great Plains Grassland (Lowe and Brown, 1973; Brown et al., 1979). Great Basin desert scrub dominated by sagebrush species, interfingers with grassland north of the Mogollon Rim on lower drier sites. Other, typically Great Basin dominants such as shadscale (*Atriplex confertifolia*) and *Coleogyne ramosissima* may be present (Brown et al., 1979; Lowe and Brown, 1973). The occurrence of both Great Plains and Great Basin communities in northern Arizona suggests that much of southern Colorado Plateau vegetation has its origins to the northeast, north, and northwest.

Hay Lake is bordered by mixed conifer forest on south facing slopes and spruce-fir forest in cooler, wetter areas. A grassy meadow borders the lake on the south and north sides and smaller open areas dot the remaining lake edge. Meadowlands occupy much of the larger region surrounding Hay Lake (Fig. 6). The coring locality is on the southern edge

Fig. 6. Hay Lake and surrrounding forested versus treeless vegetation.

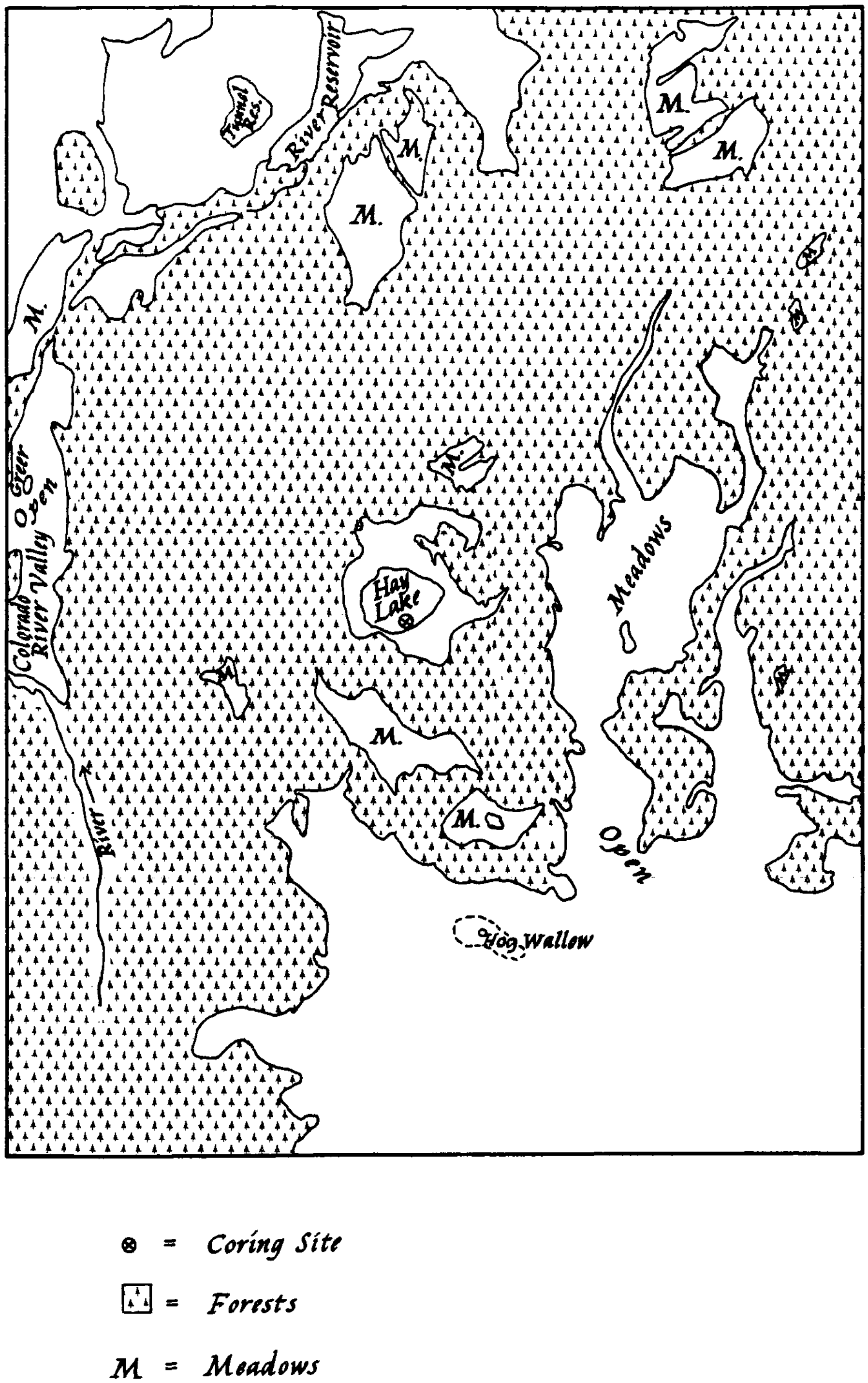

Fig. 6. Hay Lake and surrounding forested versus treeless vegetation.

of the lake (Fig. 6). In the immediate vicinity, dwarf juniper and quaking aspen grow at the forest edge. The forest immediately adjacent to the coring site is composed of ponderosa pine, Douglas fir, southwestern white pine and some white fir. The substrate is basaltic and the predominant understory shrub is dwarf juniper.

Trees have been cleared on the north side of Jacob Lake near state route 260. The remainder of the lake is bordered by ponderosa pine forest. Some gambel oak (*Quercus gambellii*) and quaking aspen (*Populus tremuloides*) trees grow in association with the ponderosa pine. During the fall season the lake basin is dry and supports grasses and sedges.

CHAPTER TWO

METHODS

Field Work

I collected lake-bottom sediments from the White Mountains-Mogollom Rim region for pollen analysis in order to answer the paleoclimatic and biogeographic questions posed at the outset of this study. Pollen grains were extracted from sequential portions of sediment cores, placed on slides, identified so far as possible, and relative frequency of taxa determined generally for a minimum of 300 pollen grains per slide. Relative frequencies of pollen grains were used to determine vegetation, and reconstructed vegetation for temporally successive samples allowed me to reconstruct past climates. Temporal control was from superposition within cores calibrated with radiocarbon dates.

A total of 21 cores was collected in an initial survey of over 30 sites. I sought continuously deposited lake sediment from sites near lower and upper treeline. Ideally, the sedimentary record would encompass the time period from th present to the Pleistocene. The lake basin sought was to be between about 50 and 300 m in diameter so that the pollen source area would include both regional and local vegetation (Jacobson and Bradshaw, 1981). Lakes with inflowing or outflowing streams were avoided because of the possible disruption to constant sedimentation and the possibility of allocthonous alluvial pollen which could be as much as 80 percent (Bonny, 1978). The lakes were to be perennial because pollen is best preserved in such sites.

Field work began in May 1980 with a survey of sites along the Mogollon Rim and in the White Mountains region. Cores were collected with a Dachnowsky, 2.5 cm diameter, piston corer which yields 25 cm segments. The core segments were stored in a relatively cool place until they could be refrigerated. Most of the cores were from lakes approximately 2130 meters in elevation, surrounded by ponderosa pine forest. Several attempts were made to obtain samples from lower elevation sites in pinyon-juniper or juniper grassland communities. These shallow, dry basins, however, contained consolidated, usually oxidized, clays. They were either too disturbed, too oxidized, or proved impenetrable to more than about 1 meter. Samples weighing 20-40 grams from 7 of an initial 19 cores were submitted to Geochron Laboratories for radiocarbon age determinations. Concordant results on two-day counts were obtained for one sample from each of three cores, and less precise ages were determined for 2 samples from 2 additional cores. The lower portions of the cores are late Pleistocene.

The dated cores are from lakes surrounded by ponderosa pine forest. The Jacob Lake core was chosen for further analysis because it was relatively long (3.6 m) and met the requirements discussed above for basin size and integrety (lack of associated streams). No perennial lakes suitable for my purpose were found at elevations lower than about 2400 m. In February 1981 Jacob Lake was recored using 5 cm diameter, 55.9 cm long core barrels to collect more material for radiocarbon dates. The coring apparatus was built by Charles Robinson and Associates. A small engine, set up on one leg of a 10 m tripod, lifted a large weight that drove the core barrel into the lake mud. Samples at 222, 59, and 29 cm depth were submitted for radiocarbon analysis at the University of Arizona.

In the fall of 1980, Hay Lake (2780 m) was cored with a 2.5 cm diameter Dachnowsky piston corer. This high elevation site met all of the standards described above. Two initial radiocarbon dates showed a basal age in excess of 37,000 years.

Laboratory Analysis

Each section of core was cleaned by scraping the outermost 1-2 mm with a clean metal spatula and cut into 2 cm-long slices. The sample length depended on compression of the sediments, which differed depending upon the diameter of the core barrel and sediment composition. If the

Dachnowsky cores were compressed to a length of less than 25 cm, the segment was cut into 12 equal slices thought to represent 2 cm of uncompacted sediment each. The 13th, bottommost slice, was half as long and represented one cm. Descriptions of sediment color, texture, and presence of plant macrofossils or weathered nodules, were recorded (Tables 1 and 2). Each 2 cm slice of sediment was cut longitudinally in half (into quarters in the case of the 5 cm diameter core) to provide duplicate samples. These were placed in a low temperature oven to dry, then weighed.

Laboratory preparation began with the addition of prepared aliquots of tracer pollen. A mixture of absolute alcohol and Fagus or Eucalyptus pollen was prepared in 1 pint containers. The contents of the container were mixed by using a magnetic stir-bar. Aliquots of 1 ml were removed by a volumetric pipette. Aliquots were placed in 1 dram vials to which 1 ml of glycerin was added. The alcohol was fully evaporated by placing the aliquot mixture on a slide warmer for 24-48 hours. The aliquots were then calibrated using a standard Neubauer haemocytometer. Care was taken to mix each vial for an equivalent period of time, one minute, before putting samples onto the haemocytometer.

Further preparation procedure follows standard methods (Faegri and Iversen, 1975; Birks and Birks, 1980). In cases where samples contained little visible organic matter, acetolysis was omitted and in other cases the sample

Table 1. Stratigraphy at Hay Lake.

Depth (cm) 14C Dates	Sediment Description
0-5	Peat
5-25	dark brown clay
25-50	brown with varying bands of black clay
50 cm; 4070±30 (A-2474)	
50-75	brown-gray clay with some black. Iron staining 70-75.
75-100	gray brown clay, some black mottling
105 cm; 12,060±530 (A-2476)	
100-125	dark gray clay with small amounts of iron staining
125-150	gray clay with some iron staining
150-158	brown clay with abundant iron staining
158-162	decrease in iron staining
163 cm; 13,710±320 (A-2477)	
162-175	gray clay wih black mottling; some iron staining
175-193	dark gray clay (gypsum crystals from 175-187)
193-200	dark gray clay with iron staining
200-206	gray clay with iron nodules
207-225	dark brown clay
212 cm; 24,550±920 (A-2391)	
225-250	brown with some iron staining; slightly silty clay
250 cm; 25,920±3000 (A-2475)	
250-275	gray clay
275-289	brown-gray clay
289-293	dark brown clay
293-300	black clay; very organic
300-310	brownish gray clay
310-313	brownish gray clay with black bands of plant fragments
313-317	plant fragments between laminations; brown-gray clay

Table 1. Continued.

Depth (cm) 14C Dates	Sediment Description
317-320	same as above with carbonized plant fragments
320-325	same as above325-334 laminated dark gray clay
334-350	black organic laminated clay
350-375	dark brown organic clay
375-400	black to dark brown clay; curmbly
400-420	dark brown clay
420-425	blue-green silty clay
425-500	alternating blue-green to turguoise silty clay to sandy silt.

Table 2. Stratigraphy at Jacob Lake

Depth (cm) 14C Dates	Sediment Description
0-4	Fibrous, organic, root zone
4-14	Organic, black, decomposed, slightly fibrous
14-18	Clay, black, organic
18-20	Black to gray, organic, iron mottled clayey, silt
20-37	Clayey silt to clay. Brown to dark brown with iron staining
29 cm;	750±200 (A-3089)
38-40	Brown clay
40-54	Brown clay with iron staining
54-66	Dark brown clay with iron staining
59 cm;	3310±160 (A-2479)
66-90	Increasing gray clay and iron staining. Decreasing dark brown clay
90-98	Iron stained gray clay with charcoal fragments
108-118	Brown-gray clay with iron staining and charcoal fragments
118-138	Gray clay with some iron staining
138-148	Gray clay
148-162	Clay with abundant iron staining
162-168	Yellow-orange oxidized clay
168-174	Mottled gray clay
174-188	Slightly mottled, slightly silty clay
188-216	Slightly silty gray clay
216-230	Very slightly oxidized gray clay
222 cm;	14,770±1600 (A-2478)
230-235	Slightly silty gray clay
235-236	Gray and brown clay
236-269	Slightly silty gray clay
269-275	Silty clay; gray with some iron staining
275-279	Clayey silt; gray with some iron staining
279-281	Gray silt to silty clay
281-293	Gray silty clay
293-296	Gray sandy silt
296-297	Gray sand

was placed for 10 minutes in HNO_3 to prevent the formation of colloids (Mehringer, 1967). The samples were stored and mounted in glycerine and stained with basic fuchsin.

Pollen slides were studied using a Leitz Vario-Orthomat or Leitz Laborlux microscope. Pollen grains were identified and counted along parallel transects across the slide. Care was taken so that transects did not overlap. In most cases counts exceeded 300 grains and were made at magnifications of 400x, 630x, or 950x, depending on ease of identification. Exotic tracer pollen, pollen from aquatic plants, spores, and indeterminate grains were counted outside the total pollen sum. Unknowns, included in the sum, were grains that could be described, whereas, indeterminate grains were corroded or crumpled beyond any chance of later identification. Identifications were made by comparison with a reference collection of modern pollen (approximately 100 species used by me in absentia from the University of Arizona) and published pollen floras (e.g., Kapp, 1969; Adams and Moore, 1972; McAndrews, Berti, and Norris, 1973).

Pollen grains were identified to the lowest taxonomic level possible. Where grains were specially analyzed for pine identification, the pollen were identified to species. In most cases, identification could be made to genus i.e., *Quercus*, *Picea*, *Populus*, or family (i.e., Gramineae or Cyperaceae). In the case of Cheno/Am, pollen of the family

Chenopodiaceae and the genus Amaranthus (of the Amaranthaceae family) were indistinguishable.

Pine pollen was assigned to species to resolve questions regarding past distributions of presently disjunct groups. If accurate, species identifications yield more precise ecologic and climatic information from the pollen data than generic identifications.

Most previous studies of pine pollen made for the purpose of species identification utilize size as the determining characteristic. In many cases, size ranges overlapped from species to species (Hansen, 1947; Ting, 1966; Mack, 1971). While some authors consider this problem to be unresolvable (Mack, 1971), others feel that at least some information can be gleaned by applying the results of these studies to fossil pine pollen grains (Ting, 1966; Hansen, 1947). Ting's method (1966) was based on measurments made on various pine species populations. Each species had a characteristic "ratio index" derived from a combination of ratios involving mean corpus length, mean total length and mean bladder length. This identification scheme requires measurement of 70 to 100 grains of a single species for identification and does not allow for identification of individual fossil pine grains. On a single-grain basis size is probably too variable a character to be used alone in any pine identification scheme.

Whatever array of species one may choose to include in a pine identification scheme, there is always the possibility of other, unexpected species occurring in the fossil record. Therefore, in any pine identification scheme the researcher must weigh the risk of omitting pine species that actually were present at the locality in the past against the error of including too many species in the identification scheme, making descrimination of the species too difficult. The pine species that I considered likely to be encountered in the Mogollon Rim fossil record are: *Pinus ponderosa*, *P. strobiformis*, (both at the site today); and *P. aristata*, *P. flexilis*, *P. contorta*, and *P. edulis*, reported from the fossil pollen record of the Chuska Mountains (Wright et al., 1973).

Identification of these taxa was based on a key devised by Hansen and Cushing (1973) and modified to suit my needs and my proficiency at pine species identification (Table 3). Fossil pine grains from the two lakes were placed in the following four categories: 1) *P. ponderosa/P. contorta*, 2) *P. aristata*, 3) *P. flexilis/P. strobiformis*, and 4) pinyon pines.

P. ponderosa and *P. contorta* were placed in the same category because diagnostic characteristics were judged insufficient for their separation. *P. flexilis* and *P. strobiformis* are closely related species whose vegetative morphologies are very similar (Steinhoff and Andresen, 1971).

Table 3. Pine pollen identification key. Modified after Hansen and Cushing (1973).

A. Furrow membrane verrucate (Subgenus <u>Haploxylon</u>).*

B. Outline of bladder and cap indented at their intersection as seen in equatorial view, no pronounced blistering of the bladder near its intersection with the cap; bladder shape spherical to hemispherical in polar view.

C. Pollen grains smaller than 70 microns in total length;* bladders more hemispherical than spherical in shape; bladder length more than 30 microns.
......Pinyon Pine

CC. Pollen grains larger than 70 microns in total length; bladder length more than 30 microns; bladders more spherical than hemispherical in shape.
......<u>P. flexilis/P. strobiformis</u>

B.B. Outline of bladder and cap not indented at their intersection; pronounced blistering of the bladder near its intersection with the cap on proximal side;* bladder shape irregular to hemispherical
......<u>P. aristata</u>

A.A. Furrow membrane psilate to scabrate; no verrucae present (Subgenus <u>Diploxylon</u>).*
......<u>P. ponderosa/P. contorta</u>

* = Special distinguishing characters.

Though few modern grains of _P. strobiformis_ were studied, I thought it unlikely that these two species could be distinguished in the fossil record.

A study of reference slides was undertaken to determine if, given its presence in the samples, _P. monophylla_ could be distinguished from _P. edulis_. Reference slides of _P. edulis_, _P. monophylla_, and _P. flexilis_ were chosen from the University of Arizona pollen reference collection. The samples were collected from United States Forest Service herbaria and prepared by Dr. Allen Solomon (see Appendix B). All the samples were mounted in silicone oil. The size ranges for the two pinyon species were nearly identical, the mean sizes were only 1 micron apart, and morphological characters were similar (Fig. 7). I therefore consider the pollen of different pinyon pine species indistinguishable in the fossil record.

Pollen preservation must be good to reveal diagnostic features. Most pollen from Jacob Lake were not well enough preserved to allow pine species identifications. Hay Lake pollen, especially in the lower half of the core, were excellently preserved and adequate for the analysis. Pine grains from each of the chosen samples were scanned until one hundred were identified. Identification was made on a combination of the 11 characters with emphasis placed on special distinguishing characters (Table 3). For example, Hansen and Cushing (1973) found that in almost all cases

Fig. 7. Comparison of 8 morphological characters for 3 pine species.

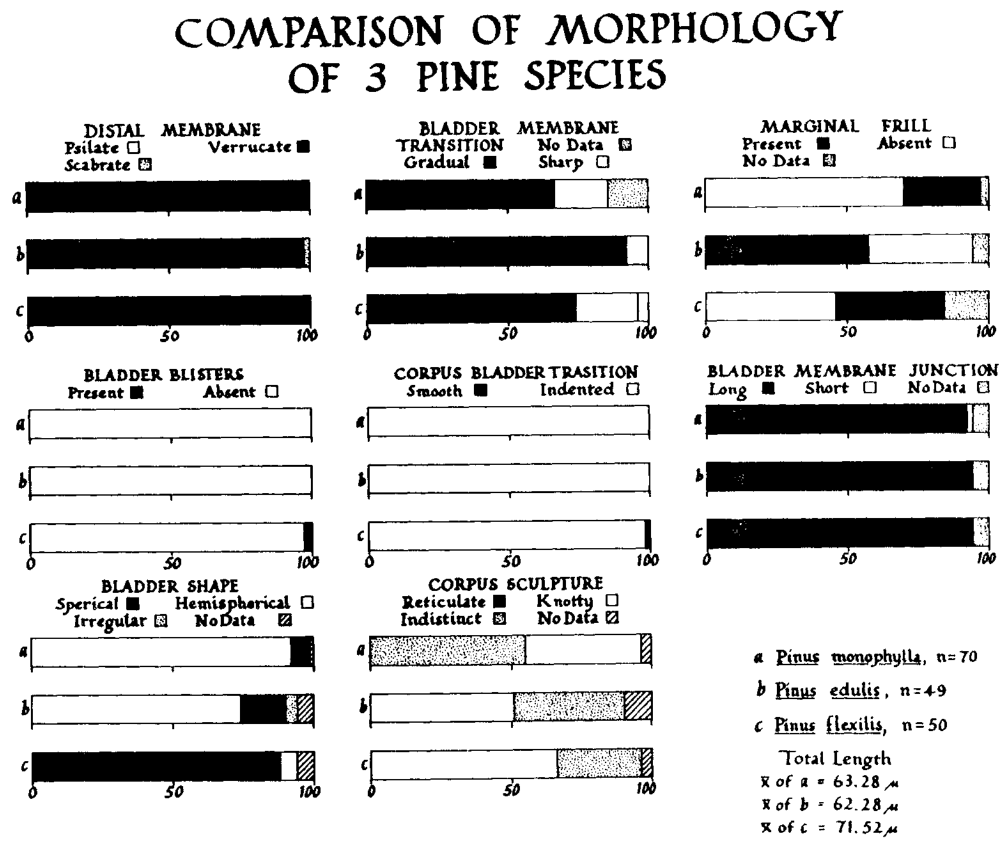

Fig. 7. Comparison of 8 morphological characters for 3 pine species.

bristlecone pine grains had bladder blisters and a smooth outline in lateral view. Thus, if only 7 of the eleven characters could be scored, and 2 of the characters were those just mentioned the grain was identified as *P. aristata*. Other aspects of the pine analysis will be considered in the results and discussion section.

CHAPTER THREE

RESULTS

The results of the pollen analysis of the Hay Lake and Jacob Lake sediments are complementary though they may not always be directly comparable. The pollen data from Hay Lake provide a record of vegetation change at a high elevation (2780 m) from which I infer the depression of upper treeline during colder climates. This record also provides data that can be used to develop hypotheses regarding the biogeography of some pine speies. Pinus aristata, only found in Arizona today in the San Francisco Mountains, was present in the White Mountains during the Pleistocene. The Jacob Lake (2285 m) pollen record may reflect changes in the structure and composition of coniferous forests as a response to climatic change. Together these data can be used to develop a model of vegetation and climatic change in Arizona and the Southwest.

The pollen diagrams (Figs. 8, 9, and 10) are divided into informal biostratigraphic zones according to the American Code of Stratigraphic Nomenclature (1970). The zones, based on changes in relative pollen percentages, simplify discussion of vegetation and climatic change in the study areas. These zones will not necessarily coincide with

Fig. 8. Relative pollen percentages for Hay Lake; plotted by depth (cm).

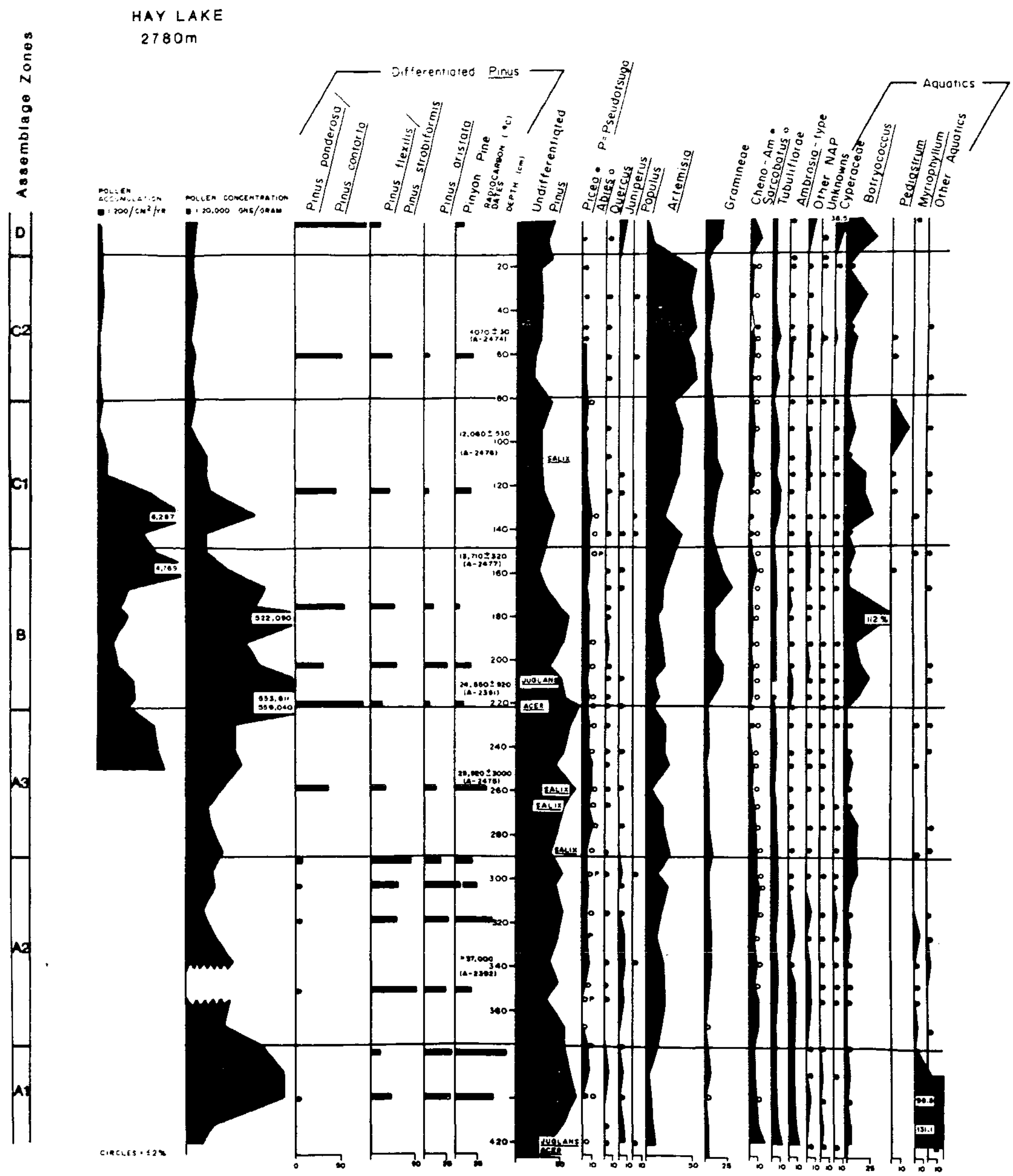

Fig. 8. Hay Lake pollen diagram, plotted by depth.

Fig. 9. Relative pollen percentages for Hay Lake; plotted by time.

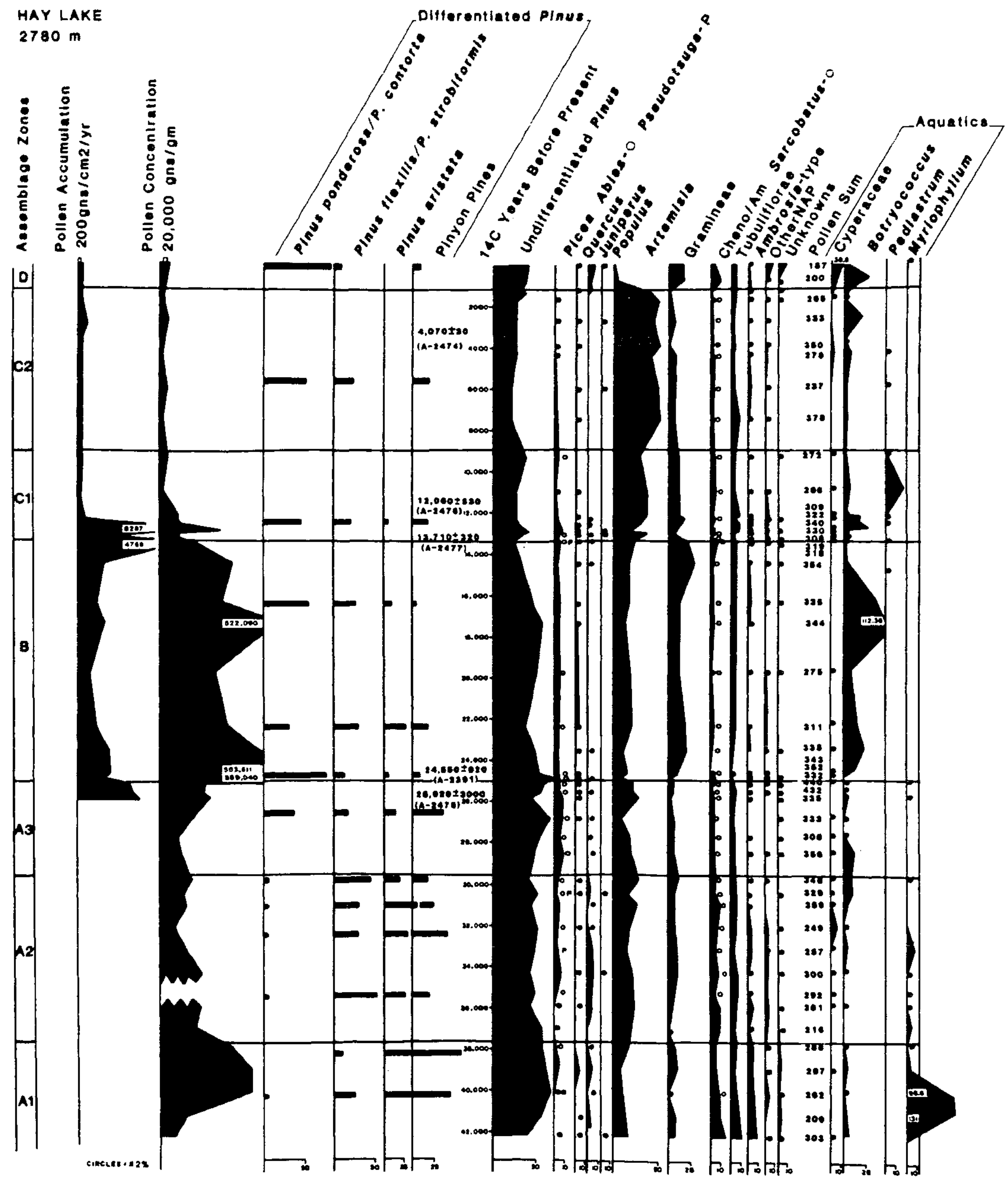

Fig. 9. Hay Lake, pollen diagram plotted by time.

Fig. 10. Relative pollen percentages for Jacob Lake.

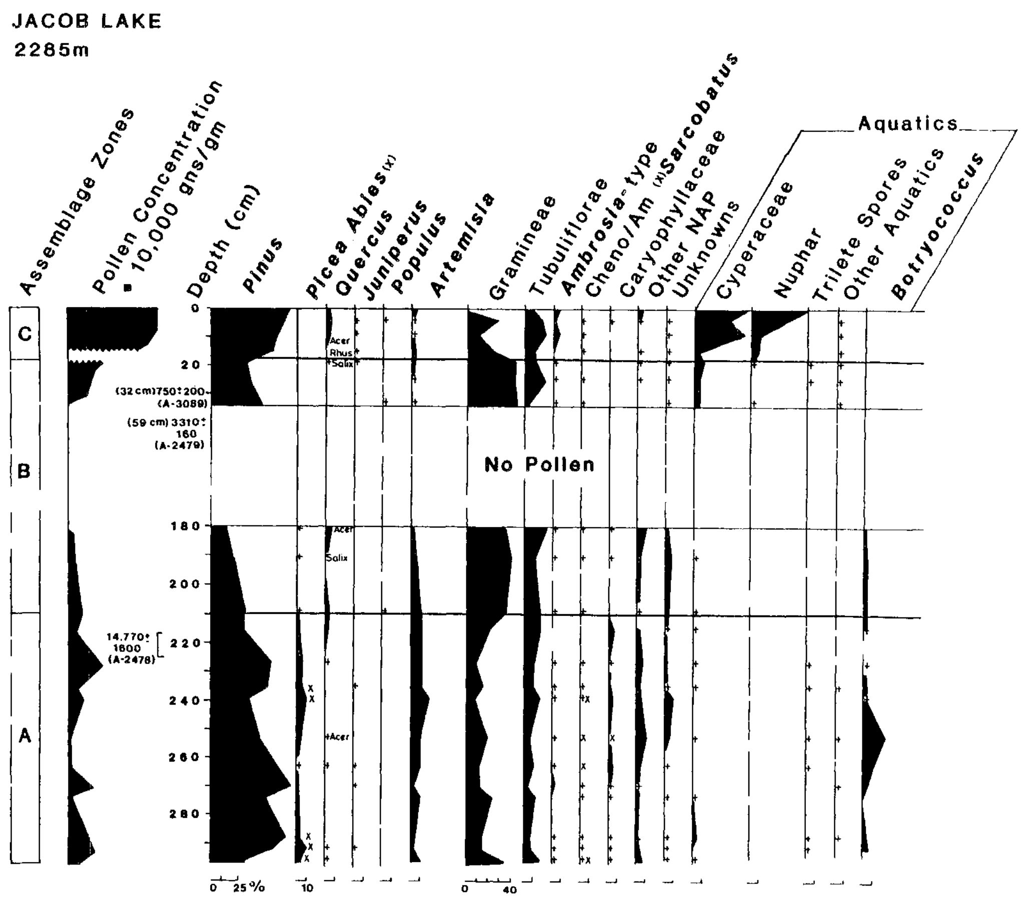

Fig. 10. Relative pollen percentages for Jacob Lake.

divisions in other pollen diagrams from the Southwest. The nature of biostratigraphic zones is such that they represent facies as well as time and the boundaries are time transgressive.

Hay Lake

Subzone A1, Hay Lake. Pinyon pine-*Juniperus*-*Myriophyllum* subzone. 42,000 B.P. to 38,000 B.P.; 376-421 cm.

Subzone A1 is characterized by high *Pinus* percentages, the consistent presence of *Juniperus*, *Ambrosia*-type, other NAP (non-arboreal pollen) and 3-5% unknowns. More than 98% of the pines are haploxylon dominated by pinyon pine (45% and 60%). The remainder of the pines were identified as *P. aristata* and *P. flexilis*/*strobiformis*. *Artemisia* is present in relatively low percentages. The Cheno-Am (Chenopodiaceae and *Amaranthus*) category is consistently higher from 304 cm to the bottom of the core than for the rest of the core. *Myriophyllum*, counted outside the sum, is present in very high (98.8 and 131.1) percentages. The pollen concentration for subzone A1 reaches 440,000 grains/gram and is relatively high for all but the bottommost sample.

Table 4 lists the pollen of herbaceous taxa and some arboreal riparian taxa identified in the Hay Lake pollen samples but present in quantities too small to warrant individual listing in the pollen diagrams (Figs. 8 and 9).

Table 4. Distribution of "Other non-arboreal pollen" in Hay Lake core. Amounts greater than 1.0 percent are as indicated.

Assemblage zones	DEPTH (cm)	Caryophyllaceae	Ranunculaceae	Phlox	Ribes	Selaginella	Liguliflorae	Celtis	Lewisia	Potentilla	Umbelliferae	Saxifragaceae	Labiatae	Polygonaceae	Rosaceae	Cruciferae	Shepherdia	Geum	Rubus	Claytonia	Gilia	cf. Lithocarpus	Salix	Juglans	Acer	Rhus	Malvaceae	Leguminosae	DEPTH (cm)	^{14}C Dates
D	0	x					x							x															0	
	10																												10	
	20	x	x	x																									20	
	30		x(1.14%)											x															30	
	40																												40	
C2	50	x			x																							x	50	4070±30 (A2474)
				x									x																	
	60		x																										60	
	70																												70	
		x																								x	x			
	80	x																											80	
	90																												90	
		x	x																									x		
	100																												100	12,060±530 (A-2476)
	110	x	x	x	x					x				x															110	
C1		x(1.47%)			x																		x							
	120																												120	
		x	x		x	x				x				x																
	130																												130	
				x																										
	140																												140	
	150	x	x	x	x									x															150	
	160	x	x		x	x			x														x						160	13,710±320 (A-2477)
	170	x				x																							170	
		x	x											x	x															
B	180		x		x			x																					180	
	190	x																											190	
	200	x(1.79%)			x																								200	
	210	x	x																					x					210	24,550±920 (A-2391)
		(1.82%)x	x									x																	220	
	230	x				x					x																		230	
	240	x				x																							240	
A3	250	x												x														x	250	25,920±300 (A-2475)
	260	x			x									x									x						260	
																							x							
	270																												270	
		x			x					x																				
	280																												280	
	290														x								x					x	290	
													x																	
	300																												300	
	310																												310	
		x	x												x													x		
	320																												320	
A2	330				x					x				x														x	330	
	340		x								x			x			x												340	
	350									x			x																350	>37,000 (A-2392)
			x							x				x		x				x										
	360																												360	
	370									x			(1.39%)x	x															370	
	380		x																										380	
	390		x				x											x	x										390	
A1	400															x(1.15%)					x							x(1.15%)		
	410																												410	
	420		x																					x					420	

They are summed on the diagrams in the category "Other NAP" (non-arboreal pollen). The herbaceous pollen in subzone A1 (Table 4) are diverse and the presence of *Gilia*, *Geum*, and *Rubus* are limited to this part of the core.

Assemblage subzone A1 is dated by extrapolation from a date of 25,920±3000 B.P. (A-2475) at 250cm and the projected average sedimentation rate for the entire core, of 96 yrs/cm. Fig. 11 shows the relationship between depth and age based on 5 radiocarbon dates. There appears to be much variation in sedimentation rate and the error bars for some dates do not touch the regression line so extrapolated ages below 250cm may be in error.

Subzone A2, Hay Lake. *Pinus* -*Picea*-*Juniperus* subzone. 38,000 B.P. to 29,000 B.P.; 376 cm to 290 cm.

Subzone A2 differs from subzone A1 by a decrease in undifferentiated *Pinus*, unknowns, *Myriophyllum*, and *P. edulis*. *Artemisia* percentages increase from 10 percent in subzone A1 to 20 percent in subzone A2 and *Juniperus* and *Picea* percentages remain approximately the same. Pollen concentration decreases to between 140,000 and 180,000 grains/gm above subzone A1.

Subzone A3, Hay Lake. *Pinus*-*Picea* subzone. 29,000 B.P. to 25,000 B.P.; 290 cm to 222 cm.

Subzone A3 is characterized by an increase in *Picea* from four to six percent to between eight and ten percent.

Fig. 11. Relationship of depth and time at Hay Lake.

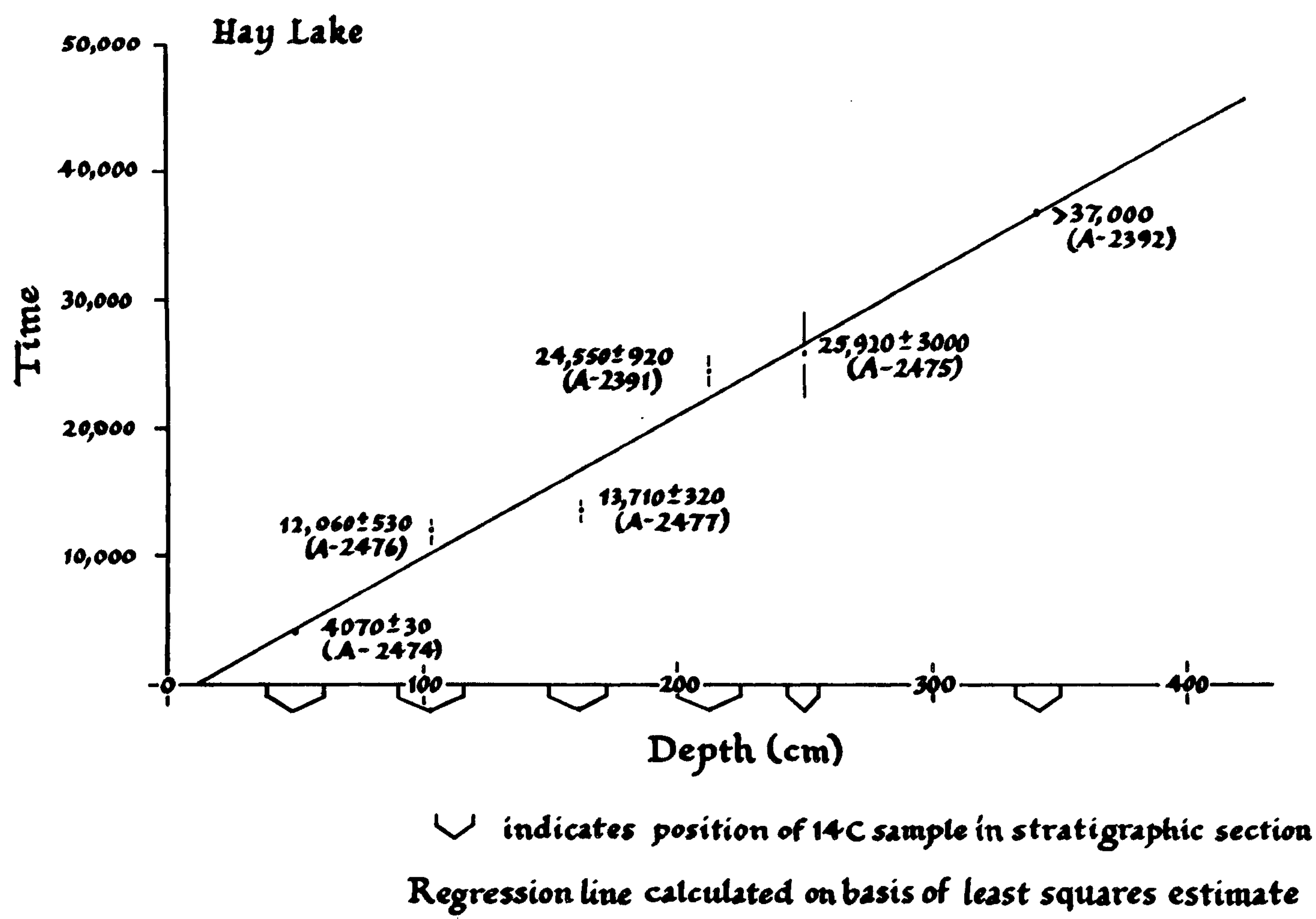

Fig. 11. Relationship of depth and time at Hay Lake.

Undifferentiated pine percentages are high (50% and higher) and yellow pines appear for the first time in large percentages (35%). Pinus aristata and P. flexilis and/or P. srobiformis pollen decrease relative to previous zones. Other NAP, Ambrosia type and Myriophyllum drop to less than two percent in subzone A3. Botrococcus is an aquatic alga that increases above 296 cm and shows a persistence throughout the rest of this zone. There are less than half as many herbaceous taxa present in subzone A3 than in lower or upper horizons (Table 4).

Zone B. Gramineae zone. 25,500 to 13,700 B.P.; 222 cm to 150 cm.

Zone B differs significantly from Zone A in pollen content and concentration. Characteristic of Zone B are high Gramineae percentages (10-30%) and high undifferentated pine percentages; more than 70% at the base, otherwise 50 to 60%. Picea pollen is not as abundant as in the upper part of zone A but at least 5% is consistently present.

Because the sedimentation rate is slow, 180 yrs/cm for this zone versus the average 95.8 yrs/cm, the characteristics of Zone B are more readily visible when plotted against time (Fig. 9) than when plotted against depth (Fig. 8). The relatively close sampling intervals in Fig. 9 show the suddenness of a major change about 25,500 B.P..

Pinyon pines have relatively low values with a minimum of five percent of identified pines at about 16,500

B.P.. This is half the amount found at the surface of the core. _Pinus flexilis/strobiformis_ averages around 20% and _P. aristata_ is less abundant than in zone A with only one sample exceeding 10%. Yellow pines dominate the pine assemblages. The source of the yellow pine pollen may be either _Pinus contorta_ and/or _P. ponderosa_. _Myriophyllum_ is absent and _Botryococcus_ reaches its highest proportions in this section of the core.

Pollen concentrations are highest for the core in Zone B. This is most likely due to the slow sedimentation rate for this time period. Pollen accumulation rate, hereafter called influx, is much lower in the central section of Zone B than it is in the upper or lower parts of this zone. The average influx value for the central part of the curve between 220 and 168 cm is 1309 grains/cm^2/yr. The brief high influx periods are synchronous with brief peaks in the undifferentiated pine curve.

The herbaceous pollen are more diverse than in subzone A3 (Table 4). However, above 160 cm diversity declines somewhat and above 100 cm _Ribes_, _Selaginella_, and c.f. _Phlox_ occur more sporadically.

Subzone C1, Early Holocene, Hay Lake. _Artemisia_ - Gramineae subzone. 13,700 to 9,000 B.P.; 150-80 cm.

The beginning of this subzone marks the transition to the Holocene. It is demarcated by a brief peak in _Pinus_ spp.

and a small, brief peak in _Picea_ (10%) at the base of the zone and an increase in _Artemisia_ above the zone. Above 134 cm _Picea_ declines to less than five percent. Gramineae decreases rapidly at about 13,700 B.P. from a high of 30% to a low of 10%. _Artemisia_ begins to increase at 12,000 B.P. to a maximum in this subzone of 40% and declines slightly toward the top of the subzone, about 9,500 years ago.

Pollen preservation is not good in the Holocene segment. Consequently, only two samples could be analyzed for pine species identification. The ratios of pine types at 122 cm (about 12,500 B.P.) is similar to that in the full glacial section.

Herbaceous taxa other than Gramineae include abundant Tubuliflorae which exceed five percent beginning in subzone C^1. Other herbaceous taxa present in lower zones such as Umbelliferae, Saxifragaceae and _Lewisia_ (Table 4) drop out in subzone C1. However, most other herbaceous taxa, including _Selaginella_ which is characteristic of the full glacial, continue to occur in subzone C^1.

Botryococcus increases briefly 13,000 years ago to 30% but declines again and remains present throughout this subzone in lower percentages than in zone B. _Pediastrum_ is present for the first time in this subzone. In all but one sample (94 cm, 11,000 B.P., 20 percent) it never exceeds two percent. Pollen concentration and influx both decline dramatically at 115 cm.

Zone C2, Hay Lake. Artemisia zone. 9,000 to 1,500 B.P.; 150 to 15 cm.

The most salient feature of subzone C2 above subzone C1 is the high percentage of *Artemisia* pollen. *Artemisia* reaches 55% about 7,700 B.P. (72 cm) and is present in percentages of 50% or more until about 2,000 B.P. (21 cm). *Picea* diminishes from just under five percent to less than two percent about 4,500 B.P.. Gramineae remains low, (less than 10 percent) throughout the Holocene. *Sarcobatus*, present throughout the core in low percentages, briefly increases to five percent 4,000 years ago. Undifferentiated pine averages about 30% in the Holocene samples. This is low when compared with the rest of the core. Pine species counts were made on one sample at 60 cm (about 5,800 B.P.). Two grains of *Pinus aristata* were found and *P. edulis* totalled 20% of the counts which is twice as much as found in the surface sample. Yellow pines make up 50% of the pollen sum. *Pinus flexilis*/*strobiformis* makes up the remaining 25% of the sum, more than two times the amount found for these species at the surface.

Botryococcus percentages remain low throughout zone C with the exception of one sample where it amounts to 20%. There are only six herbaceous taxa (Table 4) in the NAP category in zone C and most of these occur sporadically.

The pollen concentration and influx are very low from about 11,000 B.P. to the present. The average concentration for the Holocene is 35,000 grains/gram and the average influx rate for the same time period is 172 grains/cm^2/yr.

Zone D, Hay Lake. Pinus-Juniperus - Gramineae zone. 1,500 B.P. to modern; 15 cm to 0 cm.

Zone D is characterized by 40 percent undifferentiated pine pollen, five to 10 percent *Juniperus* pollen, five percent *Artemisia* pollen and about 20 percent Gramineae pollen. Cheno/Am increases in the sample at 10 cm to 10 percent and Other NAP and Unknowns are high (near 10 percent) at the surface.

The most notable change in zone D from zone C is the decline in *Artemisia* pollen and the increase in *Juniperus* and Gramineae pollen. Yellow pines make up 80 percent of the pine pollen at the surface and *P. aristata* is absent.

Hay Lake Stratigraphy

A major feature of the core at Hay Lake (Table 1) is that the sediments below 280 cm are darker and more organic than those above this level. Below 421 cm the sediments are blue-green silty clay, and do not contain pollen. The contact between the barren sediment and the overlying dark brown clay is sharp. The clay is black between 400 and 376 cm and above this it again becomes dark brown. This pattern is repeated three more times to 290cm with the black sections decreasing in thickness. Occasionally the alternating black and brown clays are laminated and/or contain plant macrofossils of the Monocotyledonae between laminations. Above 280 cm the clay becomes gray to brownish-gray and includes iron nodules, evidence of periodic oxidation, more frequent between 210 and 140 cm. Between 176 and 188 cm small (less than 1 mm) crystals of gypsum occur. The clay becomes darker (gray brown) above 120 cm. Lenses of dark organic matter appear within brown clay between 50 and 30 cm. Partially oxidized brown clay occurs between 22 and 8 cm. This is overlain by modern, fibrous organic matter.

Jacob Lake

Zone A, Jacob Lake. _Artemisia_-_Picea_ zone. 23,000 to 14,000 B.P.; 296 cm to 210 cm.

The Jacob Lake pollen diagram (Fig. 10) is divided into three zones based on changes in relative pollen frequencies. Zone A is characterized by relatively high percentages of _Pinus_ (50%) and _Picea_ (five to 10%), and low _Artemisia_ percentages (10%). The number of herbaceous pollen types and the number of unknowns are high relative to zones B and C. Other taxa present in relatively low percentages but characteristic of this section are Caryophyllaceae and _Sarcobatus_. _Botryococcus_, is more abundant than in following zones. A radiocarbon analysis on sediment from 218 to 226 cm yielded a date of 14,770 ± 1600 (A-2478) and essentially dates the top of zone A.

Zone B, Jacob Lake. Gramineae zone. 210 to 18 cm.

The dominant pollen type is Gramineae, exceeding 30 percent throughout this section. The NAP and unknowns categories remain high below the barren zone and together equal 10% of the pollen sum. Caryophyllaceae drops to less than two percent in this section and *Sarcobatus* is absent. *Botryococcus* diminishes towards the top of zone A and remains low, five percent or less, in zone B.

From 181 cm to 210 cm *Picea*, *Artemisia*, and *Botryococcus* decrease to relatively low percentages. Only a few *Picea* grains are present in this interval and *Abies* is no longer represented. *Quercus* percentages rise in section B although oak pollen was not seen between 190 and 208 cm.

Few pollen were recovered between 181 and 32 cm, precluding a 200 grain count. The samples were scanned at a magnification of 40X and in a few cases, some pollen were encountered. No one pollen type seemed to be differentially preserved; pollen preservation changed rapidly from 181 to 179 cm and from 32 to 34 cm.

From 32 to 18 cm Gramineae remains the dominant pollen type. Pine pollen is 45% of the sum at the top of the barren zone but abruptly declines to 32% at the top of section B. *Artemisia* is present in percentages similar to those below the barren zone. However, other non-arboreal pollen and unknowns are present in percentages of less than two percent. *Botryococcus* is not present in any sample above the barren zone. Oak pollen is also missing from the upper part of section B. There are brief peaks in the Tubuliflorae category at 181 cm, 26 cm and 10 cm.

Zone C, Jacob Lake. *Pinus* - Compositae zone. 18 to 0 cm.

Zone C is characterized by a decrease in Gramineae pollen and a corresponding increase in *Pinus* pollen. *Pinus* reaches a maximum of 70% at the surface whereas Gramineae decreases rapidly between 19 and 15 cm from 44% to 24%. Grass pollen continues to decrease toward the surface where it reaches a low of less than two percent. *Ambrosia*-type is present in zone C for the first time in percentages above five percent. *Juniperus* is present consistently in zone C in low percentages (less than two percent). *Quercus* returns and remains present at about three percent to the top of the core.

The aquatic pollen types differ significantly in zone C from zones B and A. Cyperaceae increases markedly above 15 cm from five percent to 45% at 10 cm. *Nuphar*, present for the first time at 34 cm (zone B), also increases significantly above 15 cm and is highest at the top of the core (23%).

Pollen concentration is low throughout most of the Jacob Lake sediments. Below 30 cm it never exceeds 60,000 grains/gram. The concentration varies positively with the relative pine percentages.

Jacob Lake Stratigraphy

The core from Jacob Lake reveals lacustrine or marsh clay or silty clay (Table 2). The bottommost segment of material is composed of well-sorted, gray sand that prevented further penetration of the coring tube. This is immediately overlain by uniformly gray sandy silt from 296 to 293 cm. From 293 cm to 236 cm the material is gray silty clay and between 269 cm and 275 cm is stained with iron. Above 236 cm, where the sediment is gray and brown clay, the sediment is more thoroughly and consistently oxidized. This is evident from the abundance of iron stains and mottled appearance of the clay. Charcoal fragments are present from 108 to 118 cm and again between 90 and 98 cm. Although evidence of oxidation continues above 90 cm, the sediment becomes darker and presumably more organic. A black organic clay lens is present between 14 and 18 cm. Above this, from 14 to 4 cm, the sediment consists of decomposed slightly fibrous organic matter. A fibrous organic root zone is present from 0 to 4 cm.

CHAPTER FOUR

DISCUSSION

The precision of climatic reconstructions is dependent upon the nature of the link between climate and the proxy being used in the reconstruction. For example, foraminifera that have narrow ecological tolerances are used to reconstruct past sea surface temperatures with reasonable precision (Imbrie and Kipp, 1971). Pollen are vagrant representatives of past vegetation and less precise representatives of climate. Therefore, unless the network of pollen records is dense and well-dated, climatic reconstructions based on pollen records must be general and simplified. Hypothetical climatic reconstructions proposed in this study will be based on the additional information provided by the Hay and Jacob Lake polen records an on paleoecological information already available for the Southwest. Although the quantity of available information is not small (see Table 5), the density of sites and time control is not sufficient for detailed climatic reconstructions. Climatic reconstructions herein will be proposed with reference to features (e.g., circulation patterns, storm tracks, etc.) of modern climate in the Southwest (see Chapter One). Vegetation reconstructions for the various pollen assemblage zones may be compared by the reader with the modern vegetation at the sites discussed on page 22.

Hay Lake

Subzone A1, Hay Lake. Pinyon pine-*Juniperus*-*Myriophyllum* subzone. 42,000 B.P. to 38,000 B.P.; 421 to 376 cm.

Vegetation. Pine pollen, which averages more than 50 percent in subzone A1, is notorious for being produced in copious amounts. Percentages of pine pollen in modern lake sediments was found to be higher than percentages of pine trees in the local plant community (e.g., Davis and Goodlett, 1969). This overrepresentation of pine trees by pine pollen can be particularly troublesome when co-dominants or dominants in the local plant community are poor pollen producers (Janssen, 1967). The interpretive problem lies in deciding if pine is present at the site or if its pollen has extralocal origins and is masking the presence of locally abundant but poor pollen-producing plants. For example, pine percentages range from 40 to 90 percent in surface samples from ponderosa pine forests of Arizona (Martin, 1963b; Hevly, 1968) and New Mexico (Bent and Wright, 1963). But, surface samples from the alpine tundra of southwestern Colorado also contain between 20 and 60 percent extralocal pine pollen blown to the site from lower elevations (Maher, 1963). Pine percentages in subzone A1 at Hay Lake are within the range of pine percentages in surface samples from both open alpine and pine forest environments. However, consideration of pollen influx, and the total pollen assemblage diminishes the problem of pine pollen source area. Pollen influx was found to be much lower to lakes in tundra environments than to lakes in forested environments (Davis, Brubaker, and Webb, 1973). Pollen influx could, therefore, help distinguish between local and long-distance sources for coniferous pollen. Unfortunately, subzone A^1 is beyond the range of radiocarbon dating and influx rates cannot be calculated. The rest of the pollen assemblage will be discussed to help resolve the problem of pine pollen source area. Although pinyon pines make up 45 and 60 percent of the differentiated pine pollen in subzone A1, it is highly unlikely that during the Pleistocene pinyon pine was growing around Hay Lake. This would require higher mean annual temperatures and longer growing seasons than today. Also, the presence of as much as five percent _Picea_ pollen indicates that _Picea_ was growing near the site, albeit, in small numbers. Surface sample studies show that _Picea_ pollen is not dispersed far from its point of origin especially when compared with _Pinus_ (Maher, 1963). _Picea_ is a high elevation cold tolerant conifer and its local presence at Hay Lake supports the hypothesis that pinyon pine was not growing at the site and that its pollen arrived there by long-distance transport. Therefore, the source area for at least 45 to 60 percent of the pine pollen in subzone A1 is regional, or, some distance from the site.

In Midwestern lakes sediments near the lake edge were found to contain disproportionately high amounts of extralocal pine pollen (Davis, Brubaker and Beiswenger, 1971). Internal features of the lake, i.e., water circulation and the bouancy of pine pollen, are responsible for this pattern. Differential deposition of pine pollen at the lake edge could explain the high percentage of extralocal pine pollen in subzone A1 at Hay Lake.

The distance of the other pine species from Hay Lake cannot be precisely determined. However, *Pinus aristata* and *P. flexilis* are high elevation conifers associated together, and often with *Picea*, in modern plant communities. These pine species may have been growing at the site or some distance away but would have been at higher elevations, or closer to the site, than pinyon pine.

In the surface sample at Hay Lake 10 percent of the pine pollen is pinyon pine. The nearest stand of pinyon-juniper woodland today is about 13 km to the east of Hay Lake and 500 meters lower in elevation. Other researchers have also found pinyon pine pollen transported upslope to higher elevation plant communities. Wright and others (1973) found 15-23 percent pinyon pine in a surface sample from ponderosa pine forest. In a ponderosa pine community with only 10 to 20 percent pinyon pine trees, Fall (Pers. Comm.: 1983) found as much as 50 percent of the pine pollen was pinyon pine in soil surface samples. In surface samples from pinyon-juniper woodlands, however, Wright et al. (1973) and Fall (Pers. Comm.: 1983) found 20 percent and 10 percent of the pine pollen was ponderosa pine respectively. Schoenwetter and Eddy (1964) found only two to six percent ponderosa pine pollen in pinyon-juniper woodlands in Arizona. Other researchers have found upslope movement of pollen via daytime rising air an important pollen transport mechanism that is more effective than nighttime downslope movement (Markgraf, 1980; Solomon, Blasing, and Solomon, 1982). If pinyon communities were more extensive at lower elevation during the Mid-Wisconsin than they are today, yet not far below their modern upper elevational limit, a greater proportion of the extralocal pollen reaching Hay Lake would be pinyon pine. In addition, the more local conifers, _Pinus flexilis/P. strobiformis_, _Pinus aristata_, and _Picea_, may not have produced as much pollen as the lower elevation pinyon species. Markgraf (1980) found subalpine conifers produced nine times less pollen during a given year than lower elevation species.

Informal pine identification tests showed that I was less likely to mistake other pines for pinyon pine than the reverse. Probably all, or nearly all, of the pinyon pine grains are identified properly and the high percentage in this category is not a function of identification technique.

I conclude that pinyon pine was more widespread at lower and middle elevations than it is today throughout the period represented by zone A and especially in subzone A1. Today it is restricted to a narrow belt around the Mogollon Rim between 1890 and 2290 meters. If the habitat were favorable for pinyon at modern or near-modern elevations, and at elevations below its modern lower limit, the surface area occupied by pinyon pine would be much greater than today. This postulated distribution for pinyon pine during the Mid-Wisconsin can be tested by obtaining packrat middens of the appropriated age from localities between 2000 and 2300 m, and below 1890 m.

At Dead Man Lake in the Chuska Mountains, Wright et al. (1973) found pinyon pine percentages ranging from 30 to 60 percent in the zones older than 27,000 years. The upper part of this section (with less pine and more spruce) is interpreted as representing near treeline vegetation. The lower section contains high percentages of pine, mostly pinyon, and high percentages of Artemisia. This is thought to represent alpine tundra vegetation with abundant pinyon pollen blown in from below. They also postulate more widespread pinyon communities at lower elevations. While the pollen assemblages from the Chuska Mountains share some similarities with the assemblages from Hay Lake (e.g., high pinyon pine percentages), there are important differences as well. When pinyon pine is highest at Dead Man Lake, so is *Artemisia*. This is not the case at Hay Lake. Without additional radiometric age control there is little possibility for further correlation.

In subzone A1 the aquatic pollen assemblage (counted separately from the pollen sum) is dominated by large percentages of the submerged aquatic, *Myriophyllum*. Only one species of *Myriophyllum* is native to Arizona today, *M. exalbescens*. This species can grow at depths from 0.3 to nearly six meters and is usually rooted in a fine-grained substrate (Hutchinson, 1975). Water depth at the coring locality today is between 0.6 and 0.3 meters and though it is muddy and organic, supports little *Myriophyllum*. The abundance of this taxon in subzone A1 implies that the water level at Hay Lake was higher than today. Higher lake level could be the result of a greater amount of water reaching the lake as runoff and/or precipitation, decreased evaporation, or less sediment in the lake basin. A combination of these factors is probably responsible for the higher lake level in subzone A1.

All species of *Gilia* in Arizona today grow at elevations below Hay Lake. *Geum* and *Rubus* both grow today at elevations similar to Hay Lake with the exception of one species in each genus that grows in the alpine tundra of the San Francisco Mountains (Fig. 1). Though the presence of these three genera in subzone A1 may have climatic significance, these single grain occurrences must be interpreted with caution.

Pollen concentration in subzone A1 exceeds 440,000 grains/gm. High concentrations are the result of greater pollen productivity and influx or from slow sedimentation rate. The deposition rate in subzone A1 may be slower than in parts of the core having less organic sediments and/or pollen influx may have been higher.

Subzone A2, Hay Lake. *Pinus*-*Picea*-*Juniperus* subzone. 38,000 B.P. to 29,000 B.P.; 376 cm to 290 cm.

Juniperus pollen is present consistently only in subzones A1 and A2 between 290 and 421 cm and is present in amounts greater than five percent in the surface sample. Today, *Juniperus communis*, a high elevation species, grows densely at the forest edge and the coring locality. Most of the *Juniperus* pollen at the surface probably originates with these shrubs and it is likely that some of the *Juniperus* pollen in Zone A is of this species as well. Some *Juniperus* pollen could have reached the site via long-distance transport from lower elevations where today other juniper species grow in association with pinyon pine.

The average percentage of *Artemisia* in subzone A2 is about 20 percent. Its association with *Picea* and other subalpine coniferous pollen is common in fossil pollen assemblages from the Southwest. *Artemisia* percentages of 20 percent or more in association with *Picea* pollen have been found in Pleistocene pollen assemblages from a variety of elevations and environments (Martin, 1963a, b,;Maher, 1972; Wright et al., 1973; Whiteside, 1965).

The highest percentages of *Artemisia* found in modern pollen studies in Arizona, New Mexico and Colorado have come from open pinyon-juniper or juniper woodland (Hevly, 1968; Wright et al., 1973), timberline (Maher, 1963), or sagebrush steppe (Schoenwetter and Eddy, 1964; Fall, Unpubl.). Rarely does *Artemisia* make up more than 20 percent of the pollen sum in surface samples even where it is the dominant plant. *Artemisia* is underrepresented in sagebrush steppe and overrepresented in alpine communities in the Southwest. Only in areas of vast sagebrush steppe such as in the Great Basin do *Artemisia* percentages exceed 20 percent and reach values greater than 40 percent (Bright and Davis, 1982; Mack and Bryant, 1974). Therefore, its nearly ubiquitous occurrence in Pleistocene sediments in amounts of 20 percent and more indicates it was widespread in the Southwest at that time.

The occurrence of *Artemisia* (about 20 percent) in association with *Picea* at Hay Lake is not surprising. At Dead Man Lake in the Chuska Mountains, Mid-Wisconsin *Artemisia* percentages average about 40 percent (Wright et al., 1973). Perhaps as Wright and others (1973) suggest, much of the *Artemisia* is extralocal. Dead Man Lake at 36° N was was interpreted as having been at or above treeline in the Mid-Wisconsin (Wright et al., 1973) while I interpret Hay Lake at 34° N as having been below treeline. Therefore, extralocal Artemisia pollen would be expected to make up a greater percentage of the pollen sum at Dead Man Lake than at Hay Lake where conifers, which are abundant pollen-producers, were present locally.

Herbaceous species of Artemisia grow in the White Mountains in the vicinity of Hay Lake today but contribute less than four percent to the modern pollen rain (Batchelder and Merrill, Unpubl.). More extensive cover by herbaceous Artemisia and/or the presence of shrubby Artemisia species at or near Hay Lake would account for the Artemisia pollen present in the Pleistocene samples.

Herbaceous taxa such as, Polemonium, Caryophyllaceae, Rosaceae and Selaginella have been used as indicators of alpine environment when found in Pleistocene sediments (Baker, 1970; Legg and Baker, 1980). Though the herbaceous pollen assemlage (Table 4) for subzone A2 at Hay Lake is diverse and comprises taxa that occur in alpine and subalpine communities (e.g., Caryophyllaceae, Potentilla, Ranunculaceae), there is nothing about this assemblage that would necessarily indicate an alpine environment.

The sediments of subzone A2 alternate between black organic clays and dark brown clays. Plant macrofossils of the Monocotyledonae are present between laminations from 300 to 326 cm. These may be indicative of relatively rapid sedimentation which could be responsible for much lower pollen concentration here than in subzone A1. Low pollen concentration could also be the result of a decrease in pollen influx or a change in pollen deposition within the lake. There is no means for measuring pollen influx at this depth in the core because of the lack of ^{14}C control. Pollen deposition may have changed (at the coring site) with a change in water depth. The decrease in *Myriophyllum* above 376 cm does suggest a decrease in water depth.

To summarize, between 29,000 B.P. and 42,000 B.P. (subzones A1 and A2) pinyon pines (discussed earlier) were more widespread at lower elevations and probably close to their modern upper elevational limit. If the same climatic parameter, cold temperatures, restricts the growth of all tree species at their upper limit, then subalpine conifers too, would have been able to survive close to their modern upper limit. Though they were south of their present distributions, *P. flexilis* and *P. aristata* were very likely growing at the elevation of Hay Lake. The vegetation at Hay Lake between about 42,000 and 29,000 B.P. was probably dominated by *Pinus aristata* and *Pinus flexilis* and/or *Pinus strobiformis* with *Picea* as a co-dominant. *Juniperus communis* may have made up the shrub layer in this mixed coniferous forest along with a shrubby species of *Artemisia*. The herbaceous community was diverse and included Gramineae, Compositae, Chenopodiaceae/*Amaranthus* and perhaps herbaceous species of *Artemisia*. Treeline was probably above the site as it is today, but a more precise estimate of treeline elevation cannot be made based on the pollen data from these subzones.

Subzone A3, Hay Lake. *Pinus*-*Picea* subzone. 29,000 B.P. to 25,000 B.P.; 290 cm to 220 cm.

The increase in *Picea* and presence of abundant (35%) yellow pine pollen in subzone A3 indicates a change in the composition of the subalpine forest in the Hay Lake area. Surface samples from *Picea* forest in Colorado and local stands of *Picea* in New Mexico and Arizona contain from five to 50 percent *Picea* pollen (Maher, 1963; Bent and Wright, 1963; Whiteside, 1965). Though *Picea* was certainly present at Hay Lake during subzone A3 time in greater numbers than during previous zones, the source of the pollen of other subalpine conifers is problematic. *P. ponderosa* and/or *P. contorta* as well as *P. flexilis* and/or *P. strobiformis*, and *P. aristata* could have been at the site or some distance from it. The percentage of pinyon pine in the sample from 258 cm is high (35%) and I interpret this as indicating pinyon pines wer no farther from the site than in previous subzones. There are fewer herbaceous taxa in subzone A3 than in other zones (Table 4) and in general, the herbaceous non-arboreal pollen is a minor component of the total pollen sum. There is no evidence, therefore, of a tundra environment at Hay Lake.

The vegetation around Hay Lake between about 29,000 B.P. and 25,000 B.P. probably consisted of a subalpine coniferous forest dominated by *Picea*. *Pinus contorta* and/or *P. ponderosa* was (were) probably present. Codominant taxa were *Pinus aristata* and *P. flexilis/P. strobiformis* although these species may have been some distance from the lake or present in small numbers.

Wright et al., (1973) identified pine pollen to species and separated *P. contorta* from *P. ponderosa*. In the Chuska Mountins between about 25,000 B.P. and 30,000 B.P. the dominant yellow pine was *P. ponderosa*. *P. contorta* never exceeds ten percent. *P. strobiformis* was not included in the pine identification scheme for the Chuska Mountains. However, *Pinus flexilis* was present in similar percentages to those for the category *P. flexilis* and /or *P. strobiformis* at Hay Lake.

Zone A-*Pinus* zone (Subzones A1, A2, A3), Hay Lake. 42,000 to 25,000; 421 to 222 cm.

Climate. The primary difference between present vegetation and that reconstructed for zone A is the distribution of pine species. *P. ponderosa* is present at Hay Lake today and is distributed in continuous stands across central Arizona. Only single grains were identified as yellow pine in subzones A1 and A2. This is strong negative evidence of the absence of *P. ponderosa* and *P. contorta* from the Hay Lake region. *P. aristata*, present in zone A, does not grow in the White Mountains today but occurs in small stands at high elevations in the San Francisco Mountains and is scattered throughout the southern Rocky Mountains and eastern Great Basin. *P. strobiformis* grows near Hay Lake today in mixed coniferous forests but the closely related *P. flexilis* is absent. *P. flexilis* grows in association with *P. aristata* at many localities including the San Francisco Mountains and its presence during the Pleistocene at Hay Lake is likely. These are cold-tolerant conifers able to survive on rocky, dry substrates (Peet, 1978). Their distributions are in part limited by the presence of competitors (Schubert and Rietveld, 1970); which is one explanation for their presence most often on only the most inhospitable microsites. These taxa were also found in Pleistocene sediments greater than 28,000 years old from the Chuska Mountains (Wright et al., 1973) where they do not occur today. The presence of *Pinus aristata*, and possibly *P. flexilis*, near or at Hay Lake with the associated presence of *Picea* is indicative of climates cooler than today. These taxa were farther south and at lower elevations than today.

A cooler climate at Hay Lake does not conflict with the hypothesized expansion of pinyon pine at lower and middle elevations. Pinyon pines require a 120 day frost-free period and grow best in areas where the precipitation is between 25 and 38 cm (Tueller and Clark, 1975). In the present day Sonoran desert the frost-free period is 365 days in some places and annual rainfall varies from 8 cm to about 40 cm. The present rainfall regime is one dominated by summer precipitation with a secondary maximum in winter. Greater winter rainfall would create additional habitat for pinyon pines at lower elevation. A minor decrease in the frost-free period and relatively mild winters would be in accord with pinyon at elevations near its modern upper limit.

What broadscale circulation patterns would account for the climate just described for central Arizona? The following simplified climatic scheme is in accord with the hypothesized vegetation and local climatic reconstructions. A southward displacement of mid-latitude westerlies and associated northeast Pacific storm tracks would produce greater winter precipitation. Moderate development of subtropical highs would bring less frequent summer storms and would be coincident with cooler summer temperatures. A similar scheme has been suggested by several authors to explain Southwestern climate during the full glacial (e.g., Bryson and Wendland, 1966; Van Devender and Spaulding, 1979) and, indeed, it fits well with the paleoeclogical data for that period. Further discussion of this climatic model with reference to the Mid-Wisconsin is needed.

As stated in the introduction, the southwestern United States is located at the junction of two major climatic systems. These two systems are interdependent and even small perturbations in one or the other can result in marked changes in Arizona's climate.

Areas of the souteastern part of the Southwest receive almost all of their yearly precipitation from the Gulf of Mexico in the summer months. During the Mid-Wisconsin, records from Isleta Cave (Harris, 1977) and Shelter Cave (Thompson et al., 1980), New Mexico, are interpreted as representing a relatively mesic, mild climate (Table 5). Evidence of summer precipitation is present in both records.

Reconstructions proposed for other sites in the Southwest are almost unanimous in calling for interstadial conditions (i.e., mild relative to the full glacial). In the Great Basin, packrat middens (Mehringer and Ferguson, 1969) and lake level records (Mehringer, 1977; Street and Grove, 1979) indicate that the climate was wetter than today, but not as wet as the full glacial. In the Sonoran desert, a packrat midden record from the Artillery Mountains (Van Devender and King, 1971) contained <u>Pinus edulis</u> var. <u>fallax</u> associated with <u>Juniperus osteosperma</u>, showing that pinyon-juniper woodlands were at least as low as 720 m. Thus, at least at that locality, there was more effective moisture

Table 5. Paleoenvironmental data for Mid-Wisconsin, Full glacial, Late glacial, and Holocene intervals

Locality	Latitude	Elevation	Proxy	Reconstruction	Reference
MID-WISCONSIN 50,000??B.P. to 25,000 B.P.					
Llano Estacado, New Mexico	32°N-34°N	820-1463m	pollen, fossil vertebrates	23,500-32,000, Rich Lake Interpluvial	Wendorf, 1961
Isleta Cave, New Mexico	32°N	945m	fossil vertebrates	>25,000, More effective warm season moisture, Interstadial	Harris, 1974
Shelter Cave, New Mexico	32°N	1400m	packrat middens	Mid-Wisconsin, more effective moisture than late Wisconsin >26,000 B.P.	Thompson et al., 1980
Chuska Mtns, Dead Man Lake, New Mexico	36°N	2780m	pollen	pollen zones 4 and 5, cool and cold. Treeline below site, depressed approximately 1000m	Wright et al., 1973
White Mtns., Arizona	34°N	2865m	pollen	approximately 40,000-50,000 B.P., warm, dry. 40,000-32,000 B.P., warm, wet.	Batchelder & Merrill, Unpubl.
San Francisco Mtns., Arizona	35°N	2496m	pollen	32,000-42,000 B.P., Spruce-fir forest. treeline above site. 25,000 B.P., treeline at or below site.	Berry & McCormick, Unpubl.
Artillery Mtns., Arizona	$34^{\circ}22'$N	720m	packrat middens pollen	_Pinus edulis_ var. _fallax_ with _Juniperus monosperma_, _Quercus turbinella_ >30,000 B.P., 68% _Artemisia_	Van Devender & King, 1971
Grand Canyon, Arizona	36°N		packrat middens	>27,000 B.P., mild Interstadial	Cole, 1981
Grand Canyon, Arizona	36°N	645m	packrat midden	29,000 B.P., Interstadial	Phillips, 1977

Table 5, continued page 2

Rampart Cave, Grand Canyon, Az.	36°N	530m	trace elements, pollen, plant macrofossils	>35,000 B.P., warm, dry	Martin, Sabels & Shutler, 1961
Tule Springs, Nevada	37°N	703m	pollen	>37,000 to about 17,000 B.P., Yellow pine parkland in Las Vegas Valley or on bajadas	Mehringer, 1965
Sheep Range, Nevada	37°N	1800m	packrat middens	Colder than today, wet, not as cold as full glacial	Spaulding, 1977
Frenchman Flat, Nevada	37°	1550m	packrat middens	<u>Pinus monophylla</u>, <u>Juniperus osteosperma</u>, >40,000 B.P.	Wells & Jorgensen, 1964
Clark Mtn., Nevada	37°N	1910m	packrat middens	23,600 and 28,720 B.P., Interpuvial but not as hot or dry as today	Mehringer & Ferguson, 1969
Sawmill Canyon, California	37°	2090m		Tahoe-Tioga Interglaciation dated 53,000±44,000 B.P. (mean of 4 dates) on basalt	Dalrymple, Burke & Birkeland, 1982
Laguna de las Trancas, Calif.	37°N	170m	pollen	Interstadial 30,000-24,000 B.P., Cool, dry	Adam, Byrne & Luther, 1981
Clear Lake, California	39°N	404m	pollen	32,000-47,000 B.P., Mid-Wisconsin Interstadial, 1-2°C warmer than full glacial	Adam, Sims & Throckmorton, 1981; Adam & West, 1983
Searles Lake, California	36°N	495m	pollen	24,000-33,000 B.P., Woodland forms decrease slightly	Spaulding, Leopold & Van Devender, in press
Yellowstone Park, Wyoming	44°N	2200m	pollen	Interstadial beneath Pinedale Till	Baker & Richmond, 1978
Puget Lowland, Washington	47°30'N		pollen	34,000-28,000 B.P., Olympia Interglaciation	Heusser, 1977
White Mtns., Arizona	34°N	3050m	glacial geomorphology	Smith Creek Glaciation, Early Wisconsin, Mt. Baldy Glaciation, Late Wisconsin	Merrill & Pewe; 1977

Table 5, continued page 3

San Francisco Mtns., Arizona	35^oN	3050m	glacial geomorphology	Core Ridge Glaciation, Early Wisconsin, Snowslide Spring Glaciation, Late Wisconsin	Updike, 1969
Southwest	north of 37^oN			Interpluvial >24,000 B.P. Low lake levels 40,000-30,000 B.P.	Mehringer, 1977
Southwest				30,000-26,000 B.P., near end of Mid-Wisconsin, Interstadial; lakes begin to rise	Street & Grove, 1979
Southwest				40,000-50,000 B.P., warm, dry. Coincides with various named Interglacials	Hevly & Karlstrom, 1974
Northeast Pacific	30^oN-34^oN		carbonate microfossils	warmer temperatures >30,000 B.P. but not as warm as post glacial	Gorsline & Prensky, 1975
Northeast Pacific	43^oN-46^oN		pollen	29,000 to about 32,000 B.P. Olympia Interstade	Florer-Heusser, 1975
Global				23,000-50,000 B.P. Last part of a series of interstades	Dreimanis & Raukas, 1975
FULL GLACIAL 14,000 B.P. to 25,000 B.P.					
northern Chihuahuan desert			packrat middens	cooler, relatively dry. Woodlands depressed 800m; mesic montane forest depressed 400m	Wells, 1966
northern Chihuahuan desert		1525-550m	packrat middens	pinyon-juniper woodland 22,000-11,000; Pinus edulis, P. cembroides var. remota	Van Devender & Spaulding, 1979

Table 5, continued page 4

northern Chihuahuan desert	32°N	1100-2350m	vertebrate fauna	25,000-10,000 B.P. extra local fauna. More winter ppn. Cool summers, milder winters	Harris, 1974
Llano Estacado	32-34°N	820-1460m	pollen and fossil vertebrates	22,000-17,000 B.P. pine and spruce, cooler than today	Wendorf, 1961
San Augustin Plains, N. Mex.	34°N	2130m	pollen	cooler than today, spruce forest	Clisby & Sears, 1956
Willcox Playa, Arizona	32°N	1260m	pollen	vertical displacement of 900-1200m; Yellow pine parkland	Hevly & Martin, 1961
Willcox Playa, Arizona	32°N	1260m	pollen	yellow pine parkland	Martin, 1963
Isleta Caves, New Mexico	32°N	945m	fossil vertebrates	cooler, especially in summer. Twice present ppn. occurring in late winter and spring	Harris & Fendley, 1964
Sacramento Mtns., New Mexico	33°N	1585-1690m	packrat middens	16,200-18,300 B.P. Cooler summers, greater ppn. in winters. Pinyon-juniper woodland	Van Devender, Betancourt & Wimberly, Unpubl.
Chuska Mtns., New Mexico	36°N	2700-2780m	pollen	alpine tundra, treeline depression of 900-1000m	Wright et al., 1973
Devlins Park, Rocky Mtns., Colorado	40°N	2953m	pollen	22,000-12,000 B.P. alpine tundra 500m lowering treeline. 15 cm greater annual ppn. 5°C cooler	Legg & Baker, 1980
White Mtns., Arizona	34°N	2865 m	pollen	colder wetter. Full glacial 25,000 B.P. Spruce fir with white pines. 335m treeline depression	Batchelder & Merrill, Unpubl.
Potato Lake, Mogollon Rim, Arizona	34°N15'	2211m	pollen	open spruce forest with shrubs, grasses, herbs. Cool and moist, transition to Holocene 14,000 B.P.	Whiteside, 1965

Table 5, continued page 5

Walker Lake, Arizona	$35^{o}21'$	2496m	pollen	32,000-15,000 B.P. Sagebrush steppe 804m treeline depression. Decrease summer ppn. Cooler, increase winter ppn. treeline at or below site	Berry & McCormick, Unpubl.
Southwestern Arizona	south of $35^{o}N$	365-890m	pollen from packrat middens	juniper woodland with some pine and sagebrush	King, 1977
Artillery Mtns., southwest Az.	$34^{o}22'N$	720m	packrat middens and pollen from middens	18,320 B.P. pinyon juniper woodland	Van Devender & King, 1971
Rampart Cave, Grand Canyon, Az.	$36^{o}N$	430-700m	packrat middens	24,000-14,000 B.P. juniper woodland 1000m depression	Phillips & Van Devender, 1974
Grand Canyon, Arizona	$36^{o}N$	735-925m	packrat middens	13,660 junipers. 575m lower than today	Van Devender & Mead, 1976
Grand Canyon, Arizona	$36^{o}N$		packrat middens	600-1000m lowering of most plant spp. Modern analogue in northeast Great Basin, northern Utah more continental; colder; mean annual ppn.= today. Mainly winter ppn.	Cole, 1981, 1982
Rampart Cave, Grand Canyon, Az.	$36^{o}N$	530m	packrat middens	24,000-14,000 B.P. juniper woodland	Phillips, 1977
Rampart Cave, Grand Canyon, Az.	$36^{o}N$	530m	trace elements in cave sediments	cool, moist	Martin, Sabels & Shutler, 1961
Great Basin, Nevada	north of $37^{o}N$		packrat middens	bristlecone pine and limber pine widespread, no summer rain, cold, dry, summer temperatures reduced	Thompson & Mead, 1982
Great Basin, Nevada	$37^{o}N$		packrat middens	subalpine conifers surrounded by woodland, xerophytic juniper woodlands in lowlands and subalpine forest above. Cold, drier, 5-8^{o}C colder, little or no increased annual ppn.	Spaulding, 1981

Table 5, continued page 6

Sheep Range, Nevada	37^{o}N	1980m	packrat middens	wetter than today	Spaulding, 1977
Frenchman Flat, Nevada	37^{o}N	1525-1830m	packrat middens	juniper woodlands	Wells & Jorgensen, 1964
Coastal California				steeper climatic gradient Aleutian low farther south semi-arid as today	Johnson, 1977
Laguna de las Trancas, Calif.	37^{o}N	170m	pollen	2^{o}-3^{o}C cooler, ppn. 20% higher, stronger westerlies, longer winter rains	Adam, Byrne & Luther, 1981
Clear Lake, California	39^{o}N	404m	pollen	7^{o}-8^{o}C lower temperature in full glacial, pines higher on glacials vs. higher % of oak pollen in interglacials	Adam, Sims & Throckmorton, 1981; Adam & West, 1983
Puget lowland, Washington	47^{o}30N		pollen	colder, 25,000-10,000 B.P. Fraser glaciation	Heusser, 1977
Puget lowland, Washington	47^{o}N	282m	pollen	16,000-26,000 B.P. treeline, open landscape, more xeric, continental	Barnowsky, 1981
Northeast Pacific Ocean	30^{o}-34^{o}N		foraminifera	maximum cold 12,000-30,000 B.P.	Gorsline & Prensky, 1975
Llano Estacado, Texas	32^{o}-34^{o}N		lake level data	increased runoff and ppn.; reduced evaporation	Reeves, 1966
New Mexico			geomorphology	glacials coincident with pluvials. Greater ppn. and lower temperature	Antevs, 1954
Southwestern United States			geomorphology	high lake levels	Mehringer, 1977

Table 5, continued page 7

Southwestern United States	pollen	1200m depression of spruce Pine parkland displaced >1000m	Martin, 1964; Hevly & Martin, 1961
Southwestern United States	packrat middens	persistent summer rainfall pattern in southwest. Enhancement of summer rainfall to southeast (Texas and New Mexico)	Wells, 1979
Southwestern United States	various	no summer rains. Relatively dry north of 36^{o}N, south of 36^{o}N enhanced annual ppn. Mild winters, increased cloud cover. Montane or subalpine conifers above juniper or pinyon-juniper woodland in low deserts	Spaulding, Leopold & Van Devender, in press
Global		for July and August sea surface temperatures-7.1^{o}C in eastern equatorial Pacific. Southwest, 11-16^{o}C cooler in July. 3 times less net July northward transport	CLIMAP project members, 1976
Texas High Plains	fossil vertebrates	more continental than today	Hibbard, 1960
Southwest	geomorphology	23,000-17,000 B.P. Greater continentality. 10^{o}C cooler summers. No great increase in ppn. south of Utah	Galloway, 1970
Southwest	geomorphology	27,000-13,000B.P. 8^{o}-7^{o}C lowering of annual temperatures, ppn. equal of today's	Brakenridge, 1978

Table 5, continued page 8

Southwest			lake level data	most southwest lakes high, northwest Calif. coast and Lake Estancia(?) intermediate. 26,000-21,000 B.P. onset of last glacial maximum. ITCZ south of today	Street & Grove, 1979
Sonoran and Mohave deserts		1525-550m	packrat middens	22,000-11,000 B.P. Pinyon-juniper woodland. P. monophylla	Van Devender & Spaulding, 1979
LATE GLACIAL 14,000 to 10,000 B.P.					
Artillery Mtns., Arizona	34°22'	610m	packrat midden pollen	juniper woodland with Quercus turbinella, 10,250 B.P.	Van Devender & King, 1971
Peach Springs, Grand Canyon, Az.	36°N	860m	packrat middens	12,000 B.P. Mixture of modern vegetation and higher juniper woodland, juniper woodland 860m lower	Van Devender & Mead, 1976
Grand Canyon, Arizona	36°N		packrat middens	13,500-8500 B.P. transition extralocal to modern dominant plant species	Cole, 1982
Grand Canyon, Arizona	36°N		packrat middens	11,000-15,000 B.P. Gradual loss of extralocal Great Basin species	Cole, 1981
Rampart Cave, Grand Canyon, Az.	36°N	530m	packrat middens	14,000-11,000 B.P. Some woodland species drop out and desert species increase	Phillips, 1977
Rampart Cave, Grand Canyon, Az.	36°N	530m	pollen and sedimentary trace elements	10,000-12,000 B.P. warm and dry	Martin, Sabels & Shutler, 1961
Cowboy Cave, Utah	38°N	1710m	plant macrofossils	11,800-13,000 B.P. Opuntia, Pseudotsuga, Picea, Juniperus scopulorum. Colder than today, wetter	Spaulding & Petersen, 1980

Table 5, continued page 9

Cowboy Cave, Utah	38^{o}N	1710m	plant macrofossils	11,800 B.P. Spruce and douglas fir macrofossils blew into cave in sandstone substrate	Spaulding & Van Devender, 1977
Sloth Cave, Williams Cave, Guadalupe Mtns., Texas	$31^{o}55'$	1500m 2000m	packrat middens and pollen	12,000, 13,000 B.P., pinyon juniper woodland, subalpine forest	Van Devender, Spaulding & Phillips, 1979
northern Chihuahuan desert			packrat middens	pinyon juniper woodland vegetation depressed 800m between 11,560-14,800 B.P.	Wells, 1966
Shelter Cave, New Mexico	32^{o}N	1400m	packrat middens and pollen	12,000-11,000 B.P. xeric juniper woodland (xeric slope)	Thompson et al., 1980
Canyon de Chelly, Arizona		1800m	packrat middens and pollen	11,900 B.P. spruce, sagebrush association (mesic slope)	Betancourt & Davis, Unpubl.
Alkali Creek, central Colorado	$38^{o}45'$N	1710m	pollen	~13,000-10,000 B.P. pine-spruce	Markgraf & Scott, 1981
Benny Creek, White Mtns., Az.	34^{o}N	2865m	pollen	13 or 14,000 B.P. increase in sagebrush signaling permanent transition to Holocene	Batchelder & Merrill, Unpubl.
Laguna Salada, Arizona	34^{o}N	1920m	pollen	open sagebrush dominant conifers nearby. Vegetation depressed less than 1000m	Hevly, 1964
Potato Lake, Arizona	$34^{o}26'$	2211m	pollen	transition to Holocene 13,000-10,000 B.P. Less spruce and sagebrush, more pine	Whiteside, 1965

Table 5, continued page 10

Snowbird Blg, Wasatch Mtns., Utah	40°34'N	2470m	pollen	deglaciation prior to 12,500 B.P. 12,300-∿8000 B.P. cool/dry	Madsen & Curry, 1979
Swan Lake, Idaho	42°20'N	1460m	pollen and plant macrofossils	12,000-11,400 B.P. Colder and probably wetter. Limber pine, lodgepole pine, some spruce	Bright, 1966
Cub Creek Pond, Yellowstone, Wyo.	44°27'N	2485m	pollen	∿12,000-11,500 B.P. alpine tundra	Waddington & Wright, 1974
Yellowstone Lake, Wyoming	44°N	2390m	pollen	11,600-10,100 B.P. lodgepole pine-white bark pine forest. Cool-dry. 12,000-14,500 B.P. high subalpine or low alpine, cool, moist	Baker, 1976
Yellowstone Lake, Wyoming	44°N	2300m	pollen	Late Pinedale-tundra; cold moist, treeline lowering of 610m. 11,550 B.P. change to white-bark pine and lodgepole pine, cool, dry	Baker, 1970
Mohave desert, Nevada			packrat middens	pinyon-juniper woodland	Wells & Berger, 1967
Las Vegas Valley, Nevada	37°N	700m	pollen	high elevation Mohave desert or Great Basin desert vegetation in Las Vegas Valley until 7000-8000 B.P.	Mehringer, 1965
Clark Mtn., Nevada	37°N	1910m	packrat middens	wetter than today. pinyon juniper woodland. warmer than full glacial	Mehringer & Ferguson, 1969
Great Basin	north of 37°N		packrat middens, fossil vertebrates	trend toward decreasing effective moisture after 13,000 B.P.	Thompson & Mead, 1982

Table 5, continued page 11

Mohave desert, Nevada	area of 37^{o}N		packrat middens	few data from 15,500-10,000 B.P.; these indicate relatively high moisture	Spaulding, 1981
Ladder Cave, Smith Creek Canyon, Nevada		2050m		more effective moisture than today and probably cooler 13,230-11,000 B.P. Drier after 11,000 B.P.	Thompson, 1978
Lake Cleveland, Idaho		2590m	pollen	15,400-11,000 B.P. Open, dry meadow. Site above treeline	Davis, 1981
Western Sierra Nevada, Calif.	$36^{o}48'$N	920-1270m	packrat middens	drier, eastern Sierran species present, but not as dry as eastern Sierra	Cole, 1982
Hoh Valley and Kalaloch sites, Washington	$47^{o}30'$N		pollen	pollen correlated with 25,000-10,000 B.P. Vashon and Evans Creek Stades of Fraser Glaciation	Heusser, 1977
Davis L.S. Puget, Lowland, Wash.	47^{o}N	282m	pollen	16,000-10,500 B.P. More woodland than full glacial. lodgepole pine. some spruce fir	Barnowsky, 1981
Southwest and globe			lake levels	global warming began 13,500 B.P. High lake levels in southwest 11,000-12,000 B.P. most lakes high in southwest	Street & Grove, 1979
Southwest				13,000-10,000 B.P. mild winters. less severe than present in southwest. increased winter ppn.	Bryson and Wendland, 1966
Southwest			packrat middens	pinyon-juniper woodlands at low elevations	Van Devender & Spaulding, 1979

Table 5, continued page 12

Southwest			pollen	rapid recovery of post glacial vegetation after 12,000 B.P.	Martin & Mehringer, 1965
Lake Lahontan				very high stand of Lake Lahontan, 13,500-11,000 B.P.	Benson, 1981
HOLOCENE 10,000 B.P. to PRESENT					
South Soefje Bog, Texas			pollen	stable environment 8000 B.P.-present	Graham & Heimsch, 1960
Dona Ana County New Mexico	32°30'N		pollen	dry Altithermal. change from shrub to grass dominance after 4000 B.P. Slightly more arid after 2200 B.P.	Freeman, 1972
Sacramento Mtns., New Mexico	33°N	1585-1690m	packrat middens	modern desert flora after 5000 B.P. but most modern taxa present by 10,000 B.P.	Van Devender, Betancourt & Wimberly, Unpubl.
Chaco Canyon, New Mexico	36°N	1860-1945m	packrat middens	10,000 B.P. Cooler summers, wetter. Gap 9460-5550 B.P. 5550 B.P.-present establishment of modern climate and vegetation	Betancourt & Van Devender, 1981
Murray Springs, Arizona	31°40'	1243m	alluvial stratigraphy	5000-7000 B.P. unknown, 4000-5000 B.P. wetter than today	Martin, Mehringer & Haynes, 1967
Southwest	south of 36°N	desert	pollen	Altithermal, summers wetter. Yearly ppn. may have increased (~4000-8000 B.P.)	Martin, 1963
Benny Creek, White Mtns., Arizona	34°N	2865m	pollen	Holocene-3000 B.P., scattered pines with dense sagebrush. 3000 B.P.-present cool and wet pine, spruce fir forest. Little sagebrush	Batchelder & Merrill, Unpubl.

Table 5, continued page 13

Laguna Salada, Arizona	34^{o}N	1920m	pollen	4550-7300 B.P. high grease wood, lower pine, juniper. Interpretation-no evidence of warmer, drier hypsithermal	Hevly, 1964a&b
Potato Lake, Arizona	$34^{o}26'$N	2211m.	pollen and loss on ignition	stable throughout Holocene with historic decrease in organic content of sediments	Whiteside, 1965
Rampart Cave, Grand Canyon, Az.	36^{o}N	530m	packrat middens	woodland aspect until 8500 B.P. desert after 8500 B.P.	Phillips, 1977
Grand Canyon, Az.	36^{o}N		packrat middens	upward displacement of pinyon juniper woodland; hotter and/or drier than today 6800-8500 B.P. Modern taxa present by 8590 B.P.	Cole, 1981, 1982
Twin Lakes, La Plata Mtns., Colorado	$37^{o}30'$N	3290m	pollen	timberline higher than mean starting 8600 B.P., lower treeline 4000 B.P., higher than mean, 2500 B.P.	Petersen & Mehringer, 1976
Alkali Creek, Colorado	$38^{o}45'$N	1710m	pollen	expansion downward of pinyon pine prior to 4000 B.P. Expansion of Bermuda high. Neoglacial conditions after 4000 B.P.	Markgraf & Scott, 1981
Hurricane Basin, San Juan Mtns., Colorado	37^{o}-38^{o}N	3650m	pollen	9600-8400 B.P. cooler and/or wetter, 8400-3000 B.P. warmer, 3000-280 B.P. cooler and/or wetter, 280 B.P.-present, warmer	Andrews et al., 1975
Redrock Lake, Boulder Co., Colorado	40^{o}N	3095m	pollen	site at treeline 9500-8000 B.P., 7500-6700 B.P. like today, 3000-6700 B.P. cooler than today, 3000-present like today. No evidence of mid-postglacial warm and/or dry period	Maher, 1972

Table 5, continued page 14

Redrock Lake, Front Range, Colorado	40^{o}N	3100m	pollen	6000-3000 B.P. hypsithermal warm-dry 3000-present modern	Pennak, 1963
Meadow Valley Wash, Nevada	$37^{o}30'$N	1615m	pollen	pinyon juniper woodland to-day; juniper sagebrush prior to 7000 B.P. juniper, then pine come in 3700 & 900 B.P.	Madsen, 1972
Mohave desert	north of 36^{o}N		packrat middens	woodlands persist in Mohave until 7800 B.P.	Wells & Berger, 1967
Tule Springs, Nevada	37^{o}N	703m	pollen	higher elevation vegetation in desert until 7000-8000 B.P. Drier after 7500 B.P.	Mehringer, 1965
Mohave desert, Nevada	approx. 37^{o}N		packrat middens	early Holocene greater than present winter ppn. Last half of Holocene, increase effective moisture with re-gional increase in summer ppn. Lower temperatures late Holocene	Spaulding, 1981
Sheep Range, Nevada	37^{o}N	1740m	packrat middens	wetter, warmer than today between 3310-1990 B.P.	Spaulding, 1977
Gatecliff Shelter, Triple T Shelter, Nevada	39^{o}N	2178m 2367m	pollen and packrat middens	9000 B.P.-~6000 B.P. Sage-brush dominant. Pinyon and juniper migrate to east cen-tral Nevada by 6000 B.P. Possibly cooler, wetter win-ters 2800-1500 B.P. and 800-present	Thompson & Kautz, in press; Thompson & Hattori, in press
Utah		1400-2000m	modern botany	evidence of expansion of <u>Quercus turbinella</u> northward during a past warmer, drier period	Cottam, Tucker & Drobnick, 1959

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Zion National Park, Beatty Lake	37°30'N	1280-1920m	pollen	4000-2000 B.P. drier than today or before 4000 B.P. Brief moist interval 34,000-35,000 B.P.	Hevly, 1979
Cowboy Cave, Utah	38°19'N	1710m		transition to modern environment 8700 B.P. More xeric after 8700 B.P.	Spaulding & Petersen, 1980
Snowbird Bog, Utah	40°34'N	2470m	pollen	6000-5200 B.P. warm/wet, 5200-present cool/wet, warm/wet, cool/dry	Madsen & Curry, 1979
Swan Lake, Idaho	42°20'N	1460m	pollen and seeds	10,300 B.P. transition from cold to warmer like today. No evidence of mid-Holocene maximum warm period	Bright, 1966
Lake Cleveland, Idaho		2519m	pollen	11,000-6300 B.P. upward migration of shadscale and greasewood, more xeric. Maximum upward migration of conifers 6300-3500 B.P.	Davis, 1981; Bright & Davis, 1982
Rattlesnake Cave, Idaho		1596m	pollen	upward migration of shadscale steppe 8300-7200 B.P.	Ibid.
Cub Creek Pond, Yellowstone, Wyo.	44°27'N	2485m	pollen	maximum warmth 9000-4500 B.P. lodgepole pine dominant	Waddington & Wright, 1974
Yellowstone Park, Wyoming	44°N	2377m	pollen	dry locally 10,160-5000 B.P. Altithermal, lodgepole pine forest. Cooling after 5000 B.P. cooler and moisture after 2800 B.P.	Baker, 1970, 1976
Lost trail pass bog, Montana	47°N	2152m	pollen	warm and moist 7000-4000 B.P. 4000-present modern	Mehringer, Arno & Petersen, 1977

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White Mtns., California	$37^{o}30'$N	3500m	tree rings tree remnants	trees 120-150m above present treeline 3000 B.P.	LaMarche & Mooney, 1967
East-central Nevada	39^{o}N	3350-3500m	tree rings tree remnants	2000-4000 B.P. trees grew 91m above present treeline. Maybe due to warmer and drier summers	LaMarche & Mooney, 1972
White Mtns., California			tree rings	3500-1300 B.C. higher treeline, 1300-200 B.C. cool summers, 200 B.C.-300 A.D. warm summers, renewed cooling after 300 A.D. with brief warm period 1200 A.D.	LaMarche, 1974
Santa Barbara Basin, Northeast Pacific	$34^{o}15'$N		pollen	6000-3000 B.P. climatic optimum. Change to cooler and/or wetter conditions after 4300 B.P.	Heusser, 1978
Western Sierra Nevada, Calif.			disjunct plant populations	1-2^{o}C warmer summers in mid-Holocene 5000-3000 B.P.	Axelrod, 1981
Southern Puget lowland, Wash.			pollen	10,000-5500 B.P. 2^{o}C warmer in July decrease in rainfall. Neoglacial since 5500 B.P.	Barnowsky, 1981
Puget lowlands, Washington			pollen	Hypsithermal 8000-4000 B.P. Neoglacial 4000 B.P.-present	Heusser, 1977
Southwest			packrat middens	pinyons dropped out leaving xeric juniper woodlands by 8000 B.P.	Van Devender & Spaulding, 1979
Southwest	106^{o}-117^{o}W 32^{o}N-38^{o}N		packrat middens	last record of juniper woodland in present desert 8000 B.P. Change to modern climate 8000 B.P.	Van Devender, 1977

Table 5, continued page 17

Continental United States	various	general biota	8000 B.P. Fewer deep lows over southwest, drier climate. Cooler climate 3500 B.P.	Bryson & Wendland, 1966
Globe		computer simulation	9000 B.P. More than 7% increase in global solar radiation for July. Average ppn. for June-August 9000 B.P. increased 8% over northern hemisphere	Kutzbach, 1981
Southwest		various	buried soils, nonalluviation, unconformities in alluvial deposits 7000-4500 B.P. in northern Arizona. Maximum postglacial conditions 6000-5000 B.P. Neoglacial follows.	Hevly & Karlstrom, 1974
Northeast Pacific	30^{o}-34^{o}N	planktonic foraminifera	postglacial maximum warm period 6000 B.P.	Gorsline & Prensky, 1975
Southwest		various	8000-9000 B.P. most lakes low, 5000-6000 B.P. all lakes low, 10,000-4500 B.P. Reestablishment of monsoon rains Africa and India. Rapid oceanic warming	Street & Grove, 1979
Western United States		various	climatic and lake level data for western U.S. is mainly noncoincident and variable	Mehringer, 1977
Lake Lahontan			9000-5000 B.P. extremely low lake level	Benson, 1981
Colorado Front Range		glacial geology	Pleistocene glacier remnants disappeared from front range in mid-Holocene 5000-2500 B.C. Neoglacial Temple Lake 2800 B.P. Historic-last century	Outcalt & MacPhail, 1965

Table 5, continued page 18

Colorado Front Range		glacial geology	postglacial hypsithermal ends prior to 3000 B.P. Neoglacial 2800-2600 B.P. and last few centuries	Porter & Denton, 1967
Colorado Front Range		glacial geology	peak aridity and warmth 7500-6000 B.P. Glacial advances 5000-3000 B.P., 1850-950 B.P., 300-present	Benedict, 1973
Western United States	Sierra Nevada to Laramie Basin	glacial geology	7300 B.P. to late Holocene. Warm, wet summers, winter temperatures fluctuating around freezing	Curry, 1974
Western United States			Anathermal (7000 B.C.-5000 B.C.), subhumid, semiarid; Altithermal (5000 B.C.-2500 B.C.), arid; Medithermal (2500 B.C.-present), arid, semiarid	Antevs, 1948, 1962
Southeastern Arizona		alluvial stratigraphy	increasing aridity from early Holocene until 4500 B.P. Possible hiatus in Double Adobe pollen section	Haynes, 1968

than today before 30,000 radiocarbon years ago. Pollen records from the Mogollon Rim region (Berry and McCormick; Batchelder and Merrill; Merrill and Pewe, 1977) are also interpreted as representing an interstadial climate warmer than the full glacial.

In summary, the climatic model for the Mid-Wisconsin that is compatible with the Hay Lake pollen record is also compatible with other paleoecological records from the Southwest. A southward displacement of mid-latitude westerlies with associated storm tracks brought more winter precipitation than today but not as much as during the full glacial. Subtropical high pressure systems were weakly developed when compared with today but stronger than during the full glacial.

In subzone A3 a change takes place in the compostion of the pine asemblage. Yellow pines (*Pinus ponderosa*/*P. contorta*) are present for the first time and *Picea* percentages increase. I interpret this relatively brief period at the end of Zone A (29,000 to 25,000 B.P.; 290 cm to 220 cm) as a vegetational and climatic transition from the Mid-Wisconsin to the full glacial. An increase in precipitation and perhaps a decrease in temperature permited the expansion of spruce at Hay Lake. The presence of yellow pines at or near the site is difficult to interpret because *Pinus ponderosa* and *P. contorta* have different though overlapping ecological requirements.

Zone B, Hay Lake. Gramineae zone. 25,000 B.P. to 13,700 B.P.; 222 cm to 150 cm.

Vegetation. Zone B is characterized by high percentages of Gramineae pollen and relatively low percentages of pinyon pine pollen. Pollen concentrations are the highest for the core in this zone though pollen influx is fairly low.

Modern pollen samples from *Artemisia* steppe, forest meadows, parklands and tundra or the forest-tundra ecotone contain from 10 percent to 20 percent Gramineae pollen (Hevly, 1968; Birks, 1973; Baker, 1976; Mack, Bryant and Pell, 1978; Maher, 1963). In surface pollen studies involving transects through a variety of plant communities, Gramineae pollen is usually overshadowed by better-dispersed, more abundant pollen from other taxa. For example, in Yellowstone National Park, Wyoming, Gramineae pollen is consistently present in samples from areas where grass is abundant and coniferous trees are rare or absent (e.g., openings in *Pinus contorta* forests or subalpine parkland and tundra). In samples from closed *P. contorta* forest, Gramineae pollen never exceeds two percent of the sum (Baker, 1976). In some cases, Gramineae pollen in surface samples from grassland make up less than ten percent of the sum (Maher, 1963) or are rarely present (Potter and Rowley, 1960) due to the abundance of pollen from nearby coniferous forests.

In zone B Gramineae pollen is consistently present in amounts between 10 and 20 percent. Based on the surface studies just mentioned, the grass pollen in zone B is indicative of open vegetation around Hay Lake dominated by grasses. Conifers would have been rare or scattered as they are today at the forest-alpine tundra ecotone. *Picea* pollen consistently makes up about five percent of the pollen sum indicating the presence of the tree locally in small numbers. This is in agreement with an upper treeline interpretation for the vegetation around Hay Lake at this time.

The compostion of the coniferous taxa composing the upper forest boundary during zone B time is difficult to ascertain. The yellow pines, *P. aristata* and *P. flexilis* or *P. strobiformis* could have been present at or near the site, or, the pollen of these taxa could have blown in from some distance away. Though the pollen of *P. flexilis* and *P. strobiformis* were not distinguished from one another, *P. flexilis* is likely to be represented in the full glacial pollen rain. It has a more northerly distribution today than *P. strobiformis* and is often associated with *P. aristata*. It is also present in full glacial pollen assemblages from the Chuska Mountains (Wright, et al., 1973). *P. flexilis* and *P. aristata* are found today in mixed coniferous forests, high elevations, and in dwarfed and krummholz form at the forest-tundra ecotone (Peet, 1978; LaMarche and Mooney, 1972). *P.*

flexilis can also act as a successional species, dominate high elevation sites in the absence of other high elevation conifers (Peet, 1978), or co-dominate at middle elevations with *Pseudotsuga menziesii* in the absence of *P. ponderosa* (Baker, 1976). Therefore, its ecological significance at Hay Lake remains obscure, especially because the pollen assemblages suggest it was associated in some way with other subalpine conifers.

I interpret the abundance of Gramineae pollen associated with *Picea* as indicating a high elevation parkland at the forest-tundra ecotone and not a yellow pine parkland or meadow. Instead, I interpret the abundance of yellow pine pollen as indicating that *Pinus ponderosa* and/or *P. contorta* were present in relatively large stands at lower elevations than Hay Lake. Neither of these taxa grow at treeline today (Rehfeldt, 1980; Moir and Ludwig, 1979; Layser and Schubert, 1979), *P. ponderosa* being the less cold-tolerant of the two.

Pinyon pines make up less than 10 percent of the identified pine grains in two of the three zone B differentiated pine samples. In these two cases less pinyon pine pollen was reaching Hay Lake than today. This implies that pinyon pines were farther from the site during the full glacial than today. Full glacial packrat midden data support this view as pinyon pine macrofossils are reported from areas now occupied by Sonoran, Chihuahuan, and Mohave desert (Van

Devender and Spaulding, 1979).

The nonarboreal pollen taxa are as diverse as during the Mid-Wisconsin but slightly different. Gilia, Claytonia, Rubus, Geum, Shepherdia, and Cruciferae drop out before the end of the Mid-Wisconsin and Selaginella appears for the first time during the full glacial (Table 4). None of these taxa are restricted in ecological range today. However, a change in the herbaceous flora associated with a change in the arboreal taxa is likely to reflect a change in climate.

Because Botryococcus, concentration increases dramatically at the beginning of zone B and first appears where Myriophyllum disappears (300 cm), it is tempting to induce changes in water depth to explain the Botryococcus curve. Though the curve undoubtedly has some ecological significance, it is not possible to deduce what that is. Regarding Botryococcus, Hutchinson (1967) says, "It can be extremely abundant, but under conditions that are so varied that nothing can be said of its ecological determination." The most that can be said about Hay Lake from the aquatic flora after 31,000 B.P. (303 cm) is that water depth probably diminished and remained low relative to the period older than 31,000 B.P..

Pollen influx never exceeds 5000 grains/cm^2/yr in this zone and, for the most part, averages around 1000 grains/cm^2/yr. The sedimentation rate is slow during the full glacial, 180 yrs/cm, and thus accounts for high pollen concentration despite the relatively low influx. An average influx of 1000 grains/cm^2/yr is not unusually low for a lake surrounded by tundra vegetation. Pollen traps in Canadian tundra collected 5 - 800 grains/cm^2/yr while influx from reconstructed tundra communities in the eastern United States and England range from 100 to 5000 grains/cm^2/yr (Davis, Brubaker, and Webb, 1973). Influx to pollen traps in the Canadian forest-tundra ecotone range from 275 to 2000 grains/cm^2/yr (Ritchie and Lichti-Federovich, 1967). Influx values for open or closed vegetation in one region, however, may not be the same as for another region. Forested regions of the western United States, for example, do not produce as much pollen as eastern deciduous forests. Holocene sediments at forested Redrock Lake, Colorado, ranged between 4000 to 6000 grains/cm^2/yr as opposed to between 15,000 and 80,000 grains/cm^2/yr reported for lakes in the Midwest and East (Maher, 1972).

Influx values for the full glacial at Hay Lake are in accord with values for other sites surrounded by open vegetation or at the forest-tundra ecotone. Though influx values alone should not be used to determine the surrounding vegetation they do not conflict here with the proposed reconstruction.

In summary, the vegetation at Hay Lake between 25,000 B.P. and 13,700 B.P. (222 cm to 150 cm) was open and dominated by grasses and herbs. Picea was present locally suggesting the site was close to treeline. P. aristata may have been near Hay Lake in a subalpine community codominated by possibly P. flexilis/P. strobiformis and perhaps P. contorta. However, the distance to these conifers cannot be determined from the pollen percentages.

Early vegetation reconstructions for the full glacial in the Southwest relied on the concept of vegetation zones and their theoretical behavior as cohesive units. Abundant pine pollen from Willcox playa was interpreted as representing a 900 m to 1200 m depression of yellow pine parkland and other vegetation zones on nearby mountian ranges (Martin, 1963a; Martin, 1964; Hevly and Martin, 1961). In 1973, Hansen and Cushing devised a method of pine pollen species identification which was applied to fossil deposits from the Chuska Mountains, New Mexico (Hansen and Cushing, 1973). With this advantage, the pollen record disclosed the presence of Rocky Mountain coniferous taxa such as, Pinus aristata, P. contorta and P. flexilis, during the Pleistocene in the Chuska Mountains where they are extinct today. Although this represents a latitudinal displacement of conifer species the the record was interpreted with the prevailing zonal concept in mind. The Chuska Mountain record was interpreted as representing a depression of the upper forest limit by 900 to 1000 m and the lower ponderosa belt by less than 500 m (Wright et al., 1973). Thus, telescoping of vegetation zones was hypothesized for the full glacial of New Mexico. With additional pollen data and the more detailed taxonomic information supplied by packrat midden analyses, it became clear that this approach in the Southwest may be too simplistic.

Great Basin plant taxa were found in packrat middens south of the Mogollon Rim in Arizona and at low elevations in the Grand Canyon (Cole, 1981, 1982; Van Devender and Spaulding, 1979). Pinyon-juniper woodlands were widespread across the lowland Southwest while montane and subalpine conifers grew at higher elevations (Spaulding, Leopold and Van Devender, In press). There was more of a rearrangement of high elevation, higher latitude, plant taxa at lower elevations than a mass movement of zones. This is reflected in the pollen assemblages at Hay Lake where Rocky Mountain conifers such as *P. aristata* and possibly *P. flexilis*, now absent in the White Mountains, grew during the Pleistocene.

The position of upper treeline can be used as an indicator of summer temperatures and the length of the growing season (e.g., Daubenmire, 1974; LaMarche, 1974). Estimates of full glacial treeline in the Southwest are varied primarily due to differences in interpretation of pollen diagrams by palynologists. Full glacial treeline depression estimates for Arizona and New Mexico range from 1200 m to 335 m. Based on the zonal vegetation change concept and in accord with the state of knowledge at the time, early estimates for treeline depression in the Southwest were somewhat larger than later estimates (Table 5). Berry and McCormick (Northern Arizona University, Flagstaff) estimate an 800 m (Unpubl.) treeline depression; and Batchelder and Merrill estimate 335 m for the White Mountains, (Pers. Comm., 1980). Modern treeline in Arizona is between 3350 and 3500 m. A conservative estimate for treeline depression during the full glacial in the Hay Lake area is 570 m.

Climate. The primary limiting factor for high elevation tree growth is generally accepted to be cold temperatures (LaMarche, 1974; Daubenmire, 1974). The length of the growing season is essential because young shoots must develop frost hardiness before winter conditions set in (Wardle, 1974; Tranquillini, 1979). Trees adapted to drought stress are also more likely to be cold hardy (LaMarche and Mooney, 1972). This may explain the expansion of cold-tolerant, drought-tolerant *P. aristata* and *P. flexilis*/*P. strobiformis* during the full glacial and possibly the absence of more sensitive subalpine conifers such as *Abies concolor* and *Pseudotsuga menziesii*.

The 570 m depression of treeline in the Hay Lake region and presence of drought and cold-resistant conifers suggests the growing season was shorter than today and warm season temperatures were lower. The presence of drought hardy trees does not necessarily indicate summer drought but it means that less summer precipitation during the full glacial is a possibility.

The gypsum crystals between 222 and 150 cm could have been incorporated into the Hay Lake sediments during deposition or could have precipitated in place with fluctuating lake levels. This cannot be determined from the sediments themselves or the pollen content. However, a dry climate would have allowed for the precipitation of salts. This is in accord with very little sediment influx (slow sedimentation) and greater oxidation (iron oxides) due to shallow water. It is possible that much of the precipitation at Hay Lake was in the form of snow during most of the year. Some runoff would occur during summer snowmelt but overall sedimentation would be very slow if summer rains were diminished.

Longer winters and cooler drier summers are in agreement with many reconstructions of full glacial climate for the Southwest and feasible according to modern synoptic climatology (discussed above). A comprehensive summary of reconstructions (Spaulding, et al., In press) for full glacial vegetation and climate in the Southwest concludes that south of 36° N winter precipitation was greater than today and summer precipitation was diminished. Packrat midden data indicate that large areas of what are now lowland deserts were occupied by juniper or pinyon-juniper woodlands extending up in elevation as high as 1525 m, over 700 m below their modern upper limit (Van Devender and Spaulding, 1979). This supports the Hay Lake data which suggest pinyon woodland was farther from the site than today. Pollen data from the Mogollon Rim (Whiteside, 1965) supports the hypothesis that open subalpine or montane communities occupied elevations above 2000 m in Arizona (Spaulding et al., In press). This is also supported by the Hay Lake data which include high percentages of montane and subalpine pine species.

Diminished summer precipitation from 25,000 to 13,700 B.P. could have resulted from contraction of subtropical and tropical sea and air circulation northward. Bermuda high pressure cells that bring summer moisture to Arizona would have been less influential. Independent data sources, such as deep sea cores and global lake level changes, confirm that subtropical monsoons, dependent upon northward migration of tropical storm tracks, were greatly reduced during the full glacial (CLIMAP project members, 1976; Street and Grove, 1979). A reconstruction for shallow-water marine climate off the California coast also indicates a contraction of tropical waters (Addicott, 1966).

Moisture for winter and spring precipitation originates in the Pacific. An increase in winter storms may have produced the expansion of woodlands into lowland deserts south of 36° N (e.g., Van Devender and Spaulding, 1979).

Addicott's (1966) reconstruction for Pleistocene shallow-water marine climate indicates expansion southward of cool temperate waters; in accordance with the theory that the Aleutian low was displaced southward. This would bring longer, wetter winters to the Southwest.

With few exceptions, reconstructions for full glacial climate on Table 5 call for cooler summers and greater winter precipitation south of about 37° N latitude. Two reconstructions involve greatly reduced annual or summer temperatures, greater continentality and no increase in precipitation (Galloway, 1970; Brakenridge, 1978). Brakenridge's (1978) annual temperature depression of 7°-8° C is based on a treeline depression of 1000 m. The Hay Lake data do not support this amount of treeline depression. Galloway (1970) assumes that full glacial timberline, given a summer temperature reduction of 10° C, was at 2,050 m. This is far lower than any reconstructed for the Southwest, including Hay Lake, on the basis of pollen analysis. Wells' (1979) hypothesis is that the modern summer rainfall pattern was enhanced in Texas and New Mexico during the full glacial. The Hay Lake pollen data do not directly conflict with this hypothesis but do not support it. Cooler summer temperatures and longer winters would be very unlikely in Arizona if the summer monsoons were enhanced.

To summarize, the full glacial climate at Hay Lake was one of cooler, and possibly drier summers. Winters were longer and probably wetter than today. Most precipitation was in the form of snow and the net effect at Hay Lake was a colder, drier climate. Winter storm tracks were farther south than they are today and subtropical monsoons were constricted.

Subzone C1, Early Holocene, Hay Lake. *Artemisia* - Gramineae zone. 13,700 to 9,000 B.P.; 150 to 80 cm.

Early Holocene. The Holocene (Recent) is an informal term used to define the time period succeeding the Pleistocene. The Pleistocene Epoch is a formal name given originally to ice age climate. Though the term Holocene is generally accepted by students of geology and paleoclimatology, it is becoming apparent that this recent period is another interglacial climatically very much a part of the Pleistocene. I will use the Holocene here as it is a well accepted term for post-Wisconsin time.

The boundary between the last major glaciation of the Pleistocene (the Wisconsin) and the Holocene is time transgressive and poorly defined. On the basis of climatic reconstructions the Wisconsin-Holocene boundary can be drawn anywhere from 14,000 B.P. to 10,000 B.P. or later depending on the locality. As a compromise, the Holocene Commission for INQUA placed the Pleistocene-Holocene boundary at 10,000 radiocarbon years ago (Bowen, 1978). However, there is no official stratotype for this boundary and its definition on a geological or biological basis remains obscure. Despite the determination of the boundary at 10,000 B.P., researchers continue to recognize the Pleistocene-Holocene boundary locally usually on the basis of biological data. For example, Van Devender and Spaulding (1979) choose 11,000 B.P. as the end of the Pleistocene with a transitional early Holocene ending 8,000 B.P.. The transition from one climatic regime to another may be gradual and necessitate the naming of transitional time periods. For example, Cole (1981) recognized late glacial (11,000 - 15,000 B.P.) and early Holocene (8590 - 10,760 B.P.) periods based on fossil plant remains from the Grand Canyon.

In this paper I will place the Wisconsin-Holocene boundary according to changes in the pollen record at Hay Lake. Here, as at the Grand Canyon, the boundary is gradual and transitional periods will be identified. The major change at the end of the Wisconsin takes place about 13,700 B.P. and is recognized on the basis of the change in pollen percentages at 150 cm. Subzone C1, the early Holocene is characterized by pollen assemblages between 150 and 80 cm (about 13,700 to 9000 B.P.). These assemblages have some characteristics of the Wisconsin (high Gramineae percentages) but bear greater resemblance to the rest of the Holocene pollen assmeblages by having high _Artemisia_ and low _Picea_ percentages. Therefore, they make up a subzone (C1) of zone

C. These boundaries are informal, local and not necessarily correlative with other biostratigraphic zones.

Vegetation. The vegetation at Hay Lake during the time represented by subzone C1 was open, dominated by *Artemisia*, Gramineae, and Compositae associated with a variety of other herbaceous taxa. *Picea* was at the site at the beginning of subzone C1 but diminished after about 12,500 radiocarbon years ago. *Pinus* species may have been present at or near the site.

The increase in pollen concentration and pollen influx and a peak in arboreal pollen at the beginning of subzone C1 may indicate that more pollen was reaching the lake as a result of an increase in local pollen production by conifers. The decrease in pollen concentration and influx and a reduction in arboreal pollen above 122 cm may indicate that the vegetation around Hay Lake was becoming more open at this time.

The influx values at Hay Lake in subzone C1 (250 grains/cm^2/yr) are lower than most values published for various vegetation types (Birks and Birks, 1980). Influx values for prairie range from 1,000 to 15,000 grains/cm^2/yr and for forested areas from 2,000 to 78,300 grains/cm^2/yr (Davis, et al., 1973). Although there is considerable overlap in range, and variation from region to region, in general, forested vegetation produces more pollen than non-forested vegetation. The mean value for prairie is 9,500 grains/cm^2/yr and in the same region, means for forested areas are 37,300, 46,800, and 13,700 grains/cm^2/yr (Davis, et al., 1973). Low influx values in subzone C1 supports the hypothesis that vegetation at the site was open though poor pollen preservation may have been a contributing factor.

Reconstructions for other sites for the period 13,700 B.P. to 9000 B.P. are included on Table 5 in the categories late glacial and Holocene. Generally, the sites record a slow transition beginning around 13,000 B.P. and in many cases ending around 8000 B.P.. North of about 37° N cold, glacial environments perisited until about 11,500 to 10,500 B.P. (e.g., Davis, 1981; Thompson, 1978) though many sites show evidence of an amelioration of climate before the end of this period (Madsen and Curry, 1979; Markgraf and Scott, 1981; Baker, 1976; Bright, 1966; Baker, 1970; Heusser, 1977; Barnowsky, 1981; Andrews et al., 1975).

Not including the Grand Canyon records, the end of the Pleistocene in the desert Southwest is designated 11,000 B.P. on the basis of plant macrofossils in packrat middens collected at elevations below 1600 meters (Van Devender and Spaulding, 1979). Pollen sites above this elevation contain late glacial-early Holocene records showing significant changes before 11,000 B.P.. Potato Lake (2211 m) on the Mogollon Rim (Whiteside, 1965) records a change from spruce woodland to pine forest between 13,000 and 10,000 radiocarbon years ago. Batchelder and Merrill (Pers. Comm., 1980) also record a change in vegetation between 14,000 and 13,000 B.P. in the White Mountains (2865) signifying the transition to the Holocene. The retreat of subalpine conifers at high elevations before some low elevation conifers (such as pinyon pines and *Juniperus*) may be indicative of a change to warmer climate before the modern precipitation regime was established. However, additional pollen and plant macrofossil sites are needed from middle and high elevations to test this hypothesis.

Elsewhere on the Colorado Plateau, J. Betancourt (Univeristy of Arizona, Tucson) records packrat middens from 36° 05' to 37° 47' N between 1585 m and 2195 m containing *Picea*, *Juniperus communis* and *Pinus flexilis* below their modern limits until 10,000 to 9,000 B.P. (Unpubl.). Similarly, pollen records from southwestern Colorado, indicate conditions cooler and/or wetter than today on the basis of *Picea:Pinus* ratios until between 8,000 and 8,600 B.P. (Andrews et al., 1975; Petersen and Mehringer, 1976; Maher, 1972).

In summary, the late glacial to early Holocene in the Southwest was characterized by a gradual transformation from Pleistocene to modern plant communities. In the Mohave, Sonoran, and Chihuahuan deserts pinyon juniper woodlands remained displaced at lower elevations until 11,000 B.P.. After this time pinyon pines retreated from the deserts leaving juniper woodlands behind (Van Devender and Spaulding, 1979). In the Grand Canyon extralocal species began to disappear from lower elevations 13,000 B.P. and were gradually replaced with modern communites by 9000 B.P. (Cole, 1981, 1982; Phillips, 1977; Van Devender and Mead, 1976).

The Colorado Plateau between about 1800 and 2600 m was occupied by *Picea*, *Pinus*, *Artemisia* woodlands during the full glacial. After 13,000 B.P., *Picea* and *Artemisia* began to diminish at their lower limits (Whiteside, 1965) and increase at their upper limits at Hay Lake and at Benny Creek (Batchelder and Merrill, Pers. Comm., 1980). Packrat middens and pollen records from Arizona, Utah and Colorado show spruce lingering at lower elevations until 9000 to 8000 B.P. (Spaulding and Petersen, 1980; Betancourt, Unpubl.; Whiteside, 1965). This is coincident and probably related in an overall climatic sense to the presence of *Juniperus* in the lowland deserts until 8000 B.P..

Climate. Climatic reconstruction for the end of the Wisconsin and beginning of the Holocene is complicated by variables not present for earlier periods. The early Holocene as defined here extends from 13,700 B.P. to 9,000 B.P. lasting 4700 years. Earlier climatic episodes such as the full glacial span 11,000 years or more and interpretations of past climate are less varied than for the Holocene. The less uniform nature of Holocene reconstructions is due, in part, to the increased resolution we have for the more recent past. A greater number of radiocarbon dates, and a larger data base exist for the Holocene than for the full glacial and the Holocene has been studied by more researchers than the full glacial. With this increased resolution, we must be more cognizant of individual site differences, and differences inherent in the biological systems being used for climatic reconstructions.

Still using the principal that trees are limited by moisture at their lower limit and by temperature at their upper limit, the early Holocene in Arizona was cooler and wetter than today but not as cool and wet as during the full glacial. Some taxa such as _Picea_ and _Juniperus_ maintained populations at elevations below their modern lower limits until 9,000 - 8,000 B.P. over a large area in the Southwest. Other sites in addition to Hay Lake record changes at upper treeline. In southwestern Colorado, treeline below the modern limit is interpreted as indicating cooler summers until anywhere from 8,600 B.P. to 8,000 B.P. (Andrews et al., 1975; Maher, 1972; Petersen and Mehringer, 1976).

Artemisia fluctuations in the Hay Lake pollen record as well as at other sites are difficult to interpret in ecological or climatic terms. _Artemisia_ species currently range from desert to alpine environments. _A. tridentata_ (big sagebrush) grows from the lowlands of the Great Basin to timberline (Vines, 1960). It ranges from areas receiving 200 mm to over 1000 mm of precipitation (Sturges, 1979). Generally *Artemisia* is a cold desert plant. It photosynthesizes best at lower temperatures but it is able to adjust its photosynthetic activity somewhat to fit different temperature regimes (Caldwell, 1979). It withstands periods of drought by extracting soil moisture via deep root systems (Sturges, 1979; West, 1979). For Wyoming, Colorado, and Idaho, Sturges (1979) summarized *Artemisia tridentata's* ecological requirements as follows: "Sagebrush ... exists where temperature and moisture relationships are favorable for rapid vegetation growth only for a short period of time in the spring and early summer." Limiting factors that can be gleaned from discussions of *Artemisia* autecology are high annual temperatures and fire. Burning has long been used in the Great Basin for the eradication of sagebrush because it does not resprout after fire (Britton and Ralphs, 1979; West, 1979).

A cooler, wetter environment in the Southwest during the full glacial would create extensive habitat for shrubby *Artemisia* such as *A. tridentata* especially at lower and middle elevations. At the end of the full glacial: a) increased fire frequency and/or b) an unfavorable temperature-precipitation regime caused the demise of extensive sagebrush at middle elevations.

At Hay Lake, warmer spring and summer temperatures beginning around 13,700 B.P. would create additional favorable habitat for *Artemisia* at upper elevations than in preceding intervals. Today the mean annual precipitation at Greer, a few km from Hay Lake and 200 m lower in elevation, is 680 mm. This is well within the modern range of yearly precipitation in *Artemisia* dominated plant communities. During the early Holocene precipitation in the Hay Lake region was probably somewhat greater than 680 mm and a greater proportion of it probably fell in the winter. Though *Artemisia* was already present in the Hay Lake area during the full glacial, warm springs with moist winter soils would encourage the expansion of *Artemisia* at the elevation of the site.

The Intertropical Convergence Zone would have been moving northward as northern hemisphere temperatures increased at the end of the Wisconsin. As a result, summer monsoons would again become well developed and mid-latitude westerlies would be retreating northward. According to the biological data this was a gradual process after 13,000 B.P. and did not culminate until the middle Holocene after 8,000 B.P.. Independent data from deep sea cores indicate a rapid retreat of the polar front in the north Atlantic 13,000 radiocarbon years ago. This was followed by a brief readvance 11,000 B.P. and a more gradual retreat from 10,000 to 6,000 B.P. (Ruddiman and McIntyre, 1981). Global lake level data indicate warming began around 13,500 B.P. though at 11,000 B.P. most lakes in the southwestern United States were still at relatively high stands (Street and Grove, 1979; Benson, 1981). Thus early Holocene climate in the Southwest was warmer than the full glacial and perhaps drier but wet enough to support high lake levels and some arboreal taxa at lower than modern elevations.

Subzone C2, Hay Lake. _Artemisia_ subzone. 9,000 to 1,500 B.P.; 80 cm to 15 cm.

Vegetation. The middle Holocene is one of the more controversial time periods for southwestern paleoecologists. Since Antevs' (1948) subdivision of the Holocene into the Anathermal (7000 B.C. to 5000 B.C.), Altithermal (5000 B.C. to 2500 B.C.) and Medithermal (2000 B.C. to present), no consensus has been reached regarding either the boundaries of these subdivisions or their climatic meaning. As subzone C1 covers the period 9,000 to 1,500 B.P. I will discuss the Altithermal in light of results from Hay Lake, other high elevation sites in the Southwest and more general terms after the discussion of the Holocene at Jacob Lake.

The low pine percentages during the Holocene may be due to the abundance of _Artemisia_, that places a constraint on the relative percentages of other taxa. Differentiated _Pinus_ species show that by the middle Holocene _P. aristata_ was essentially absent from the Hay Lake area. This is the culmination of a trend toward decreasing amounts of *P. aristata* since the full glacial approximately 22,000 radiocarbon years ago. Interpretations based on the relative *Pinus* species identifications, however, must remain conservative because of the low number of samples analyzed for the last 22,000 years. Other than the drop in *P. aristata* percentages, the *Pinus* species percentages do not change very much. The white pine and yellow pine species composition may have been changing; i.e., increasing amounts of *P. strobiformis* and *P. ponderosa* towards the surface, but this is beyond detection by the identification scheme I used.

Only in the Great Basin in areas of vast sagebrush steppe do *Artemisia* percentages reach 50 percent in modern pollen samples. In some cases, as much as 80 percent *Artemisia* pollen was recorded in surface samples from big sagebrush steppe and pollen influx was unusually high as well (Davis, 1981). Contrary to the Great Basin surface data, pollen influx at Hay Lake is low, averaging 200 grains/cm^2/yr for samples in the middle Holocene. Pollen influx for Great Basin samples exceed 8000 grains/cm^2/yr for *Artemisia* alone (Davis, 1981). The unusually low pollen influx and very high *Artemisia* percentages can be explained in two ways: 1) the lake was surrounded by treeless vegetation which produced very little pollen, most of which was *Artemisia* 2) poor pollen preservation resulted in destruction of most pollen differentially preserving *Artemisia*. No one thing rules out either of these two possibilities. The preservation in the Holocene sediments is poor in general. An indication of this is that only two samples could be analyzed for pine species identifications. Most pine counts were made on the basis of bladders (two bladders = one grain) rather than the entire grain. The relative percentages could be a reflection of differential preservation, especially because deteriorated pollen grains were not included in the sum (See Appendix). Nevertheless, Artemisia is present in high percentages in some other Holocene high elevation records and at Hay Lake most Artemisia pollen are well preserved. My interpretation is that at Hay Lake poor preservation is not the main or only reason for low pollen influx and the relatively high percentages of Artemisia.

The Benny Creek pollen site (Batchelder and Merrill, Unpubl.) is approximately 8 km southwest of and at a similar elevation (2865 m) to Hay Lake. Artemisia percentages during the middle Holocene reach a maximum of about 40 percent at 7,335 ±750 B.P. and are interpreted by the authors as representing a post glacial warm and dry climate beginning 13,000 - 14,000 B.P.. Walker Lake is in a volcanic crater at 2500 m near Flagstaff, Arizona (Fig. 1). Here, too, middle Holocene Artemisia percentages exceed 30 percent (Carlson, Batchelder and Updike, 1976). There are no other high elevation pollen or packrat midden records from Arizona or the four corners region recording high percentages of _Artemisia_ during the middle Holocene. The resulting question is whether _Artemisia_ was dominant locally in the White Mountains and at Walker Lake or whether it was more widespread at high elevations across this region. The answer to this question awaits additional analysis of high elevation sites in Arizona.

If my interpretation of low influx and high _Artemisia_ percentages is correct, the vegetation at Hay Lake from about 9,000 B.P. to 1,500 B.P. (150 to 15 cm) was open and probably treeless with an extensive cover of shrubby _Artemisia_. The habitat may have resembled a large meadow with conifers growing some distance away. Evidence from other high elevation localities in Arizona is not extensive enough to say whether _Artemisia_ was the dominant plant at elevations above 2500 m but it was abundant at two other localities (i.e., Benny Creek and Walker Lake).

Climate. The climate at Hay Lake during the middle Holocene must be interpreted with regard to the predominance of _Artemisia_. As discused earlier, the main limiting factors for _Artemisia_ growth are high annual temperatures and fire. Once _Artemisia_ became established around Hay Lake 9,000 radiocarbon years ago, its expansion could be explained by a fairly wide range of general climatic conditions. These will be discussed further after consideration of the Holocene at Jacob Lake.

In addition to broadscale climatic factors, local conditions at Hay Lake may have discouraged growth of trees in an area already occupied by Artemisia. Studies of high elevation open grass meadows, discussed in chapter one, show that soil and local temperature conditions are unfavorable for tree seedling survival (Merkle, 1962).

Zone D, Hay Lake. Pinus, Juniperus, Gramineae zone. 1500 B.P. to modern; 15 cm to 0 cm.

Vegetation and Climate. Zone D is dominated by Pinus, Gramineae and Juniperus pollen and represents the modern vegetation at Hay Lake. Apparently, the change from middle Holocene to the modern environment took place quickly between 1,500 and 1,700 years ago though these dates are based on extrapolation from a radiocarbon date at 50 cm. The sudden decline in Artemisia could be due to the following: 1) the local eradication of Artemisia by early settlers 2) a climatic change 3) improved preservation of pollen taxa other than Artemisia 4) fire indirectly resulting from a change in climate. I submitted a sample to obtain a radiocarbon date at the level of this change to see if in fact the change could have taken place as the result of historic land use practices. However, there was too little carbon in the sediment to obtain the date. The sediment is consistently brown clay from the level of a radiocarbon date [4070±30 (A-2474) at 50 cm] to 8 cm. At 8 cm the sediment changes to peat (Table 1). Sudden changes in land use may be accompanied by a change in sediment texture. In this case it would mean that only the top 8 cm represent the last 50 to 100 years. This cannot be confirmed without better radiocarbon control. My assumption is that the extrapolated date at 15 cm is correct (or nearly correct) because there is no evidence of a sedimentation rate change. In this case, the date of the *Artemisia* decline is too early to coincide with early settlers.

The presumed timing of the *Artemisia* decline coincides with Neoglacial events in the Rocky Mountains (Porter and Denton, 1967; Outcalt and MacPhail, 1965). *Artemisia*, however, is a versitile plant adapted to a wide range of climatic conditions. It is unlikely that a relatively minor climatic change such as that proposed for the Neoglacial could be directly responsible for the sudden demise of *Artemisia* at Hay Lake. The third alternative exlanation, improved preservation of pollen taxa other than *Artemisia*, is unlikely for the following reasons: a) there is no sedimentological change at 15 cm that might indicate a change in local lake conditions b) pollen influx and concentration values remain low and c) pollen diversity (number of taxa) remains approximately the same across the subzone C2-zone D boundary (see also Appendix). If the climate during the middle Holocene became dry enough to promote fires during spring droughts, *Artemisia* could not have survived. The suddenness of the decline suports the idea of a catastrophic event as opposed to a gradual change in climate and vegetation. With *Artemisia* unable to reestablish itself, conifers and grasses would then come to occupy the area as they do today. Therefore, increased fire frequency at the site is the most plausible explanation for the sudden decline in *Artemisia* pollen at Hay Lake.

Jacob Lake

Zone A, Jacob Lake. *Picea- Artemisia* zone. 23,000 to 14,000 B.P., 296 cm to 210 cm.

Vegetation. Zone A at Jacob Lake (Fig. 1), characterized by *Picea* and *Artemisia* pollen, represents the full glacial and is approximately equivalent to zone B at Hay Lake. Hay Lake, at 2780 m was at treeline during the last glacial maximum and Jacob Lake, at 2285 m was surrounded by open coniferous forest with extensive shrub and herb layers.

The high pine percentages (50% or more) during most of zone A provide the evidence that Jacob Lake was surrounded by forest. Unfortunately the pines were not well enough preserved for species identifications. At least part of the pine percentage may have been pinyon pine due to its widespread distribution at lower elevations at this time (e.g., Van Devender and Spaulding, 1979).

Potato Lake (2211m) is located about 50 km WNW of Jacob Lake and contains a Pleistocene pollen assemblage similar to that of Jacob Lake for the full glacial

(Whiteside, 1965). The full glacial Potato Lake pollen assemblage is characterized by *Picea* (categorized with *Pseudotsuga* and *Abies*) and *Artemisia*. Pine percentages average 17 percent or less than half as much as at Jacob Lake. This could be due to greater herbaceous plant cover around Potato Lake.

Spaulding et al., (In press) conclude that the pine species in the vicinity of Jacob and Potato Lakes was *Pinus flexilis* on the basis of a full glacial packrat midden at a similar elevation from the Grand Canyon. There are no data on fossil plants from the Mogollon Rim to support or refute this hypothesis. However, the presence of *Pinus flexilis*/*P. strobiformis* pollen during the full glacial at Hay Lake and *P. flexilis* in the Chuska Mountains as well as at the Grand Canyon means that *P. flexilis* was more widespread in the Ariznoa-New Mexico region in the past. The disjunct population of *Pinus flexilis* on the San Francisco Mountains (Fig.1) is probably relict from the widespread Pleistocene distribution. *Pinus aristata*, is associated with *P. flexilis* in the San Francisco Mountains and is also disjunct from more northerly populations today. It was also recorded in fossil pollen records from Hay Lake and the Chuska Mountains and is presumably also a relict of the Pleistocene.

The only fossil evidence of *P. ponderosa* from the full glacial comes from the Hay Lake and Chuska Mountains pollen records. Full glacial data from fossil packrat middens of Arizona and New Mexico come from elevations below 1600 m, where juniper or pinyon-juniper woodlands predominated. Therefore, if P. ponderosa was present in Pleistocene plant communities, it would have been above the elevation of the midden sites. P. ponderosa may have been greatly reduced in range during the full glacial as compared with today.

Surface samples from spruce-fir communities of Arizona and Colorado contain from 20 percent to 50 percent Picea pollen (Whiteside, 1965; Maher, 1963; Batchelder and Merrill, Unpubl.). Lower percentages occur where Picea is scattered (as at its upper limit) or mixed with other conifers (near its lower limit). Zone A at Jacob Lake contains five to 10 percent Picea pollen indicative of its presence at the site in small numbers and/or in association with other conifers. The amount of cover by pine species at the site cannot be determined from the pollen counts. However, with reference to the earlier discussion of pine species, pines other than pinyon were likely to have been present above 1600 meters and below 2780 meters.

I interpret the non-arboreal pollen, which make up from 30 to 40 percent of the pollen sum in zone A, as indicating either an extensive understory in a Picea -Pinus woodland, or the presence of an open meadow between the lake and the forest.

The consistent presence of the aquatic alga, Botryococcus, during the full glacial at Jacob Lake indicates the presence of a lake or marsh.

Pollen concentration averages about 30,000 grains/gm, which is low relative to the full glacial at Hay Lake (maximum about 550,000 grains/gm) and lake sediments from the Front Range of Colorado [about 300,000 grains/cm3; (Maher, 1972)]. Low pollen concentration can be due to low pollen influx, poor preservation or rapid sedimentation rate.

Sedimentation rate cannot be derived for zone A because it is not braketed by radiometric dates. However, an average sedimentation rate for the core is 77.8 yrs/cm. Sedimentation rates for the lower two and upper two dates are 70.3 yrs/cm and 85.3 yrs/cm respectively. These are close to the 80 yrs/cm median sedimentation rate expected for lacustrine sediments spanning 15,000 years (Sadler, 1981). Though sedimentation rate for the section of core between 296 cm and 210 cm may have been more rapid than for these upper sections, or the expected median rate, there is no a priori reason to assume so. More importantly, pollen influx is likely to be lower in lakes surrounded by more open vegetation (Davis, Brubaker, and Webb, 1973; Birks and Birks, 1980) such as hypothesized for zone A at Jacob Lake.

Poor preservation may have affected pollen concentration adversely. The majority of pine grains were broken and may be taken as an indication of the state of preservation for the Jacob Lake samples. Diversity, however, was fairly high. More than 20 taxa were identified in many samples in this zone. Low pollen concentration in Jacob Lake in full glacial sediments, therefore, is presumably due to a combination of factors including poor pollen preservation and low pollen influx.

During the full glacial Jacob Lake was a perennial lake or marsh surrounded by an open *Picea-Pinus* woodland. The extensive understory or open vegetation around Jacob Lake had a shrub layer composed of *Artemisia*. Gramineae, Compositae, and other herbs made up the herbaceous layer.

Climate. The presence of *Picea* pollen and aquatic algae indicate more effective moisture at Jacob Lake during the Pleistocene than today. More effective moisture may be the result of increased precipitation, and/or cooler summers.

The mechanism for a cooler wetter climate during the full glacial at Jacob Lake is explained in the discussion of full glacial climate at Hay Lake. Winter precipitation at Jacob Lake, however, would not be tied up as snow for as much of the year as at Hay Lake. Therefore, the net result of increased winter precipitation and cooler summers at Jacob Lake is more effective moisture.

Zone B, Jacob Lake. Gramineae zone. 210 cm to 18 cm.

Vegetation and Climate. At the end of the

Pleistocene at Jacob Lake, 14,000 radiocarbon years ago, the *Picea-Pinus* woodland gave way to a more open landscape dominated by Gramineae, Tubuliflorae and other herbs. The continued presence of *Botryococcus* may indicate standing water. However, the climate was too dry and/or too warm to support *Picea* at Jacob Lake as it once had.

The dating of the period during which pollen is absent at Jacob Lake is important because the lack of pollen may have as much significance for climatic interpretations as the presence of pollen. The sedimentation rate between the date of 3310±160 (A-2479) at 59 cm and 14,770±1600 (A-2478) at 222 cm is 70.3 yrs/cm (Fig. 12). On this basis the beginning of the barren zone at 181 cm is 11,886 years ago. The calculated sedimentation rate between the upper two dates (at 59 cm and 29 cm) is 85.3 yrs/cm which places the end of the barren zone 920 years ago (32 cm). This long period of time could be even longer if there is a hiatus anywhere within the non-polleniferous sediments. The presence of 141 cm of clay indicates that, in fact, a lake or marsh was present. Therefore, non-deposition is not an adequte explanation for lack of pollen.

Lacustrine environments are usually good for pollen preservation because often the aqueous environment creates reducing conditions. Oxidation of the sediments may result if fluctuating lake levels expose the sediments to the atmosphere. Both biological and chemical oxidation destroys

Fig. 12. Relationship of depth and time at Jacob Lake.

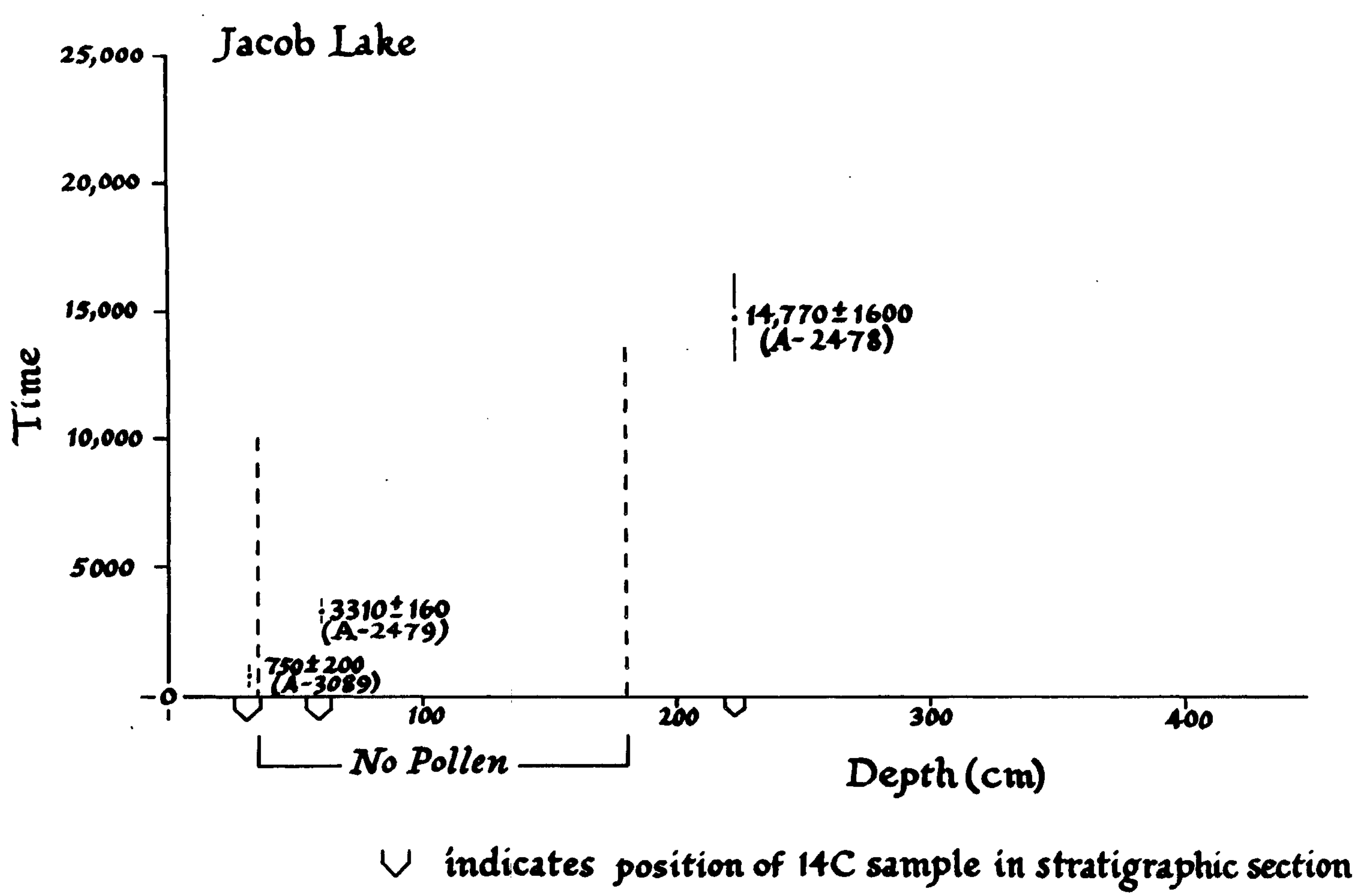

Fig. 12. Relationship of depth and time at Jacob Lake.

pollen by breaking down sporopollenin which makes up the pollen wall (Birks and Birks, 1980). Thus, rapidly fluctuating lake levels throughout most of the Holocene is a possible explanation for the lack of pollen in zone B. The sediment description given in Table 4 supports the hypothesis of fluctuating water table and increased oxidation during the time represented by the barren zone. Yellow, iron rich sediments, are usually the result of oxidation of ferric iron to ferrous oxide by leaching. A patchy occurrence of this compound, or mottling, is the result of proximity to a fluctuating water table (Birkeland, 1974).

The climate approximately 11,800 years ago at Jacob Lake was considerably drier than during the full glacial or earliest Holocene. Precise timing of Holocene events such as those suggested by Antevs (1948) and those discussed in relation to Hay Lake is not possible here because of the overall lack of pollen and poor radiometric control. Also, the lack of pollen in the lower part of the barren zone may be due to post-depositional diagenesis. Oxidation of older, deeper sediments may have taken place somtime during the middle Holocene. Thus climatic interpretations made for the early Holocene on the basis of the absence of pollen may be incorrect. Nevertheless, a general comparison can be made between the Holocene sections at Hay and Jacob Lakes. The barren zone at Jacob Lake overlaps with the early and middle

Holocene sections at Hay Lake. While *Artemisia* diminished at Jacob Lake, after 14,000 B.P. it expanded at Hay Lake. When Jacob Lake dried out, possibly 11,800 B.P. *Artemisia* percentages at Hay Lake continued to increase. Not until the end of the middle Holocene did pollen preservation resume at Jacob Lake (about 1,000 B.P.) and *Artemisia* declined at Hay Lake (about 1,500 B.P.) giving way to modern conditions.

From the Hay Lake evidence it appears that the elevational distribution of *Artemisia* may have been higher during the middle Holocene than it is today. Though a variety of climatic conditions could explain the presence of *Artemisia* at high elevations the possibilities are narrowed by the evidence of fluctuating water level at Jacob Lake. Because drought comes to Arizona when winter rains are diminished (Sellers, 1960), drought at Jacob Lake, therefore, was probably during spring and fall. According to general circulation patterns for the Southwest (see Chapter One), spring and fall rains originate with Pacific storm tracks and moisture for summer rains comes mainly from the Gulf of Mexico off the Bermuda High pressure cell. Warmer climate in the Southwest, particularly warmer summers, would be associated with the northward extension of tropical airmasses and intensified development of the Bermuda High. That is, greater northward transport of moisture originating in the tropics.

Though *Artemisia* is generally thought to be adapted to winter rainfall climate, the *Artemisia* dominated community at St. Johns, Arizona (approximately 50 km north and about 100 m lower than Hay Lake), receives more than 50 percent of its rainfall in the summer. It is conceivable that *Artemisia* would be successfull at high elevations in Arizona such as at Hay Lake under a warmer, summer-wet climatic regime.

Probably for no other time period in the Southwest is there as much information and as much confusion about climatic reconstruction as for the middle Holocene. Antevs' (1948) Altithermal was tentatively dated before the advent of radiocarbon analysis. The arid, summer dry, period was estimated to date from 7,000 B.P. to 4,500 B.P. and was based on lake level data from the Great Basin, arroyo cutting in Arizona, New Mexico and western Texas, and on pollen profiles from Oregon and Washington. Later, Deevy and Flint (1957) broadened the definition of this post glacial warm period to include several pollen-based biostratigraphic zones which cover the time period 9,000 to 2,600 B.P.. They renamed this time stratigraphic period the hypsithermal which is meant to encompass a period 2-3° C warmer than today as well as intervening cool periods. The hypsithermal is the preferred term because it is temporally well defined and is not based on climate which differs from place to place.

Regardless of the term used for the middle Holocene, discussion continues regarding climate during this period in the Southwest. Although Antevs claimed a warm and dry climate for the middle Holocene (Antevs, 1948), others have argued for wetter conditions, particularly wetter summers for this period. High pine percentages and the presence of riparian taxa in alluvial pollen records were cited as indicating more summer rainfall in the middle Holocene (Martin, Schoenwetter and Arms, 1961; Martin, 1963b; Martin, Mehringer and Haynes, 1967). These records were just as fervently disputed as unreliable (Antevs, 1962). Finally, it was shown that some of the pollen samples could have been taken from a stratigraphic section in which there was a hiatus in the middle Holocene (Haynes, 1968). The interpretation of these alluvial sections has never been resolved but additional pollen, tree-ring, and packrat midden records from across the Southwest have supported both views. In fact, both views, i.e., a warm, wet and warm, dry middle Holocene, can be accommodated by the fossil evidence.

In areas that receive primarily winter precipitation today, such as coastal California, the northwest coast, and the northern Great Basin, the middle Holocene fossil record indicates warmer, and in some cases, drier conditions (Axelrod, 1981; Barnowsky, 1981; Heusser, 1977; La Marche, 1974; LaMarche and Mooney, 1972; Bright and Davis, 1982; Waddington and Wright, 1974; Baker, 1976, 1970).

In areas that receive primarily summer precipitation today, such as southwestern Colorado, four types of climatic recontructions exist for the middle Holcene: 1) warmer (Maher, 1961; Petersen and Mehringer, 1976; Petersen, 1981), 2) warmer with an increase in summer precipitation (Andrews et al., 1975; Markgraf and Scott, 1981), 3) warm and dry (Pennak, 1963), and 4) a climate similar to today with possibly wetter summers (Maher, 1972). In nearby Chaco Canyon alluvial pollen records indicate maximum arid and warm conditions between 5600 and 2400 B.P. (Hall, 1977). On the basis of the dates given (see Table 5) these climatic events in southwestern Colorado and northwest New Mexico are not synchronous but do overlap. If all these reconstructions are correct, effective moisture in areas of summer precipitation dominance fluctuated greatly over time and space during the Holocene. Most climatic reconstructions for the southwestern Colorado region, however, are based on pollen records at or near upper treeline and these may not be sensitive to changes in annual precipitation. Yet, of the two lower elevation sites, one calls for an increase in summer rainfall before 4000 B.P. (Markgraf and Scott, 1981) and the other, maximum dryness at that time (Hall, 1977).

An alternative hypothesis is that not all the changes in the biological records are in direct response to climatic change. Different species may respond at different rates to a given climatic change. Packrat midden and pollen records of plant migration could be discordant even in a small geographic area. Unfortunately, migrational and climatic events are difficult to decipher in the fossil record.

In the Great Basin, packrat midden and pollen records show that _P. monophylla_ first reached east central Nevada approximately 6,000 B.P., possibly as the result of an earlier climatic change (Thompson and Hattori, In press; Thompson and Kautz, In press). The changes recorded in southwestern Colorado and northwest New Mexico may also be, in part, records of migrational rather than climatic events. Records of Holocene vegetation change in areas of the Southwest dominated by summer precipitation may represent a series of brief climatic changes, differential plant migration, or a combination of these factors.

On the Colorado Plateau in Arizona there are fewer data. According to Batchelder and Merrill (Pers. Comm., 1980) the Benny Creek pollen record near Hay Lake records fluctuating environments. High _Artemisia_ percentages correlate with high _Artemisia_ percentages at Hay Lake. Laguna Salada (1920 m) on the Mogollon Rim records an increase in Cheno/Am percentages from 20 to 40 percent between 7,300 B.P. and 3,550 B.P.. Though to me this indicates a decrease in lake area and drier conditions, Hevly (1964a, b; 1962) sees no evidence of less effective moisture at Laguna Salada. Potato Lake near Jacob Lake shows little change in pollen content after the early Holocene. Unfortunately, there is only one radiocarbon date (14,400±300

B.P.) for the core so the Holocene part of the core is undated.

Despite the lack of concordance with the Potato Lake record and the interpretation provided for Laguna Salada, I interpret the Jacob and Hay Lake records as indicating a decrease in winter rains with desiccation in spring and possibly intensified summer rains during the middle Holocene. Annual temperatures would have been warmer and annual precipitation would have been less than today.

This reconstruction is in accord with records of drought in the northern Great Basin and along the west coast. Intensified summer rains after spring drought would, according to some authors, increase erosion and foster arroyo cutting in the southwestern deserts (Haynes, 1968). However, this simple climatic model does not account for variations in interpretations of pollen records from the four corners region. Additional Holocene records from elevations near lower treeline are needed to clarify the climatic history of that area.

Zone C, Jacob Lake. _Pinus_-Compositae zone.

Zone C is characterized by high _Pinus_ percentages associated with Tubuliflorae pollen. _Ambrosia_-type is also present in zone C for the first time in amounts greater than two percent. A change in the lacustrine environment is evident from the sharp increase in Cyperaceae pollen along with the presence of Nuphar for the first time. Pollen concentration also increases in zone C due to an increase in pollen influx or pollen preservation or a decrease in sedimentation rate.

The zone C pollen assemblage represents the modern vegetation around Jacob Lake, a *Pinus ponderosa* forest with an understory of grasses and herbs. *Quercus gambellii* is associated with *P. ponderosa* but not abundant. This is reflected in the pollen sum where *Quercus* totals less than 10 percent. *Populus tremuloides* which is present at the site today amounts to less than two percent of the pollen sum. This genus produces thin-walled pollen which does not preserve well and is underrepresented in pollen diagrams (Birks and Birks, 1980).

Jacob Lake dries out before the onset of summer rains and is covered with plants of the Cyperaceae family and grasses. The change at 18 cm from high Gramineae percentages to high Cyperaceae percentages may represent a change in lake basin conditions indirectly related to climate or related to the filling in of the basin with sediment. Also, the decrease in Gramineae may be related to local changes that took place in historic times.

An estimated date of 465 years can be obtained for the change at 18 cm depth based on a sedimentation rate of 25.8 yrs/cm. This rate is calculated from the date of

750$\pm$200 (A-3089) at 29 cm. This places the change at 18 cm beyond the range of White settlement in the area. To obtain a minimum date for the change two standard deviations can be subtracted from the mean date at 29 cm (i.e., 750-400 years) and a new sedimentation rate of 12 yrs/cm is derived. In this case, the change at 18 cm is dated 216 years ago. This too, is beyond historic influence in the study area. However, there is a change in sediment texture and color at 18 cm (Table 2) suggesting that sedimentation rates derived from a radiocarbon sample lower in the section may be incorrect. The possibility remains that the change at 18 cm is due to the influence of early settlers on the vegetation around Jacob Lake. Some early surveys of the region mention open pine forests with abundant grasses present in the development of an understory of pine seedlings and a reduction in grass cover (Cooper, 1960; Weaver, 1967).

Although the change at 18 cm depth may have taken place before White settlers could have had an influence on vegetation in the Jacob Lake region, other evidence supports a contrary hypothesis. A sediment change at 18 cm and a sharp decline in Gramineae pollen could result from fire suppression. Early accounts of more abundant grass cover in ponderosa pine forests supports this view.

The abundance of pollen from marsh plants increases rapidly above 18 cm along with an increase in pollen concentration. A greater density of pine trees due to fire suppression would increase local pollen production and pollen influx to the lake. Increased runoff and more rapid sedimentation of organic matter may have resulted from a decrease in grass cover and increase in forest litter.

CONCLUSIONS

The Mid-Wisconsin vegetation at Hay Lake was dominated by subalpine white pines with some spruce. There was a rich herbaceous understory and Juniperus communis may have occurred locally. At lower elevations, pinyon pine was more widespread than today especially during the period 42,000 to 38,000 B.P.

Toward the end of the Mid-Wisconsin, between 30,000 B.P. and 25,000 B.P., yellow pine pollen appeared for the first time accompanied by an increase in spruce pollen. If concentration of arboreal pollen reflects structure, the forest was more closed than during the earlier part of the Mid-Wisconsin.

The vegetation records are interpreted as indicating a climate during the Mid-Wisconsin that was colder and wetter than today but not as cold and wet as during the full glacial. Based on modern synoptic climatology, this may indicate that mid-latitude westerlies were displaced southward and subtropical high pressure systems were weakly developed compared with today. However, the perturbation to these systems relative to today would not have been as great as during the full glacial. Precipitation may have increased between 30,000 B.P. and 25,000 B.P. in a transition to the full glacial, thus supporting an increased amount of spruce at Hay Lake.

During the full glacial, 25,000 to 14,000 B.P., treeline descended to the elevation of Hay Lake (2780 m). The lake was surrounded by a parkland dominated by grasses with some spruce and possibly *Pinus flexilis* and *P. aristata* nearby. Yellow pines were abundant at elevations below the site and the upper limit of pinyon pine was lower than during the Mid-Wisconsin. Upper treeline was depressed approximately 570 m.

Jacob Lake was surrounded by an open pine spruce woodland with *Artemisia* during the full glacial. Gramineae, Compositae, and other herbs made up the herbaceous layer or were present perhaps in a local meadow near the lake.

The full glacial climate was cooler with possibly drier summers due to the constriction of summer storm tracks. Winters were longer and wetter than today due to the southward displacement of winter storm tracks. This interpretation compares well with those of Bryson and Wendland (1967) and Van Devender and Spaulding (1979). At Hay Lake most of the precipitation was in the form of snow and the net effect was less effective moisture. At Jacob Lake, the net effect was more effective moisture.

The early Holocene, 14,000 to 9,000 B.P., is defined here on the basis of changes in the pollen record from Hay Lake. It was a time of gradual transition from Pleistocene to Holocene climate characterized by an increase in temperatures and summer rains when compared with the full glacial but cooler and/or wetter than today. *Picea* and *Artemisia* diminished at Jacob Lake and expanded at Hay Lake.

The Middle Holocene (approximately 9,000 to 1,500 B.P.) was drier and warmer than the time preceding or following it. *Artemisia* reached a maximum at Hay Lake creating an extensive treeless meadow. Jacob Lake was dry except for intense but brief wet periods during summers that led to leaching and oxidation of the sediments. Droughts occurred during spring and late fall.

Summer monsoons were probably intensified and winter rains were greatly diminished across Arizona. Areas of predominantly winter precipitation such as the northern Great Basin and the west coast were in most cases, drier than today (Table 5). Precipitation changes during the middle Holocene in areas dominated by summer precipitation today are poorly understood. Most sites are at high elevations where vegetation responds to changes in temperature. Plant migration during the Holocene may have been interpreted as climatic response in studies of past vegetaion. Though some records suggest an increase in summer rains during the middle Holocene, additional data are needed from low elevations.

A change took place approximately 1500 years ago at Hay Lake when modern vegetation became established. There was probably an increase in fire frequencey which obliterated the extensive _Artemisia_ cover and resulted in the success of coniferous taxa present today particularly ponderosa pine. The change was unlikely to have occurred as the result of early land use practices. The timing of this change may be correlated with Rocky Mountain neoglacial events but cause and effect is not documented.

A sedimentation change coincides with a decrease in Gramineae pollen at Jacob Lake at 18 cm. Though this change is dated between 216 and 465 years ago by extrapolation from a ^{14}C date lower in the section, this is not a reliable estimate. It is likely that the change coincides with historic disturbance of the natural forest at Jacob Lake. Fire suppression could account for the decrease in Gramineae pollen, an increase in pollen concentration, an increase in sedimentation rate and an increase in the amount of organic matter reaching the lake.

Pinus flexilis (limber pine) and _P. aristata_ (bristlecone pine) are currently disjunct on the San Franisco Mountains (Fig. 1) to other ranges in the north and east, especially in the Rocky Mountains. From the pollen record at Hay Lake it is evident that these species and, possibly _P. contorta_, were more widespread in Arizona during the Pleistocene. Their presence from the Mid-Wisconsin until the latest Wisconsin suggests that their reduction in range was relatively recent or within the last 12,000 years. The occurrence of these species in the Chuska Mountains during the Pleistocene, where they are extinct today, supports the idea that their range was extended southward in the past. The disjunct population of P. flexilis and P. aristata in the San Francisco Mountains is relict from the Pleistocene.

APPENDIX A

The possibility of differential preservation in sections dominated by one taxon such as *Artemisia* in subzone C2 at Hay Lake was descussed on pages 81, 83 and 84. The number of indeterminate grains (corroded, crumpled, or broken grains beyond recognition) can be indicative of the general state of preservation of pollen in the sample. If the indeterminate grains are included in the pollen sum they can make a significant difference in the shape of the pollen curve by being interdependent with the relative percentages of other pollen types. Therefore, one sample from each of the six pollen assemblage zones at Hay Lake was recounted for the following reasons: 1) so that indeterminate pollen grains could be carefully monitored and included in the pollen sum, 2) to see if the percentages of indeterminate grains significantly changed the relative percentages of the other polen types especially in subzone C2 as compared with other zones, and 3) to obtain additional information on the general state of preservation of samples from the six pollen asemblage zones.

One sample was chosen from the approximate center of each of the six pollen zones at Hay Lake. The sample was recounted to a sum close to that of the original samples (i.e., those included in Figs. 8 & 9). The numbers of

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indeterminate grains were added to the original sums and the relative percentages of all pollen types were recalculated.

Figure 13 shows a comparison of the original pollen percentages (shaded) with the recalculated percentaes (open). In all cases the number of indeterminates was small and the recalculated percentages do not differ significantly from the originals.

The results of the recounts can be interpreted in two ways. The relatively small number of indeterminates indicates that despite sometimes low pollen concentrations and low influx rates, the samples were generally well preserved. A correlate of this interpretation is that the relative abundance of one taxon such as <u>Artemisia</u> is due to something other than differential preservation. The second alternative is that the number of indeterminates cannot necessarily be used to indicate general quality of pollen preservation or differential preservation. Pollen types other than <u>Artemisia</u> may not have been preserved at all. Thus the number of indeterminates will only be high when preservation is poor but good enough to permit the remains of organic material recognizable as pollen.

Because the above interpretations are opposed and mutually exclusive, relative percentages of indeterminate polen grains in this case provide inconclusive evidence of preservation quality and of differential preservation.

Fig. 13. Comparison of original relative percentages in six pollen samples from Hay Lake with recalculated relative percentages including indeterminate pollen grains.

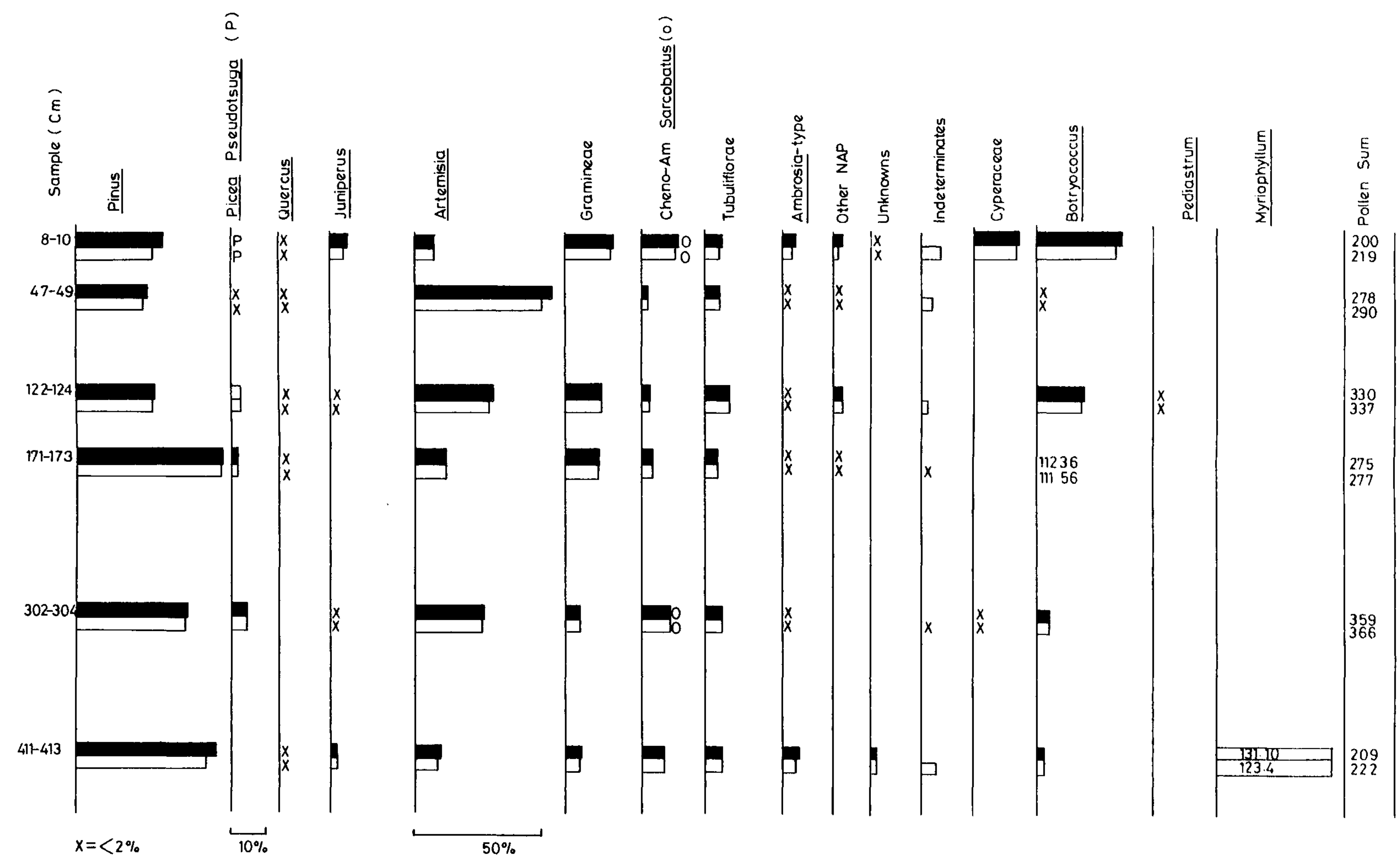

Fig. 13. Comparison of original samples (black bars) with recounted samples (white bars) that include indeterminate pollen grains.

Including indeterminate pollen grains in the pollen sum however, may be beneficial and in cases where the number is high may be significant to the overall interpretation of the data.

APPENDIX B

Slides used for the pine pollen identification analysis (Fig. 7) are from the University of Arizona pollen slide reference collection. The following data are provided so that if needed, the slides can be relocated.

1. *Pinus edulis*
   Coll. 1968 U.S.F.S.
   I.F.G. no. V3 777
   75-3-5-10

2. *P. monophylla*
   U.S.F.S., 1968 (10501)
   I.F.G. no. V4
   75-4-28-18

3. *P. flexilis*
   Coll. no. 990 (Coleman, Alberta)
   U.S.F.S.
   I.F.G. no. V7
   75-4-28-7

REFERENCES CITED

Adam, D.P., Byrne, R. and Luther, E. 1981. A late Pleistocene and Holocene pollen record from Laguna de las Trancas, northern coastal Santa Cruz County, California. Madrono 28(4):255-272.

Adam, D. Sims, J.D., and Throckmorton, C.K. 1981. 130,000 Yr continuous pollen record from Clear Lake, Lake County, California. Geology 9:373-377.

Adam, D.P. and West, G.J. 1983. Temperature and precipitation estimates through the last glacial cycle from Clear Lake, California, pollen data. Science 219:168-170.

Adams, R.J. and Moore, J.K. 1972. An atlas of pollen of the trees and shrubs of eastern Canada and adjacent United States. Parts I-IV, Univeristy of Waterloo Biology Series Nos. 8-11. Dept. of Biology, Univeristy of Waterloo, Ontario.

Addicott, W.O. 1966. Late Pleistocene marine paleoecology and zoogeography in central California. U.S. Geological Survey Professional Paper, 523-C. 21pp.

American Commission on Stratigraphic Nomenclature 1970. Code of Stratigraphic Nomenclature. A.A.P.G., Inc., Tulsa, Oklahoma, U.S.A. 22pp.

Andrews, J.T., Carrara, P.E., King, F. B. and Stuckenrath, R. 1975. Holocene environmental changes in the alpine zone, northern San Juan Mountains, Colorado: Evidence from bog stratigraphy and palynology. Quarternary Research 5:173-197.

Antevs, E. 1948. Climatic changes and pre-White man. University of Utah Bull. 38(20):168-191.

Antevs, E. 1954. Climate of New Mexico during the last glaciopluvial. Jour. of Geol. 62:182-191.

Antevs, E. 1962. Late Quarternary climates in Arizona. Amer. Antiq. 28(2):193-198.

Axelrod, D.I. 1981. Holocene climatic changes in relation to vegetation and speciation. Amer. Natur. 117:847-870.

Baker, R. G. 1970. Pollen sequence from late Quaternary sediments in Yellowstone Park. Science 168:1449-1450.

Baker, R. G. 1976. Late Quaternary vegetation history of the Yellowstone Lake Basin, Wyoming. U.S. Geol. Surv. Prof. Pap. 729-E.

Baker, R. G. and Richmond, G. M. 1977. Geology, palynology, and climatic segnificance of two Pre-Pinedale lake sediment sequences in and near Yellowstone National Park. Quaternary Research 10:226-240.

Barnowsky, C. 1981. A record of late Quaternary vegetation from Davis Lake, southern Puget lowland, Washington. Quaternary Research 16:221-239.

Benedict, J.B. 1973. Chronology of cirque glaciation, Colorado Front Range Quaternary Research 3:584-599.

Benson, L.V. 1981. Paleoclimatic significnce of lake-level fluctuations in the Lahontan basin. Quaternary Research 16:390-403.

Bent, A.M. and Wright, H.E. 1963. Pollen analysis of surface materials and lake sediments from the Chuska Mountains, New Mexico. G.S.A. Bull. 74:491-500.

Beschta, R.L. 1976. Climatology of the ponderosa pine type in central Arizona. Univeristy of Az. Agric. Exp. Sta., Techn. Bull. 228.

Betancourt, J.L. and Van Devender, T.R. 1981. Holocene vegetation in Chaco Canyon, New Mexico. Science 214:656-658.

Birkeland, P.W. 1974. Pedology, weathering and geomorphological research. Oxford University Press, London. 285 pp.

Birks, H.J.B. 1973. Modern pollen rain studies in some arctic and alpine environments in H.J.B. Birks and R. G. West eds. Quaternary Plant Ecology. John Wiley and Sons, Toronto. 326 pp.

Birks, H.J.B. and Birks, H.H. 1980. Quaternary Paleoecology. Edward Arnold, London. 289 pp.

Bonny, A. P. 1978. The effect of pollen recruitment processeson pollen distribution over the sediment surface of a small lake in Cumbria. J. of Ecol. 66:385-416.

Bowen, D.Q. 1978. Quaternary Geology. Pergamon Press, Oxford,England. 221pp.

Brakenridge, G.R. 1978. Evidence for a cold, dry full-glacial climate in the American Southwest. Quaternary Research 9(1):22-40.

Bright, R.C. 1966. Pollen and seed stratigraphy of Swan Lake, southeastern Idaho: Its relation to regional vegetation history and to Lake Bonneville history. Tebiwa 9(2):1-47.

Bright, R.C. and Davis, O.K. 1982. Quaternary paleoecology of Idaho. The Am. Mid. Nat. 108(1):21-33.

Britton, C.M. and Ralphs, M.H. 1979. Use of fire as a management tool in sagebrush ecosystems pp.101-109 in The sagebrush ecosystem: A symposium. Utah U. State Coll. Nat. Res., Logan, Utah.

Brown, D.E. and Lowe, C.H. 1980. Biotic communities of the Southwest. U.S.D.A. For. Svc. Gen. Techn. Rpt. RM-78. Map.

Brown, D.E., Lowe, C.H., and Pase, C.P. 1979. A digitized classification system for the biotic communities of North America, with community (series) and association examples for the Southwest. Az. Nev. Acad. Sci. 14(suppl.1):1-16.

Bryson, R.A. 1957. Some factors in Tucson summer rainfall. Tech. Rpt.on Met. and Climat. of Arid Regions, 4.

Bryson, R.A., and Lowry, W.P. 1955. Synoptic climatology of the Arizona summer precipitation singularity. Bull. Am. Meter. Soc. 36(7):329-339.

Bryson, R.A., and Wendland, W. 1967. Tentative climatic patterns for some late glacial and post-glacial episodes in central North America pp. 279-298 in S.J. Mayer-Oakes, ed. Life, Land, and Water. Univ. of Manitoba Press, Winnepeg.

Caldwell, M.M. 1979. Physiology of sagebrush. pp. 74-85 in The sagebrush ecosystem: A symposium. Utah State U. Coll. Nat. Res., Logan, Utah.

Carlson, A.M., Batchelder, G. L., and Updike, R.G. 1976. A recent pollen diagram from Walker Lake, Coconino County, Arizona. pp. 129-130 in AMQUA (Abstr.).

CLIMAP Project Members, 1976. The surface of the ice-age earth. Science 191:1131-1137.

Clisby, K.H., and Sears, P.B. 1956. San Augustine Plains - Pleistocene climate changes. Science 124:537-539.

Cole, K.L. 1981. Late Quaternary environments in the eastern Grand Canyon: Vegetational gradients over the last 25,000 years. Ph.D. Dissertation U. of Az.

Cole, K. 1982. Late Quaternary zonation of vegetation in the eastern Grand Canyon. Science 217:1142-1145.

Colhoun, E.A., Van de Geer, G., and Mook, W.G. 1982. Stratigraphy, pollen analysis, and paleoclimatic interpretation of Pulbeena Swamp, northwestern Tasmania. Quaternary Research 18(1):108-126.

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since White settlement. Ecol. Monogr. 30:129-164.

Cottam, W.P., Tucker, J.M. and Drobnick, R. 1959. Some clues to Great Basin postpluvial climates provided by oak distribution. Ecology 40:361-377.

Curry, R.R. 1974. Altithermal precipitation maximum. p 25 in AMQUA (Abstr.).

Dalrymple, G.B., Burke, R.M., and Birkeland, P.W. 1982. concerning K-Ar dating of a basalt flow from the Tahoe-Tioga Interglaciation, Sawmill Canyon, southeastern Sierra Nevada, California. Quaternary Research 17(1):10-122.

Daubenmire, R.F. 1974. Plants and environment; a textbook of plant autecology. Wiley, New York. 422 pp.

Daubenmire, R.F. 1943. Vegetation zonation in the Rocky Mountains. The Bot. Rev. 9(6):326-393.

Davis, M.B. and Goodlett, J.C. 1960. Comparison of the present vegetation with pollen spectra in surface samples from Brownington Pond, Vt. Ecology 41(2):347-357.

Davis, M.B., Brubaker, L.B., and Beiswenger, J.M. 1971. Pollen grains in lake sediments from southern Michigan.

Quaternary Research 1:450-467.

Davis, M.B., Brubaker, L.B., and Webb, T. III, 1973. Calibration of absolute pollen influx. in H.J.B. Birks and R.G. West, eds. Quaternary Plant Ecology. Wiley, Ne York. 326 pp.

Davis, O.K. 1981. Vegetation migration in southern Idaho during the Late-Quaternary and Holocene. Ph.D. Dissertation. University of Minnesota.

Deevey, E.S. and Flint, R.F. 1957. Postglacial hypsithermal interval. Science 125:182-184.

Douglas, A.V. and Fritts, H.C. 1973. Tropical cyclones of the eastern Northern Pacific and their effects on the climate of the western United States: A study of circulation features that may be recorded by tree-rings. U. of Az. Lab. of tree-ring Res., Final Report N.O.A.A. Contract 1-35241 Washington, D.C., U.S. Dept. Comm., Environmental Data Service, 43 pp. (Com-73-11230 N.T.I.S., U.S. Dept. Comm., Springfield, Va.).

Douglas, A.V. and Fritts, H.C. 1974. Cutoff lows in the southwestern United States and their effects on the precipitation of this region. A study of circulation features that may be recorded by tree-rings. Final Rpt. Dept. Comm. Contr. 1-35241 No. 3.

Dreimanis, A. and Raukas, A. 1975. Did Middle Wisconsin, Middle Weichselian and their equivalents represent an interglacial or an interstadial complex in the northern hemisphere? pp 109-120 in R.P. Suggate and M.M. Cresswell, eds. Quaternary Studies. Royal Society of New Zealand, Wellington.

Efford, R.C. 1970. The climate of California. pp 538-594 in N.O.A.A. Dept. Comm., Climates of the States, Vol. 2. Water Information Center, Inc., Port Wash., N.Y.

Faegri, K. and Iversen, J. 1975. Textbook of pollen analysis. Hafner Press, New York. 295 pp.

Florer-Heusser, L.E. 1975. Late Cenozoic marine palynology of northeast Pacific Ocean cores. in R.P. Suggate and M.M. Cresswell eds. Quaternary Studies. Royal Soc. New Zealand Bull. 13, Wellington. pp 133-138.

Freeman, C.E. 1972. Pollen study of some Holocene allubial deposits in Dona Ana County, Southern New Mexico. The Texas Jour. of Sci. 24(2):203-220.

Galloway, R.W. 1970. The full-glacial climate in the southwestern U.S. Ann. Ass. Am. Geogr. 60(2):245-256.

Gorsline, G.S. and Prensky, S.E. 1975. Paleoclimatic inferences for late Pleistocene and Holocene from California continental borderland basin sediments. pp. 147-154, in R.P. Suggate and M.M. Cresswell, eds. Quaternary Studies. Roy. Soc. New Zealand, Wellington.

Graham, A. and Heimsch, C. 1960. Pollen studies of some Texas peat deposits. Ecology 41:751-763.

Hales, J.E. Jr. 1972. Surges of maritime tropical air northward over the Gulf of California. Monthly Wet. Rev. 100:298-306.

Hales, J.E. Jr. 1974. Southwestern United States summer monsoon source - Gulf of Mexico or Pacific Ocean? J. Appl. Meteor. 13(4):331-342.

Hall, S.A. 1977. Late Quaternary sedimentation and paleoecologic history of Chaco Canyon, New Mexico. G.S.A. Bull. 88:1593-1618.

Hansen, B.S. and Cushing, H.J. 1973. Identification of pine pollen of late Quaternary age from the Chuska Mountains, New Mexico. G.S.A. Bull. 84:1181-1200.

Hansen, H. B. 1947. Postglacial forest succession, climate and chronology, in the Pacific Northwest. Trans. Am. Phil. Soc. 37:1-130.

Harris, A.M. 1977. Wisconsin age environments in the northern Chihuahuan desert: Evidence from the higher vertebrates pp.23-52, in R.H. Waver, and D.H. Riskind, eds. Transactions of the Symposium on the biological resources of the Chihuahuan desert region. U.S. Dept. Int. Natl. Park Svc. Trans. and Proc. Ser. No. 3.

Harris, A.H. and Findley, J.S. 1964. Pleistocene-Recent fauna of the Isleta Caves, Bernalillo County, New Mexico. Am. J. Sci. 262:114-120.

Hastings, J.R. and Turner, R.M. 1965. Seasonal precipitation regimes in Baja California, Mexico. Geograf. Annaler., 47:204-223.

Haynes, C.V. 1968. Geochronology of late-Quaternary alluvium. pp. 591-631, in R.B. Morrison and H.E. Wright Jr., eds., Means of correlation of Quaternary successions. U. of Utah Press, Salt Lake City.

Haynes, C.V. 1973. Geochronology and paleohydrology of the Murray Springs Clovis site, Arizona. Paper presented at the 1973 Annual Meetings, G.S.A., Dallas, Texas.

Heusser, C.J. 1977. Quaternary palynology of the Pcific slope of Washington. Quaternary Research 8:282-306.

Heusser, C.J. 1982. Palynology of cushion bogs of the Cordillera Pelada, Province of Valdivia, Chile. Quaternary Research 17(1):71-92.

Heusser, L. 1978. Pollen in Santa Barbara Basin, California: A 12,000 Yr. record. G.S.A. Bull. 89:673-678.

Hevly, R. 1964a. Paleoecology of Laguna Salada. pp. 171-200, in, P.S. Martin and Others, eds., Chapters in the prehistory of eastern Arizona, II. Fieldiana: Anthropology vol.55 261 pp.

Hevly, R. 1964b. Pollen analyses of Quaternary archeological and lacustrine sediments from the Colorado Plateau. Ph.D. Dissertation. University of Arizona.

Hevly, R. 1979. Paleoecology of Holocene and Pleistocene lacustrine sediments from Zion Natl. Park, Utah. in A.I.B.S. Special Publ., Research in the National Parks Symposium., New Orleans.

Hevly, R. 1962. Pollen analysis of Laguna Salada. pp. 115-117, in, R.H. Weber and H.W. Peirce, eds., Mogollon Rim Region, New Mexico Geo. Surv. Third Field Conf.

Hevly, R. 1968. Studies of the modern pollen rain in northern Arizona. Jour. Az. Acad. Sci. 5:116-127.

Hevly, R. and Karlstrom, T.N.V. 1974. Southwest paleoclimate and continental correlations. in T.N.V. Karlstrom and Others, eds., Geology of Northern Arizona. G.S.A. Field Guide 2:257-295.

Hevly, R.H. and Martin, P. S. 1961. Geochronology of pluvial Lake Cochise southern Arizona I. Pollen analyses of shore deposits. J. Az. Acad. Sci. 2:24-31.

Hibbard, C.W. 1960. An interpretation of Pliocene and Pleistocene climates in North America. The Presidents's Address, Michigan Academy, Report for 1959-1960. 30 pp.

Hutchinson, G. E. 1975. A treatise on limnology, Vol. 3.

Wiley and Sons, New York. 660 pp.

Imbrie, J. and Kipp, N.G. 1971. A new micropaleontological method for quantitative paleoclimatology: application to a late Pleistocene Caribbean core. pp. 71-181 in K.K. Turekian, eds., Late Cenozoic Glacial Ages. Yale University Press, New Haven, Conn.

Jacobs, L.L. 1981. The setting: Geology and fossils. Plateau (People of the Verde Valley) 53(1):2-5.

Jacobson, G.L. and Bradshaw, R.H.W. 1981. The selection of sites for paleovegetational studies. Quaternary Research 16(1):80-96.

Janssen, C.R. 1967. A comparison between the recent regional pollen rain and the sub-recent vegetation in four major vegetation types in Minnesota (U.S.A.). Rev. Palaeobotan. Palynol. 2:331-342.

Johnson, D.L. 1977. The late Quaternary climate of coastal California: Evidence for an Ice Age regugium. Quaternary Research 8(2):154-179.

Kapp, R.O. 1969. How to know pollen and spores. W.C. Brown Company, Dubuque, Iowa. 249 pp.

Kerr, R.A. 1982. Sun, weather, and climate: A connection? Science 217:917-919.

King, F.B. 1977. An evaluation of the pollen contents of coprolites as environmental indicators. Ariz. Acad. Sci. 12:47-52.

Kutzbach, J. 1981. Monsoon climate of the early Holocene: Climate experiment with the Earth's orbital parameters for 9,000 yrs. ago. Science 214:59-61.

LaMarche, V.C. Jr. 1974. Paleoclimatic inferences from long tree-ring records. Science 183:1043-1048.

LaMarche, V.C. Jr., and Mooney, H.A. 1967. Altithermal timberline advance in western United States. Nature 213(5080):980-982.

LaMarche, V.C. and Mooney, H.A. 1972. Recent climatic change and development of the bristlecone pine (P. longaeva Bailey) krummholz zone, Mt. Washington, Nevada. Arctic and Alpine Research 4(1):61-72.

Lamb, H.H. 1977. Climate present, past, and future. Methuen and Co. Ltd., London. 835 pp.

Layser, E.F. and Schubert, G.H. 1979. Preliminary classification for the coniferous forest and woodland series of Arizona and New Mexico. U.S.D.A. For. Svc. Res. Pap. RM-208.

Legg, T.E. and Baker, R.G. 1980. Palynology of Pinedale sediments, Devlins Park, Boulder County, Colorado. Arctic and Alpine Research 12:319-333.

Little, E.L. Jr. 1971. Atlas of U.S. Trees. Vol. 1 Conifers and important hardwoods. U.S.D.A. For. Svc. Misc. Publ. 1146, 209 pp.

Lowe, C.H. and Brown, D.E. 1973. The natural vegeation of Arizona. Ariz. Res. Inf. Syst. Publ., 2. Az. Game and Fish Dept.

Mack, R.N. 1971. Pollen size variation in some western North American pines as related to fossil pollen identification. Northwest Science 45:257-269.

Mack, R.N. and Bryant, V.M. Jr. 1974. Modern pollen spectra from the Columbia Basin, Washington. Northwest Science 48(3):183-194.

Mack, R.N., Bryant, V.M. Jr. and Pell, W., 1978. Modern forest pollen spectra from eastern Washington and northern Idaho. Bot. Gaz. 139(2):249-255.

Madsen, D.B. 1972. Paleoecological investigations in Meadow Valley Wash, Nevada. in, D.D. Fowler, ed., Great Basin cultural ecology, a symposium. Desert Res. Inst. Publ. in the social sciences, No. 8, Reno, Nevada.

Madsen, D.B. and Curry, D.R. 1979. Late Quaternary glacial and vegetation changes, Little Cottonwood Canyon Area, Wasatch Mountains, Utah. Quaternary Research 12:254-270.

Maher, L.J. Jr. 1961. Pollen analysis and post-glacial vegetation history in the Animas Valley region, southern San Juan Mtns., Colorado. Ph.D. Dissertation. University of Minnesota.

Maher, L.J. Jr., 1963. Pollen analyses of surface materials from the southern San Juan Mtns., Colorado. G.S.A. Bull. 74:1485-1504.

Maher, L. J. Jr., 1972. Absolute pollen diagram of Redrock

Lake, Boulder County, Colorado. Quaternary Research 2(4):531-553.

Markgraf, V. 1980. Pollen dispersal in a mountain area. Grana 19:127-146.

Markgraf, V. and Scott, L. 1981. The lower timberline in central Colorado during the last 15,000 yrs. Geology 9:321-234.

Martin, P. S. 1963a. Geochronology of pluvial Lake Cochise, southeastern Arizona. II. Pollen analysis of a 42-meter core. Ecology 44:436-444.

Martin, P. S. 1963b. The last 10,000 years; A fossil pollen record of the American Southwest. University of Arizona press, Tucson. 87 pp.

Martin, P. S., 1964. Pollen analysis and the full glacial landscape. pp. 66-75, in, J. J. Heefer, ed., Symposium in paleoecology. Santa Fe, Museum of New Mexico Press Fort Burgwin Res. Centr. Publ.

Martin, P. S., Mehringer, P. J. and Haynes, V. C. 1967. Murray Springs, A mid-post-glacial pollen record from southern Arizona. Amer. Jour. Sci. 265:786-797.

Martin, P. S., Sabels, B. E. and Shutler, D. Jr. 1961. Rampart Cave coprolite and eclogy of the Shasta ground sloth. Amer. J. Sci. 259:102-127.

Martin, P. S., Schoenwetter, J. and Arms, B. C. 1961. Southwestern palynology and prehistory: The last 10,000 years. Geochronology Laboratories, University of Arizona, Tucson.

McAndrews, J. H., Berti, A. A., and Norris, G. 1973. Key to the Quaternary pollen and spores of the Great Lakes region. Life Sci. Misc. Publ., R. Ont. Mus., U. of Toronto Press, Toronto. 61 pp.

McDougall, W. B. 1973. Seed plants of northern Arizona. Mus. North. Az., Flagstaff. 594 pp.

Mehringer, P. J. 1965. Late Pleistocene vegetation in the Mohave desert of southern Nevada. Jour. Az. Acad. Sci. 3(3):172-188.

Mehringer, P. J. 1967. Pollen analysis of the Tule Springs Area, Nevada. pp. 130-200. in, H. Wormington and D. Ellis, eds., Pleistocene Studies in southern Nevada.

Nevada State Museum Anthropological Papers, No. 13, Carson City.

Mehringer, P. J. 1977. Great Basin late Quaternary environments and chronology. in, D. D. Fowler, ed., Models and Great Basin Prehistory: A symposium. Desert Res. Inst., Publ. in the Soc. Sci., 12, Reno.

Mehringer, P. J. Jr., Arno, S. F., and Petersen K. L. 1977. Postglacial history of lost trail pass bog Bitterroot Mtns., Montana. Arctic and Alpine Res. 9(4):345-368.

Mehringer, P. J. Jr. and Ferguson, C. W. 1969. Pluvial occurrence of bristlecone pine (*Pinus aristata*) in a Mohave desert mountain range. U. of Az. Interim Rsh. Rep. No. 14, 16 pp.

Mehringer, P. J. Jr. and Haynes, C. V. Jr. 1965. The pollen evidence for the environment of early man and extinct mammals at the Lehner Mammoth Site, southeastern Arizona. Am. Antiq. 31:17-23.

Merkle, J. 1962. Plant communities of the Grand Canyon area, Arizona. Ecology 43(4):698-710.

Merrill, R. K. and Pewe, T. 1977. Late Cenozoic geology of the White Mountains. Arizona Special Pap. No. 1. Bureau of Geol. and Min. Techn., U. of Az.

Mitchell, V. L. 1976. The regionalization of climate in the western United States. J. Appl. Meteor. 15:920-927.

Moir, W. H. and Ludwig, J. A. 1979. A classification of spruce-fir and mixed conifer habitat types of Arizona and New Mexico. Res. Pap. Rm-207, Rocky Mtn. For. and Range Exp. Sta. U.S.D.A. For. Svc.

Moore, T. C. 1965. Origin and disjunction of the alpine tundra flora on San Francisco Mountain, Arizona. Ecology 46(6):860-864.

Nations, D. and Stump, E. 1981. Geology of Arizona. Kendall/Hunt Publ. Co., Dubuque, Iowa. 210 pp.

Nicholson, S. E. and Flohn, H. 1980. African environmental and climatic changes and the general stmospheric circulation in late Pleistocene and Holocene. Climatic Change 2:313-348.

Outcalt, S. and MacPhail, D. D. 1965. A survey of neoglaciation in the Front Range of Colorado.

University of Colorado Studies Series in Earth Sci., No. 4. U. of Colo. Press, Boulder. 124 pp.

Peet, R. 1978. Latitudinal variation in southern Rocky Mountain forests. Jour. of Biog. 5:275-289.

Peirce, H. W., Damon, P. E., and Shafiqullah 1979. An Oligocene (?) Colorado Plateau edge in Arizona. Tectonophysics 61:1-24.

Pennak, R. W. 1963. Ecological and radiocarbon correlations in some Colorado mountain lake and bog deposits. Ecology 44:1-15.

Petersen, K. L. 1981. 10,000 years of climatic change reconstructed from fossil pollen, La Plata Mountains, southwestern Colorado. Ph. D. Dissertation. Washington State University.

Petersen, K. L. and Mehringer, P. J. Jr. 1976. Postglacial timberline fluctuations, La Plata Mountains, southwestern Colorado. Arctic and Alpine Res. 8(3):275-288.

Phillips, A. M. 1977. Packrats, plants, and the Pleistocene in the lower Grand Canyon. Ph. D. Dissertation. University of Arizona.

Phillips, A. M. and Van Devender, T. R. 1974. Pleistocene packrat middens from the lower Grand Canyon of Arizona. Az. Acad. Sci. 9(3):117-119.

Porter, S. C. and Denton, G. H. 1967. Chronology of neoglaciation in the North American Cordillera. Amer. Jour. Sci. 265:177-210.

Potter, L. D. and Rowly, J. 1960. Pollen rain and vegetation, San Augustin Plains, New Mexico. Bot. Gaz. 122(1):1-25.

Pyke, C. B. 1972. Some meteorological aspects of the seasonal distribution of precipitation in the western U. S. and Baja California. Univ. Cal. Water Res. Center, Contrib. No. 139.

Reeves, C. C. Jr. 1966. Pleistocene climate of the Llano Estacado, II. Jour. Geol. 74:642-647.

Rehfeldt, G. E. 1980. Cold acclimation in populations of *Pinus contorta* from the northern Rocky Mountains. Bot. Gaz. 141(4):458-463.

Reitan, C. H. 1960. Distribution of precipitable water vapor over the continental United States. Bull. Amer. Meteor. Soc. 41(2):79-87.

Ritchie, J. C. and Lichti-Federovich, S. 1967. Pollen dispersal phenomena in arctic-subarctic Canada. Rev. Palaeobot. Palynol. 3:255-266.

Rothrock, J. T. 1875. Preliminary botanical report, with remarks upon the general topography of the region traversed in New Mexico and Arizona; its climatology, forage plants, timber, irregation, sanitary conditions, etc. Geogr. Expl. Surv. West of 100th Merid., Ann. Rept. Chief Engin., War Dept., 1875, Append. L.L.

Ruddiman, W. F. and McIntyre, A. 1981. The mode and mechanism of the last deglaciation: Oceanic evidence. Quaternary Research 16(2):125-134.

Sadler, P. M. 1981. Sediment accumulation rates and the completeness of stratigraphic sections. J. of Geol. 89:569-584.

Schaack, C. G. 1970. A flora of the arctic-alpine vascular plants of the San Francisco Mountains, Arizona. M. S. Thesis. Northern Arizona University.

Shoenwetter, J. and Eddy, F. W. 1964. Alluvial and palynological reconstruction of environments Navajo Reservoir District. Museum of New Mexico Papers in Anthropology. 13.

Schubert, G. H. and Rietveld, W. J. 1970. Bristlecone pine - Its phenology, cone maturity and seed production in the San Francisco Peaks, Arizona. U.S.D.A. For. Svc. Res. Note RM-180, Rocky Mtn. For. and Range Exp. Sta., Fort Collins.

Sellers, W. D. 1960. Precipitation trends in Arizona and western New Mexico. pp. 81-94 in, Preceedings 28th Annual Meeting Western Snow Conference, Santa Fe, New Mexico. Colorado State Univeristy, Fort Collins.

Sellers, W. D. and Hill, R. H. 1974. Arizona climate 1931-1972. University of Arizona Press, Tucson. 616 pp.

Smith, L. E. and Bender, G. L. 1974. Mt. Baldy. Office of Economic Planning and Development, Rpt. No. 63. Arizona Acad. Sci.

Solomon, A. M., Blasing, T. J. and Solomon, J. A. 1982. Interpretation of floodplain pollen in alluvial sediments from an arid region. Quaternary Research 18:52-71.

Spaulding, W. G. 1977. Late Quaternary vegetation change in the Sheep Range, southern Nevada. Jour. of the Az. Acad. Sci. 22(2):3-8.

Spaulding, W. G. 1981. The late Quaternary vegetation of a southern Nevada mountain range. Ph. D. Dissertation. University of Arizona.

Spaulding, W. G., Leopold, E. B., and Van Devender, T. R. (In press). Late Wisconsinan paleoecology of the American Southwest. in, S. C. Porter, ed., The late Pleistocene of the United States: A review. XI INQUA Congress. University of Minnesota Press, Minneapolis.

Spaulding, W. G. and Petersen, K. L. 1980. Late Pleistocene and early Holocene paleoecology of Cowboy Cave. pp. 163-177, in, J. D. Jennings, ed., Cowboy Cave. Univ. Utah, Anthro. Pap. 104.

Spaulding, W. G. and Van Devender, T. R. 1977. Late Pleistocene montane conifers in southeastern Utah. The Southwestern Naturalist 22(2):269-286.

Steinhoff, R. J. and Andresen, J. W. 1971. Geographic variation in Pinus flexilis and Pinus strobiformis and its bearing on their taxonomic status. Silvae Genetica 20(5-6):159-167.

Stones, R. C. and Haywood, L. C. 1968. Natural history of the desert wodrat, Neotma lepida. Am. Midl. Nat. 80(2):458-476.

Street, F. A. and Grove, A. T. 1979. Global maps of lake-level fluctuations since 30,000 years B.P.. Quaternary Research 12:83-118.

Sturges, D. L. 1979. Hydrologic relations of sagebrush lands. pp. 86-100 in, The sagebrush ecosystem: A symposium. Utah State U. Coll. of Nat. Res., Logan, Utah.

Thompson, R. S. 1978. Late Pleistocene and Holocene packrat middens from Smith Creek Canyon, White Pine County, Nevada. Nev. State Mus. Anthro. Pap. No. 17:363-380.

Thompson, R. S. and Hattori, E. M. In press. Packrat middens from Gatecliff Shelter and the Holocene migrations of woodland plants. in, D. H. Thomas, ed. Am. Mus. Nat. Hist. Anthro. Pap.

Thompson, R. S. and Kautz, R. R. In press. Pollen analysis of Gatecliff Shelter. in, D. H. Thomas ed. Am. Mus. Nat. Hist. Anthro. Pap.

Thompson, R. S. and Mead, J. I. 1982. Late Quaternary environments and biogeography in the Great Basin. Quaternary Research 17:39-55.

Thompson, R. S., Van Devender, T. R., Martin, P. S., Foppe, T., and Long, A. 1980. Shasta ground sloth (*Nothrotheriops shastense* Hoffstetter) at Shelter Cave, New Mexico: Environment, Diet, and Extinction. Quaternary Research 14:360-376.

Ting, W. S. 1966. Determination of *Pinus* species by pollen statistics. Univ. Cal. Publ. in Geol. Sci. vol. 58.

Tranquillini, W. 1979. Physiological ecology of the alpine timberline. Springer-Verlag. Berlin. 137 pp.

Tueller, P. T. and Clark, J. E. 1975. Autecology of pinyon-juniper species of the Great Basin and Colorado Plateau. pp. 27-40 in, G. F. Gifford and F. E. Busby, eds. The pinyon-juniper ecosystem: A symposium. Utah Agric. Exp. Sta. 194 pp.

Updike, R. G. 1969. Glacial geology of the San Francisco Peaks, Arizona. M. S. Thesis. Arizona State University.

Van Devender, T. R. 1977. Holocene woodlands in the southwestern deserts. Science 198:189-192.

Van Devender, T. R. and King, J. E. 1971. Late Pleistocene vegetational records in western Arizona. J. of Az. Acad. Sci. 6(4):240-244.

Van Devender, T. R. and Mead, J. I. 1976. Late Pleistocene and modern plant communities of Shinumo Creek and Peach Springs wash, lower Grand Canyon, Arizona. Jour. Az. Acad. Sci. 11:16-22.

Van Devender, T. R. and Spaulding, W. G. 1979. Development of vegetation and climate in the southwestern United States. Science 204:701-710.

Van Devender, T. R., Spaulding, W. G., and Phillips, A. M. III 1979. Late Pleistocene plant communities in the Guadalupe Mountains, Culberson County, Texas. pp. 13-30, in, H. H. Genoways and R. J. Baker, eds. Biological investigations in the Guadalupe Mountains National Park, Texas. Nat. Park Svc.

Vines, R. A. 1960. Trees, shrubs and woody vines of the Southwest. U. of Texas Press, Austin. 1104 pp.

Waddington, J. C. B. and Wright, H. E. Jr. 1974. Late Quaternary vegetational changes on the east side of Yellowstone Park, Wyoming. Quaternary Research 4:175-184.

Wardle, P. 1968. Engelman spruce (*Picea engelmannii*) at its upper limits on the Front Range, Colorado. Ecology 49(3):483-495.

Weaver, H. 1967. Fire and its relationship to ponderosa pine. pp. 127-149 in, Proc. of Tall timbers fire ecology conference, California. Tall timbers Res. Sta., Tallahassee, Florida. 258 pp.

Wells, P. V. 1966. Late Pleistocene vegetation and degree of pluvial climatic change in the Chihuahuan Desert. Science 153:970-975.

Wells, P. V. 1979. An equable glciaopluvial in the west: Pleniglacial evidences of increased precipitation on a gradient from the Great Basin to the Sonoran and Chihuahuan Deserts. Quaternary Research 12(3):311-325.

Wells, P. V. and Berger, R. 1967. Late Pleistocene history of coniferous woodland in the Mohave Desert. Science 31:1640-1647.

Wells, P. V. and Jorgensen, C. D. 1964. Pleistocene woodrat middens and climatic change in Mohave Desert: A record of juniper woodlands. Science 143:1171-1174.

Wendorf, F. 1961. A general introduction to the ecology of the Llano Estacado. pp 12-21 in, F. Wendorf, ed., Paleoecology of the Llano Estacado. Mus. of New Mex. Press. For Burgwin Res. Center. No. 1.

West, N. E. 1979. Basic synecological relationships of sagebrush-dominated lands in the Great Basin and the Colorado Plateau. pp. 33-41 in The sagebrush ecosystem: A symposium. Utah State U. Coll. Nat. Res., Logan, Utah.

West, R. G. 1977. Pleistocene geology and biology. Second Edition, Longman Group, Ltd., London. 440 pp.

Wheeler, G. M. 1878. Report upon United States Geographical Surveys West of the 100th Meridian. Vol. 1, Topography. Govt. Printing Office, Washington.

Whiteside, M. C. 1965. Paleoecological studies of Potato Lake and its environs. Ecology 46(6):807-816.

Wright, H. E. Jr., Bent, A. M., Hansen, B. S., and Maher, L. J. 1973. Present and past vegetation of the Chuska Mountains, northwest New Mexico. G.S.A. Bull. 84:1155-1180.