

## Holocene Climatic Variations Inferred from Treeline Fluctuations in the White Mountains, California

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Remains of dead bristlecone pine (*Pinus longaeva* Bailey) are found at altitudes up to 150 m above present treeline in the White Mountains. Standing snags and remnants in two study areas were mapped and sampled for dating by tree-ring and radiocarbon methods. The oldest remnants represent trees established more than 7400 y.a. Experimental and empirical evidence indicates that the position of the treeline is closely related to warm-season temperatures, but that precipitation may also be important in at least one of the areas. The upper treeline was at high levels in both areas until after about 2200 B.C., indicating warm-season temperatures about 3.5°F higher than those of the past few hundred years. However, the record is incomplete, relative warmth may have been maintained until at least 1500 B.C. Cooler and wetter conditions are indicated for the period 1500 B.C.-500 B.C., followed by a period of cool but drier climate. A major treeline decline occurred between about A.D. 1100 and A.D. 1500, probably reflecting onset of cold and dry conditions. High reproduction rates and establishment of scattered seedlings at high altitudes within the past 100 yr represents an incipient treeline advance, which reflected a general climatic warming beginning in the mid-19th century that has lasted until recent decades in the western United States. This evidence for climatic variation is broadly consistent with the record of Neoglacial advances in the North American Cordillera, and supports Antevs' concept of a warm "altithermal age" in the Great Basin.

### INTRODUCTION

The position of the treeline is a valuable paleoclimatic indicator because temperature is an important factor in determining the altitudinal and latitudinal limits of tree growth. However, most studies have relied on indirect evidence for the previous extent of forests, such as pollen and soils, or on the fragmentary record provided by isolated stumps and by exposures of wood or charcoal preserved in bogs, alluvium, and glacial deposits. Recent discoveries of abundant remains of bristlecone pine *in situ* above present treeline in western United States provides the basis for

more detailed study of past treeline fluctuations than has been possible in most other areas.

In this report, evidence for changes in treeline position during the past several thousand years in the White Mountains of eastern California is presented and interpreted in terms of possible climatic changes. Although reconnaissance studies were made in Nevada (LaMarche and Mooney, 1972) and Colorado, the White Mountains were chosen for special emphasis in this work. The known great age of some of the remnants in this area (LaMarche and Mooney, 1967) promised a record of maximum length. Furthermore, the absence of a krummholz zone simplifies estimation of past treeline levels, and the availability of high-altitude weather

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records permits fairly accurate characterization of present climate at upper treeline.

### PREVIOUS INVESTIGATIONS

There is evidence of broadly synchronous treeline advances and retreats during the past several thousand years at many places in the Northern Hemisphere. In northern Europe, stumps and other remains of pine (*Pinus sylvestris* L.) beyond the present tree limit have long been known to mark earlier, more northerly, forest extensions. Hustich (1966) shows the distribution of such finds in northern Finland and Norway. Citing dates from Andreev (1954) and Tikhomirov (1956), he correlates the advanced treeline position with the "postglacial thermal maximum." In the Caledonian Mountains in Sweden, pine stumps are found in bogs up to 150 m above the highest nearby living trees. Radiocarbon dating (Lundquist, 1959, 1962) places most of these remnants between 8000 and 3000 radiocarbon years before present (BP), within the same postglacial warm period. Lamb (1964) obtained a radiocarbon date of 4400 BP for a log from a bog in northwest Scotland. It is interpreted as evidence for forest expansion during the "postglacial climatic optimum." To the south, the altitudinal treeline in the Alps may have been as much as 300 m higher than at present during this period (Lüdi, 1955).

The histories of North American treelines are similar in some places to that found in Europe, but there are important regional differences. While Griggs (1937) found no evidence for earlier forest advances in his study of recent trends of the northern forest limit in Alaska, more recent evidence shows that large-scale changes have taken place. McCulloch and Hopkins (1966) found birch and spruce logs outside the present range of these species on the Seward Peninsula of northwest Alaska. Together with other evidence, dates on these logs suggest a warm period beginning at least 10,000 yr BP and continuing to about 8300 yr BP. Subsequent replacement of forest by tundra

was thought to reflect oceanic transgression and more maritime climate. An early Holocene warm period in northern Alaska is also proposed by Detterman (1970) from radiocarbon dating of a poplar log. Ritchie and Hare (1971) review the evidence for past changes in position of the treeline in northwestern North America. Although previous pollen studies were found to be rather inconclusive, new pollen and megafossil evidence from Mackenzie Delta area, together with radiocarbon dating of a rooted stump well north of the present treeline, suggest a period much warmer than present from about 4000 BP to the present. A detailed treeline history has been worked out for the area west of Hudson Bay, in northern Canada (Bryson *et al.*, 1965; Sorenson *et al.*, 1971; Nichols, 1967). Here, as shown by the distribution and ages of charred wood and podzolic soils, and from pollen evidence, the spruce (*Picea mariana* and *P. glauca*) forests moved northward following deglaciation and lake-draining about 5800 BP. The treeline retreated to the south between about 3500 and 2900 BP. Two lesser northward advances, separated by periods of retreat followed, culminating about 2500 and 1000 BP, respectively. These movements of the northern treeline are thought to be related to changes in the average summer position of the Arctic Front (Bryson, 1966), and the early advance is correlated with the "postglacial climatic optimum." Jungerius (1969) has also documented a major treeline advance in eastern Alberta between 4500 and 3600 BP. The apparent contrast in climatic history between the Hudson Bay region and northwest Canada and Alaska is tentatively explained by Ritchie and Hare (1971), in terms of air mass sources and of wave patterns in the upper westerlies.

Evidence of higher past treeline levels has been found at several localities in western United States. The work of Griggs (1937, 1938), who was interested in interpreting treeline changes in climatic terms, gave somewhat contradictory results. Part of the

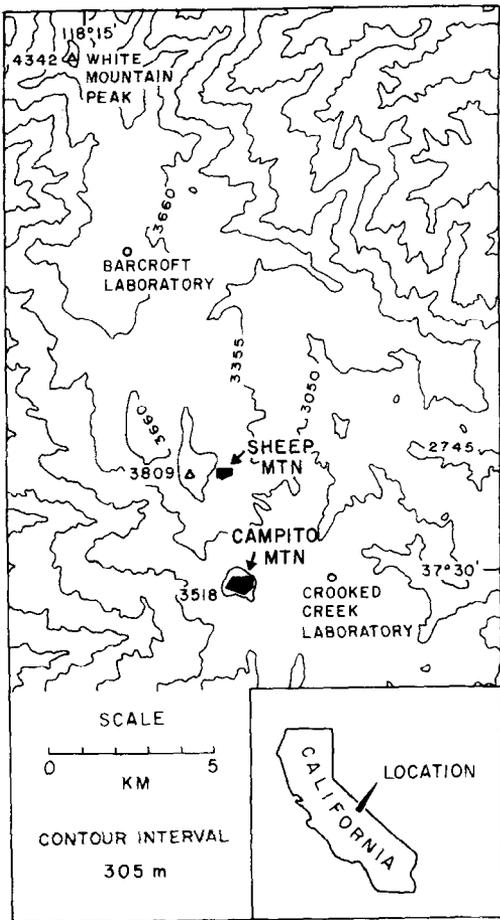


FIG. 1. Index map.

reason may be that, without modern dating techniques, he could not readily distinguish evidence of recent treeline advance in one area from evidence for a much earlier advance and subsequent retreat in another. In his work in the La Sal Mountains of southeastern Utah, Richmond (1962) related relict podzolic soils at high altitudes to a treeline advance of up to 300 m above present levels during the "altithermal" of "postglacial optimum," prior to 2800 y.a. A more recent advance, followed by retreat, is indicated by stands of large dead trunks that extend perhaps 100 m above present treeline. The death of the trees is attributed to cooler conditions during the historic "Little Ice Age," which did not end until the 1800s. Curry (1968) also described dead trees at high elevations and interpreted

these as evidence for previous higher tree-line position at many points in the Sierra Nevada, California.

A well-documented recent advance of the treeline in parts of Alaska and Scandinavia (Griggs, 1937; Haugen, 1965; Hustich, 1958) is paralleled by advances of the alpine treeline in some areas of western United States. This phenomenon may reflect the widespread warming trend observed in the Northern Hemisphere during the past 100 yr (Mitchell, 1961).

### DESCRIPTION OF AREA

The White Mountains rise high above the surrounding desert near the western edge of the Great Basin. They are formed from a triangular fault block composed of sedimentary, metamorphic, and granitic rocks locally veneered by volcanic flows, that has been elevated and tilted eastward since late Tertiary time (Knopf, 1918). The range is about 90 km long and 35 km wide. In the northern part of the range, the crest forms a narrow alpine plateau (Mitchell, LaMarche, and Lloyd, 1966), over 4000 m in altitude. The crestal area broadens and decreases in altitude south of White Mountain Peak (4345 m), located near the center of the range (Fig. 1).

Although valley glaciers filled eastward-draining canyons in the northern White Mountains during Pleistocene time (LaMarche, 1965), the southern part of the range shows no evidence of past glaciation. As a result, the topography of the crestal area is subdued. Long, smooth slopes descend from rounded peaks and ridges to broad alpine and subalpine meadows. Soils are rocky and locally thin, and show little profile development (LaMarche, 1968; Wright and Mooney, 1965; Fritts, 1969).

### Climate

Weather observations are made at the Crooked Creek (3096 m) and Barcroft (3812 m) Laboratories of the University of California White Mountain Research Station. Observations include maximum and

minimum daily temperatures, daily precipitation, snow depth, cloudiness, relative humidity, barometric pressure, and wind speed and direction. The Crooked Creek Station was established in December 1948, and the Barcroft Station, in October 1951. Crooked Creek became a cooperative U.S. Weather Bureau (now N.O.A.A.) station in 1956, and Barcroft, in 1957. They are known as White Mountain 1 and White Mountain 2, respectively, and the data are published in *Climatological Data—California*. Shorter series of measurements and incidental observations have also been made in the area (Kesseli and Beaty, 1959; Terjung *et al.*, 1969; Mooney, St. Andre, and Wright, 1962; Fritts, 1969). Although the Crooked Creek record is the longest high-altitude record in the area, a station relocation in 1954 greatly affected observed minimum temperatures, and decreases its usefulness for some purposes.

The climate at high altitudes in the White Mountains is cool and dry (Fig. 2). Average annual precipitation ranges from 350 mm at 3096 m to 480 mm at 3812 m, and probably exceeds 500 mm only in the highest parts of the range. There is a primary winter precipitation maximum, between November and January. A secondary maximum occurs in April and May, and there is a low summer peak in July. This precipitation regime is similar to that described for the region by Trewartha (1966), and is transitional between the summer-dominant pattern of Colorado and New Mexico to the east and the winter-dominant pattern of coastal California to the west. The comparative aridity of the White Mountains is due mainly to their location in the lee of a high mountain barrier—the Sierra Nevada—which lies only 50 km to the west. This barrier greatly reduces the influence of maritime air masses from the Pacific Ocean. Westerly flow of moist air in winter, associated with migratory low-pressure cells, frequently produces high precipitation on the western slopes of the Sierra, mainly as a result of orographic

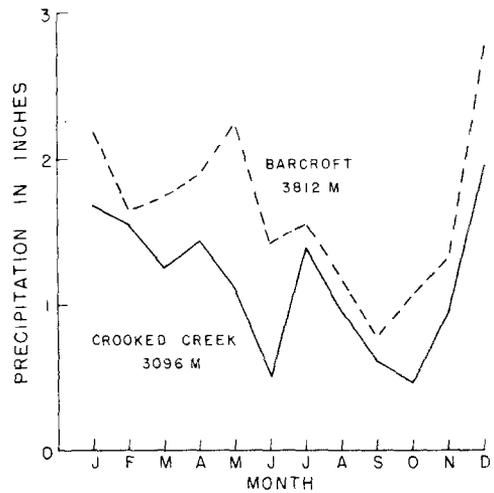


FIG. 2. Mean monthly precipitation at Barcroft (1952–1971) and Crooked Creek (1948–1971) Laboratories.

lifting. On the eastern or lee side of the Sierra, subsidence and compression dissipate clouds, greatly reducing or eliminating precipitation.

Although considerable precipitation can fall in the White Mountains in summer, associated with afternoon and evening thunderstorms, average summer rainfall amounts are small in comparison with areas farther east. One reason for this appears to be the location of the range at a great distance from the sources of the tropical maritime air that accounts for the “monsoon” rains of southwestern United States. Stidd (1967) shows that a precipitation anomaly pattern associated with “Gulf” moisture, and reflecting summer precipitation, is strongest in the eastern and southern parts of Nevada, and weakens rapidly to the west and north, in the White Mountains area. Another reason for low summer rainfall amounts is the influence of the North Pacific High. This permanent high pressure cell is responsible for the pronounced summer-dry climate of coastal California because of the northward deflection of migratory lows and because of the stability of the subsiding air flowing southward at upper levels on the east side of the high (Dale, 1959).

Winter precipitation is mainly in the form of snow at altitudes over 2500 m. Although there are normally local snow patches on the ground at high altitudes in all months except July, August, and September, deep winter snow accumulation is unusual. Average snow depth reaches a maximum in late winter, and ranges from about 250 mm at Crooked Creek to 500 mm at Barcroft. Large areas are frequently free of snow even in middle to late winter. Summer precipitation is normally in the form of rain, although snowstorms can occur even in July and August at upper elevations.

Average wind velocity increases with altitude, from 16 knots at Crooked Creek to 22 knots at Barcroft. Winds are from the southwest, west, and northwest about 60% of the time. Northerly to northeasterly winds are fairly frequent in spring, fall, and winter, but southerly to southeasterly winds occur about 30% of the time in July and August. At these altitudes, the wind direction tends to reflect prevailing upper level flow patterns, in the absence of vigorous cyclonic activity. The air is normally dry, with 8 AM relative humidity averaging only about 50%, and ranging from 40% in summer to 60% in late winter.

Air temperature in the White Mountains is, of course, strongly dependent on altitude. Daytime maximum temperatures at Crooked Creek range from 31.7°F in the coldest month (February) to 65.7°F in the warmest (July). Corresponding values for Barcroft are 22.7°F and 53.6°F, respectively. The 12.1° difference between the mean maxima at the two stations in July corresponds to an average surface temperature gradient of 5.2°F per 1000 ft altitude, very close to the dry adiabatic lapse rate. The smaller temperature difference in winter is probably related to increased maritime influence, with the increased cloudiness resulting in a lower lapse rate which is reflected in the surface temperature gradient.

The diurnal temperature range at the al-

titude of Barcroft Laboratory averages only about 16°F. Although generally clear skies and low humidity, together with the high altitude, should foster intense daytime insolation and surface heating, followed by rapid nighttime cooling; these effects are probably more pronounced within a few inches of the ground than they are at standard instrument shelter height because of the high air-movement rates. The continentality of the White Mountains—measured by annual temperature range—is somewhat less than might be expected from their geographic location, according to D'Ooge. He suggests that a tongue of maritime air frequently penetrates into this area aloft and has a moderating influence on temperatures. A "fohn" effect may also be important in the winter months, related to the dynamics of the westerly flow across the Sierra Nevada, which produces the well-known Sierra lee wave (Willet and Saunders, 1959, pp. 303–308).

Topography has an important influence on temperatures, particularly minima. This is well illustrated by the effect of the weather station relocation at Crooked Creek. The instrument shelter was originally established in a ridge-crest location at 3202 m altitude. On June 1, 1954 the shelter was moved to a new location 300 m to the west, in the bottom of the adjacent valley. Comparison of temperatures recorded before and after the move shows that mean maximum temperature increased 1.6°F. The increase is about what would be expected in a more sheltered location 106 m lower in altitude. Mean minimum temperatures, however, decreased by 7.2°F. The change is clearly related to frequent development of a nocturnal inversion resulting from cold-air drainage into the valley. To further study this phenomenon, which has a bearing on the role of temperature in determining treeline elevation, observations of minimum air temperature were made at three points intermediate in altitude between the original and present shelter locations. These observations were

made during a 48-day period in the summer of 1970, using unsheltered minimum thermometers mounted on telephone poles at 1.5 m height. The average minimum temperature increased markedly in the upslope direction. The average at the highest station (3184 m) was 7°F warmer than at the Crooked Creek shelter (3100 m) and 5°F warmer than at the lowest station (3117 m). The inversion seems to have developed most frequently between the stations 17 and 51 m above the valley bottom.

The treeline study areas are located between the Crooked Creek and Barcroft Laboratories, and weather data from these stations can be used to make estimates of temperature and precipitation at the upper treeline during recent decades. A nominal treeline altitude of 3500 m was used in these estimates. Assuming that precipitation increases linearly with altitude between the two weather stations, the estimated mean annual precipitation at treeline for the period 1953–1971 is 430 mm. Monthly mean maximum temperatures were also estimated by linear interpolation between Barcroft and Crooked Creek. Because of the affect of the inversion on minimum temperatures at Crooked Creek, simple interpolation could not be used to estimate minimum temperatures at treeline.

Temperatures estimated in this way would be much lower than those which actually occur on open slopes above local areas of cold-air drainage. Instead, the mean monthly minima at the two stations for the period October 1951 and August 1952 through May 1954 were used to calculate the average altitudinal gradient in mean minimum temperature for each month. The Crooked Creek observations during this period were made in a ridge-crest location, and should be fairly representative of temperatures at that altitude. The average gradients were then used together with the monthly mean minima at Barcroft to estimate minimum temperatures at upper treeline for the total period of Barcroft record. Averages of the estimated monthly maxi-

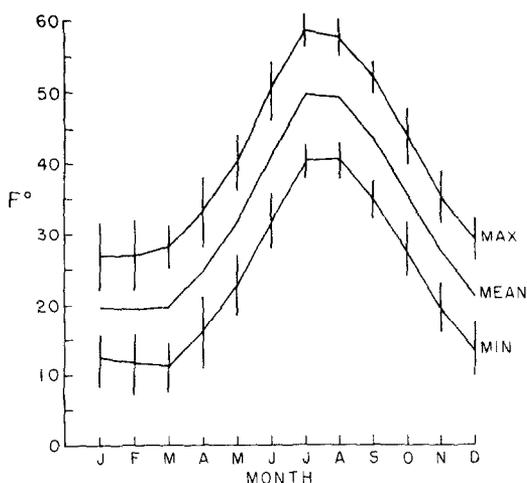


FIG. 3. Estimated average monthly temperatures at upper treeline (3500 m). Vertical bars show 1 SD range.

imum and minimum temperatures are shown in Fig. 3. The estimated mean maximum temperature of the warmest month (July) is 58.8°F, a value similar to that which coincides with the position of the upper treeline in other areas (Daubenmire, 1954).

#### Vegetation

The vegetation of the White Mountains shows pronounced altitudinal zonation (Mooney, St. Andre, and Wright, 1962). Desert shrubs occupy the surrounding basins and the lower flanks of the range. Pinyon (*Pinus monophylla*)–juniper (*Juniperus osteosperma*) woodland lies above the desert, and extends up to about 2500 m altitude. The subalpine zone lies between 2700 and 3500 m. It is a mosaic of open bristlecone pine (*Pinus longaeva*)–limber pine (*P. flexilis*) forest, and extensive unforested areas dominated by big sagebrush (*Artemisia tridentata*) or locally, by mountain mahogany (*Cercocarpus ledifolius*). Edaphic and topographic control of plant distribution is pronounced. Only a few open stands and scattered individual trees are found on sandstone and granite substrates. Most of these stands are on north-facing slopes, and, at lower altitudes, are com-

posed primarily of limber pine. In contrast, nearly continuous bristlecone pine forest covers the limestone and dolomite areas.

The alpine zone extends from upper treeline, at about 3500 m, to the range crest. Herbs—mainly “cushion plants” of several species—are most abundant. Shrubs are small and scattered, and are virtually restricted to sandstone and granite substrates.

The upper forest margin is very irregular, and its position is related to substrate and topography as well as to altitude. Only locally does it appear to form a true “climatic” upper treeline. There is a noticeable difference in treeline altitudes on different substrates. Trees extend about 100 m higher in dolomite and limestone areas than in areas underlain by sandstone and shale.

Bristlecone pines near upper treeline are comparatively short, with heights of 4–12 m. Many are multiple-stemmed, and a rapidly tapering trunk is characteristic. Although some “wind-forming” is evident, particularly of isolated trees and of those in ridge-crest locations, the bristlecone pines do not form *krummholz*. Bristlecone pines grow quite slowly near upper treeline. Trees from 50 to 100 yr old are only 3 or 4 m tall, less than 25 cm in diameter, and their wood retains juvenile characteristics, despite the fact that they begin bearing cones at the age of 20–30 yr.

#### UPPER TREELINE STUDY LOCALITIES

The two areas chosen for detailed study are located on isolated peaks whose summits extend above present treeline near the southern end of the high part of the range (Fig. 1). In each of the study areas, the forest border follows topographic contours and appears to represent a “climatic” treeline. In addition, in each area both the slope angle and direction and substrate type continue rather uniformly upslope beyond the present treeline, so that climatic change could presumably permit upward movement of the treeline, other factors remaining about constant. Finally, there are

abundant dead trees, logs, and wood remnants above treeline in each area. The Sheep Mountain study area is located on the east slope of the mountain. Here, carbonate rocks extend to higher altitudes than at any other point in the White Mountains. The treeline follows the 3500 m contour for a distance of more than a kilometer in this area. Campito Mountain is a pyramidal peak made up of sandstone and shale. There is a large stand of bristlecone pines, with a few limber pines, on the northwest slope (Fig. 4). There are 15 widely spaced trees on the east slope, and two trees at low altitudes on the south slope. The treeline lies at about 3400 m altitude, rising on the west side of the mountain and dropping down on the east side.

To provide vertical and planimetric control for subsequent sampling, detailed topographic maps were made for each area. All living trees and all snags, logs, and remnants or remnant groups—corresponding to individual dead trees—were located and plotted on the maps. The Sheep Mountain map (Figs. 5 and 6) begins below the treeline and extends upslope to include the highest wood remains on the east slope of the mountain. The Campito Mountain map area (Figs. 7 and 8) extends from the upper treeline on the northwest and east sides of the mountain up to the summit.

#### *Composition and Age Structure of Existing Stands*

Some of the characteristics of the subalpine forest below treeline in each study area were evaluated because of their bearing on the causes of the treeline and on past treeline fluctuations. The data for Sheep Mountain were collected in sample quadrats whose midpoints range from 3451 to 3526 m in altitude, or from 54 m below to 21 m above treeline. The upper sample quadrats lie within the mapped area. In each quadrat, all standing dead trees, living trees, saplings, and seedlings were counted, and the radius was measured to provide an index to age. Radius rather than diameter



FIG. 4. View of north slope of Campito Mountain.

was recorded because the strip-bark growth habit of many older bristlecone and limber pines produces stems that are very asymmetrical in transverse section (LaMarche, 1969). The radius of fully bark-covered, symmetrical stems was taken to be one-half the diameter.

Figure 9 shows the frequencies of limber pines, bristlecone pines, and standing dead trees (snags) in each of several size classes in the Sheep Mountain sample quadrats. The total density is low in comparison with stands at lower elevations (Billings and Thompson, 1957). Snags are present in all but the smallest size classes, and are most abundant at and above the present treeline (3505 m at this location). Seedlings and

saplings of both species are abundant below the treeline but scarce above it . . . a feature also shown by the study area map (Fig. 5). However, limber pines over 25 cm diam do not occur above the altitude of the lowest quadrat (3451 m).

All of the full-sized trees in the mapped area on Campito Mountain are bristlecone pines. Although stand density was not measured, it appears somewhat greater than on Sheep Mountain, if only the stand on the northwest slope of Campito is considered. Within the map area there are 59 large bristlecone pines, 15 young bristlecone pines, and 11 young limber pines—a much smaller proportion of seedlings and saplings than on Sheep Mountain. These young trees

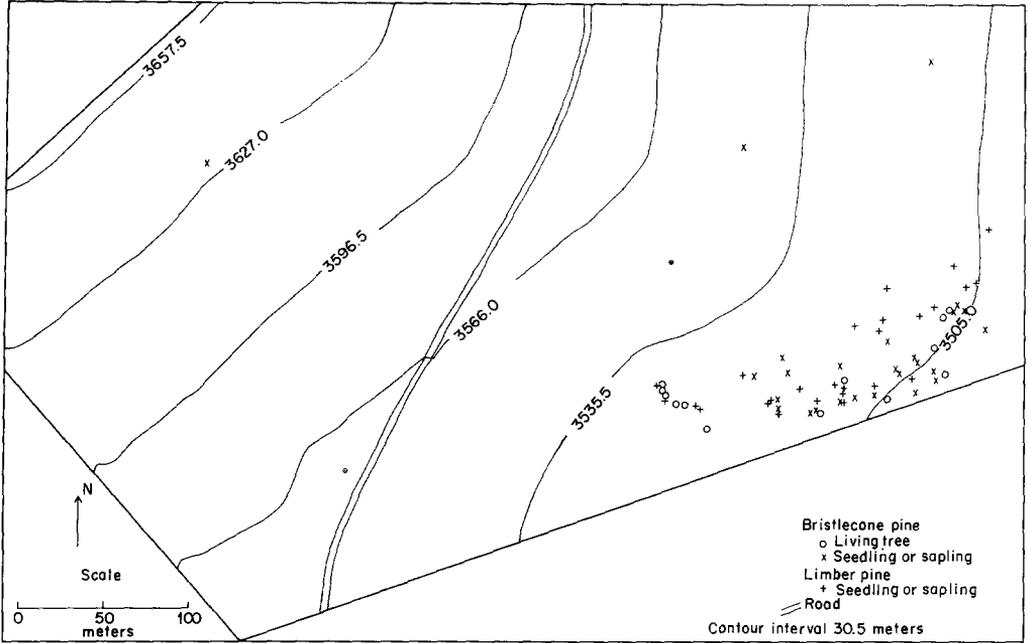


FIG. 5. Living tree distribution—Sheep Mountain.

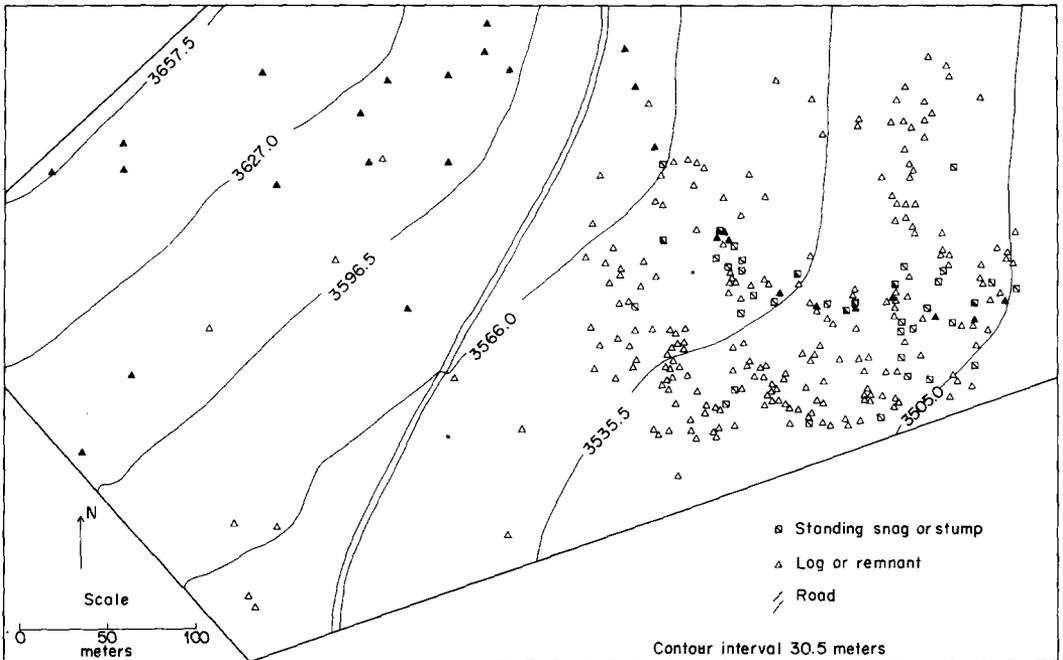


FIG. 6. Dead tree distribution—Sheep Mountain.

are within the existing stand or within a few meters above it.

An interesting feature of both areas is the abundance of young limber pines 50 m or

more above, and at least 100 m distant from the nearest mature trees of this species. Furthermore, the young limber pines show much more foliage damage than do

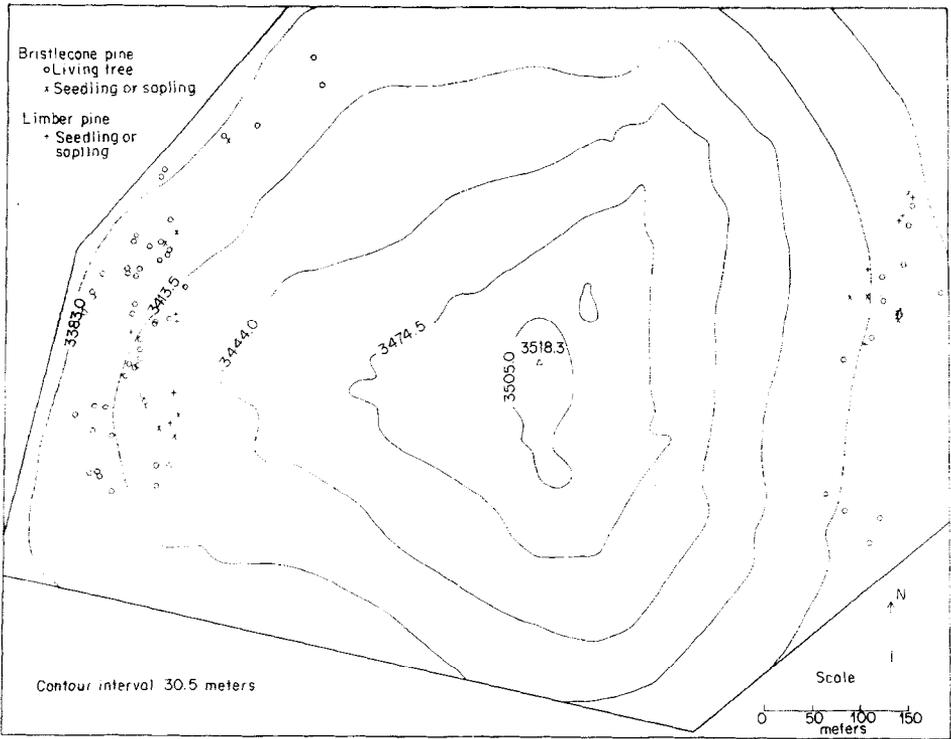


FIG. 7. Living tree distribution—Campito Mountain.

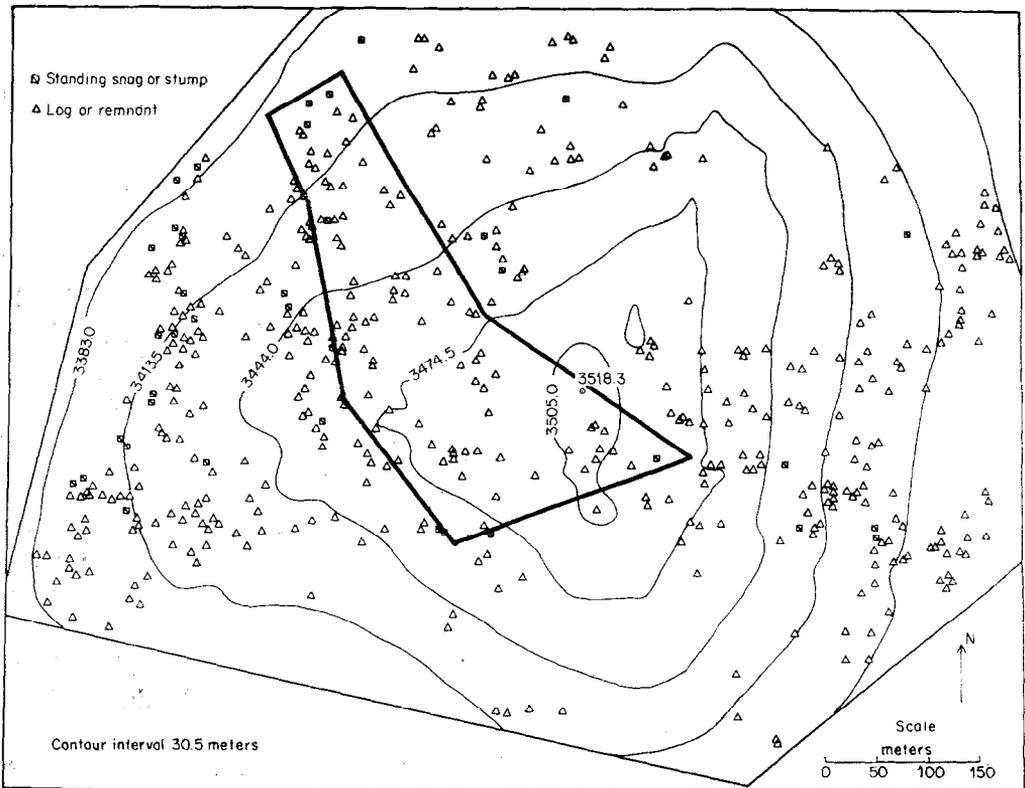


FIG. 8. Dead tree distribution—Campito Mountain.

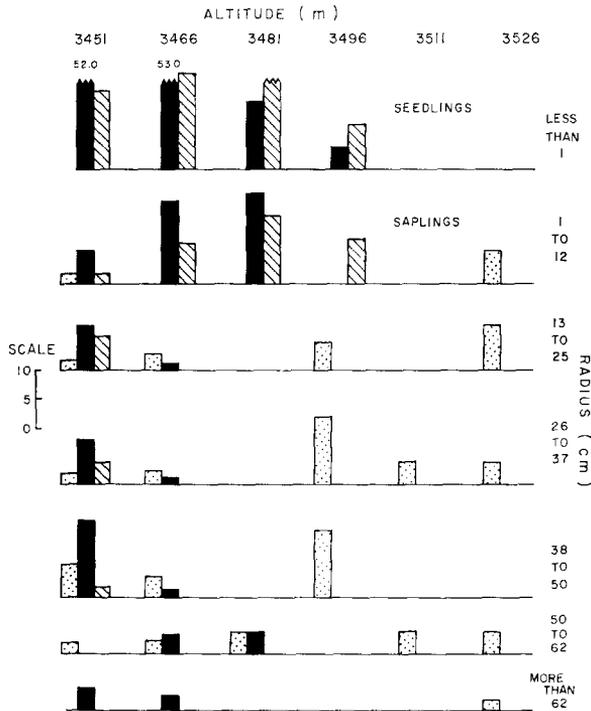


Fig. 9. Frequency of limber pines (hatched), bristlecone pines (solid), and dead standing snags (stippled) in different size classes over a range of altitudes near upper treeline on Sheep Mountain.

the bristlecone pines. On Sheep Mountain, particularly, many high-altitude limber pines are developing krummholz forms with multiple stems and flattened crowns, and numerous dead or damaged leaders projecting above crown level. Nearby bristlecone pines in the same age class are tall, erect, vigorous saplings. Although recent conditions have been favorable for limber pine reproduction at high altitudes, this has not often been the case in the past. On the basis of color, odor, and appearance of the wood, the overwhelming majority of the dead trees, logs, and remnants above tree-line are thought to be of bristlecone pine. Only one of the dated remnants on Sheep Mountain was a limber pine, and it was small-diameter, multiple-stemmed, semi-prostrate tree, probably a krummholz form.

The age structure of the stands immediately below treeline is important because of the information it can yield about reproduction rates at high altitudes during the

comparatively recent past. Age data for the Sheep Mountain area are based primarily on radius measurements of trees within the sample quadrats. The age class corresponding to each radius class was estimated from age-radius relationships in a subsample selected for increment coring. As shown in Fig. 10, the oldest trees were established between A.D. 850 and 1050. The number of trees increases in each successively younger age class until about 1450. Relatively few trees were established between 1450 and 1850, but there are large numbers of young seedlings and saplings. Increment cores were taken from near ground level on 18 of these young trees. They ranged from 4 to 19 cm in diameter, and yielded pith dates A.D. 1865-1948. There are smaller and presumably younger seedlings in the area, but these could not be dated without sacrificing the plants. The abundant trees in the two youngest age classes clearly represent an upsurge in reproduction since

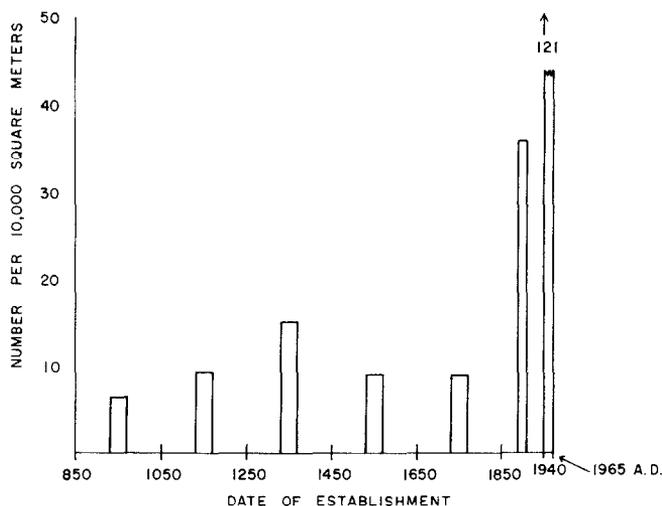


Fig. 10. Age-class distribution of living bristlecone pines on Sheep Mountain.

about 1850 or 1860, and which has continued or even increased since about 1940.

On Campito Mountain, all of the trees (except seedlings and saplings) above 3386 m altitude were sampled for age determination. Increment cores were taken on one or more radii of each tree, and the annual rings were dated. The pith date was determined wherever possible, but in some cases extensive rot had destroyed much of the heartwood. In these cases, the pith date was estimated by extrapolation based on the average growth rate shown on the inner part of the increment core, combined with

careful field measurements to determine the original position of the pith. Thus, although there is uncertainty in some of the pith dates, they are more accurate than age estimates based on diameter or radius measurements, such as those for Sheep Mountain.

The pith dates were grouped into 100-yr classes (Fig. 11), beginning in 800 B.C., the date of the oldest tree. Most of the trees were established during the past 2000 yr. There is a gradual but irregular increase in number of trees established in each period up until A.D. 1500, when reproduction

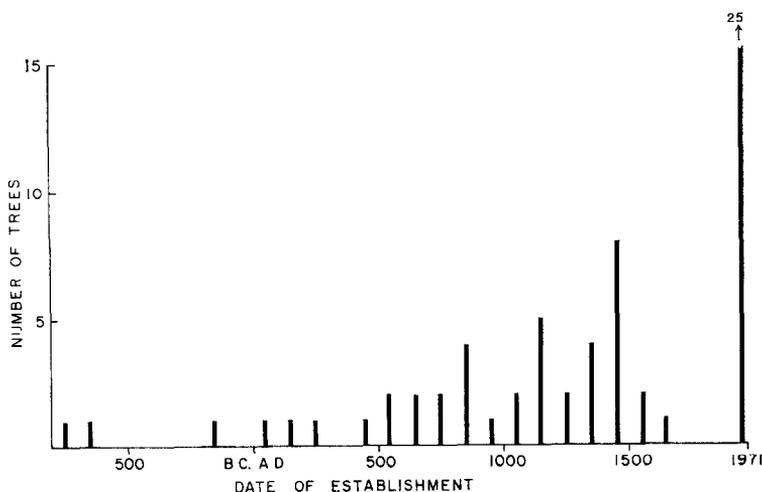


Fig. 11. Age-class data for bristlecone pines on Campito Mountain.



FIG. 12. Standing snags above Sheep Mountain treeline. Dates are A.D. 440–A.D. 1402 (left) and A.D. 571–A.D. 1413 (right).

rates declined. No surviving trees were established between A.D. 1700 and about A.D. 1900. The largest saplings are smaller and apparently younger than those on Sheep Mountain. Only three saplings were sampled, and they gave pith dates between 1920 and 1950.

The decline in reproduction beginning about A.D. 1500 and lasting until 1850–1900 is a striking feature of both areas. Close examination of the altitudinally stratified age-class data for Sheep Mountain (Fig. 9) suggests that the decline was most pronounced at high altitudes, where there are no living trees between 13 and 50 cm radius, corresponding to the period from about A.D. 1250 to 1850, analogous to the situation near upper treeline on Campito Mountain. The relatively large number of seedlings and saplings, established within the past 70–120 yr is also common to both areas.

#### *Distribution and Ages of Tree Remains*

The remains of trees are locally abundant above present treeline in the White Mountains. These may represent extensions of existing stands, such as on the east and west slopes of Sheep Mountain and on Campito Mountain, or single trees or groups of trees quite isolated from present stands, as on the southern slopes of Sheep Mountain. Remnant areas on west-facing dolomite slopes below the upper treeline are particularly prominent.

The remains of dead trees range from standing snags with many small, intact branches (Fig. 12) to remnants less than a meter long and only a few kilograms in weight (Fig. 13). Some logs are partly decayed, but the remnants are generally sound, with resinous, aromatic wood. Some of the remnants, particularly on Campito Mountain, show signs of past fire such as



FIG. 13. Remnant near summit of Campito Mountain. Dates are 994 B.C.-770 B.C.

charred surfaces. The bark on many snags is still locally present, as on protected roots and branches. Generally, however, the bark and sapwood are missing. The heartwood is much more resistant to insects, decay, and weathering.

Many dead trees have been reduced to a group of remnants, where original identity is shown by shape, surface texture, color, wood characteristics, and by cross-dating of their tree-ring records. Such groups were mapped as single occurrences. In general, the standing snags and large logs are found near the present treeline, and only deeply weathered fragments remain at the highest elevations. Because the condition of the remains should be an indication of time elapsed since a tree's death, this suggests that the high altitude remains are relatively old, a result borne out by actual dating.

On Campito Mountain, a transect about 150 m wide and 500 m in length was established within the mapped area on the northwest slope (Fig. 14), extending from the

upper treeline to the summit. All of the trees and remnants in the transect were sampled for dating purposes. On Sheep Mountain, sampling was restricted to a narrow (10 m) transect below 3570 m altitude but broadened to include nearly the entire mapped area above this altitude, because of the low density of remnants at the higher altitudes.

Core samples were obtained for most of the specimens using a Swedish increment borer. Cross sections were also cut in some cases where required to provide sufficient material for radiocarbon dating, or where specimen size, shape, or poor preservation prevented increment coring.

On Campito Mountain, all of the living trees above 3386 m altitude were cored in order to study the age structures of the stand, and to provide material for tree-ring chronology development. A smaller group of old living trees was similarly sampled on Sheep Mountain, in an area about 300 m north of the main study area.

The age of the wood was determined by

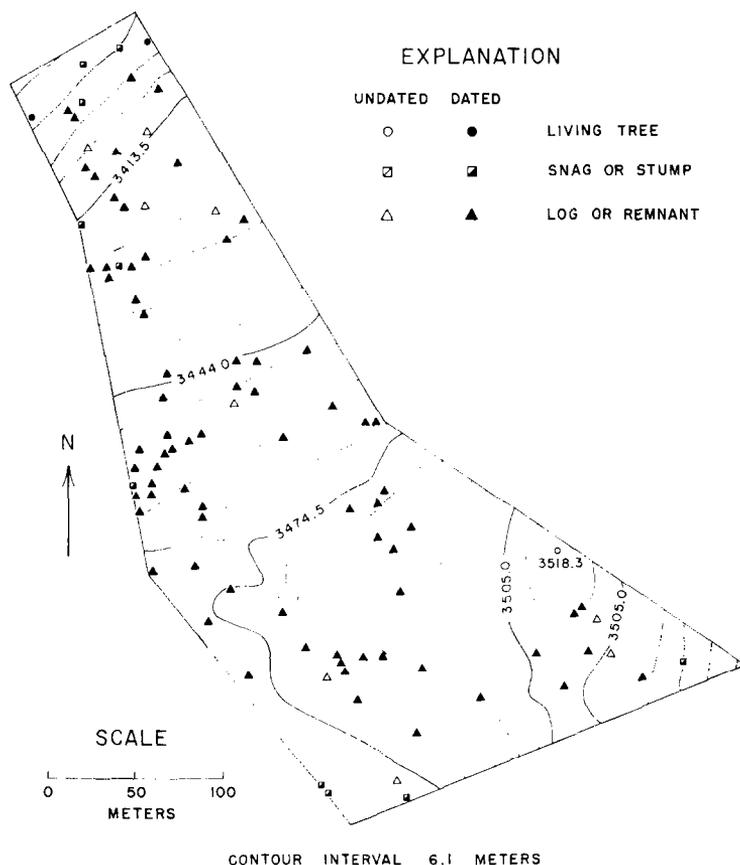


Fig. 14. Remnant sample area on Campito Mountain (see Fig. 8 for location).

tree-ring and radiocarbon dating methods. The main objective was to learn the dates of the innermost and outermost growth rings present in a tree remnant, thus giving the minimum time period during which the tree lived. Each tree-ring sample was surfaced, and the rings were counted on an arbitrary time scale. Skeleton plots, showing the relative spacing of unusually narrow rings, were made of each specimen (Stokes and Smiley, 1968). These plots were combined into a master plot. By incorporating tree-ring records of living trees in the area, the master plot was extended to the present, and calendar dates could then be assigned to the annual rings. Ring widths of selected samples were measured, the measured series converted to ring-width indices; the ring-width indices for each year were averaged to provide a ring-width index chronology

for the site. Dating of individual series was then double-checked using the plotted measurements. The Campito Mountain index chronology represents 5403 annual rings, and even the earliest calendar dates are believed to be accurate to within 2 yr, based on internal evidence and on a comparison with the chronology independently developed by C. W. Ferguson elsewhere in the White Mountains (LaMarche and Harlan, in press). Because of the poorer cross-dating qualities and generally short length of the tree-ring series, the Sheep Mountain chronology is only about 1800 yr in length. Of 36 sampled remnants, only 16 could be dated by tree-ring methods.

Some samples could not be continuously dated, because of lack of physical continuity caused by decay, or because of suppressed intervals with very narrow rings.

However, even where dates of the inner and outer rings could not be exactly determined by cross-dating, in most cases they could be closely estimated by a count of annual rings from the dated portion.

Radiocarbon age determinations were obtained for 15 Campito samples that could not be dated by tree-ring methods. In these cases, tree-ring dating methods could not be used because the ring-width series is short, or complacent, or falls into a time period prior to the beginning of the master chronology. The radiocarbon samples contain from 10 to 30 annual rings. The radiocarbon ages were first transformed to approximate calendar ages using the curve of Suess (1970). Then, the number of rings prior to the median ring of the radiocarbon sample was subtracted from the corrected radiocarbon calendar date, to give the approximate calendar date of the innermost ring. Similarly, the number of rings following the median ring was added to the radiocarbon date to give the date of the outermost ring. In six cases, cross-dating was accomplished after the sample had been submitted for  $^{14}\text{C}$  analysis. In addition, all three specimens from Campito Mountain radiocarbon-dated in earlier reconnaissance work (LaMarche and Mooney, 1967) were found to cross-date with the master chronology. Radiocarbon analysis was also used to date 20 of the Sheep Mountain samples.

#### *Interpretation of Ages*

If the treeline is defined on the basis of the altitude of the highest living trees at any point in time, the precise delineation of past treeline levels requires knowledge of the location and of the dates of establishment and death of all the trees in the area under study. Clearly, loss of wood from the pith and bark areas of the tree will make it impossible to exactly determine these dates. The date of the outermost ring of a log will be older than the date of death of the tree unless sapwood and bark are preserved. The innermost ring will approximate the date of establishment only

if the pith is present, and if the log is sampled very close to the base of the stem.

Examination of man-made stumps and logs in the White Mountains indicates that bark persists only 10–20 yr after death. The sapwood is probably removed within 100–200 yr. Study of the living trees on Campito Mountain shows that the sapwood comprises the outermost 30–150 rings, with an average of about 75 rings.

In general, the youngest remains contain the most nearly complete record of the growth of the original tree. The outermost rings of the standing snags and logs from trees that died within the past thousand years are probably within 200 yr of the date of death, and the pith is frequently preserved. The oldest specimens have been greatly reduced in size since death of the tree. Several hundred years of growth may be missing from the inner and outer parts of such specimens. Thus, the exact timing of changes in treeline elevation cannot be deduced from the limiting dates of the remaining wood. However, the fact that a tree was growing at a particular altitude during a certain time period means that the treeline must have been at that altitude or above. The minimum altitude of the treeline at any time during the past several thousand years can clearly be inferred from the data presented in Figs. 15 and 16.

#### CAUSES OF THE TREELINE

The use of treeline position as a measure of past climatic conditions is justified only insofar as climate actually determines the limits of tree growth. The systematic variation of meteorological elements, such as air temperature, precipitation, wind velocity, and cloudiness with increasing altitude in high mountain areas is well-known, and forms the conceptual basis for most theories relating the altitudinal treeline to climatic factors. It is also clear that in most areas the upper forest margin is not a simple horizontal boundary that might correspond to critical average values of altitudinally

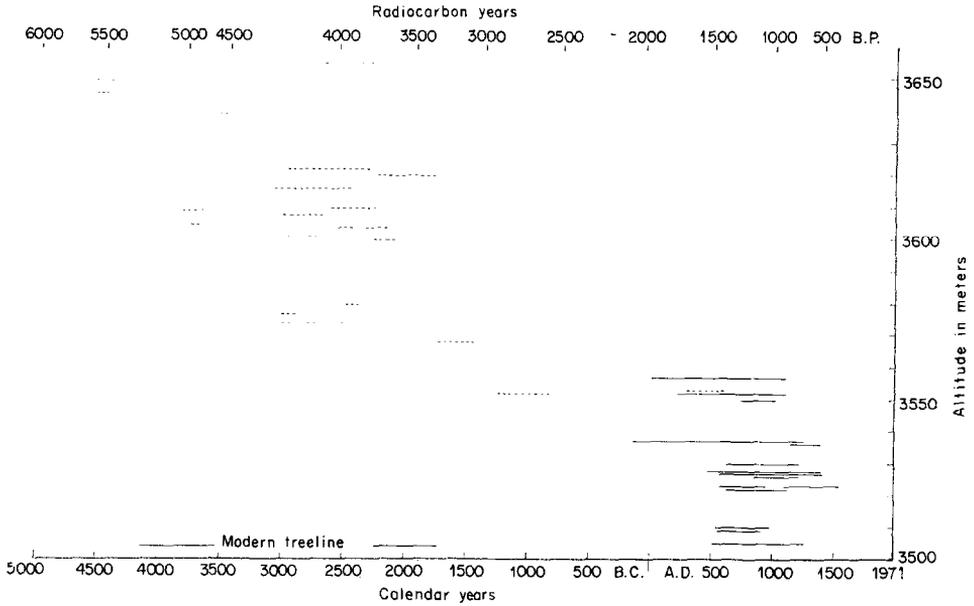


Fig. 15. Ages of dead trees on Sheep Mountain. Dashed lines show radiocarbon-based dates.

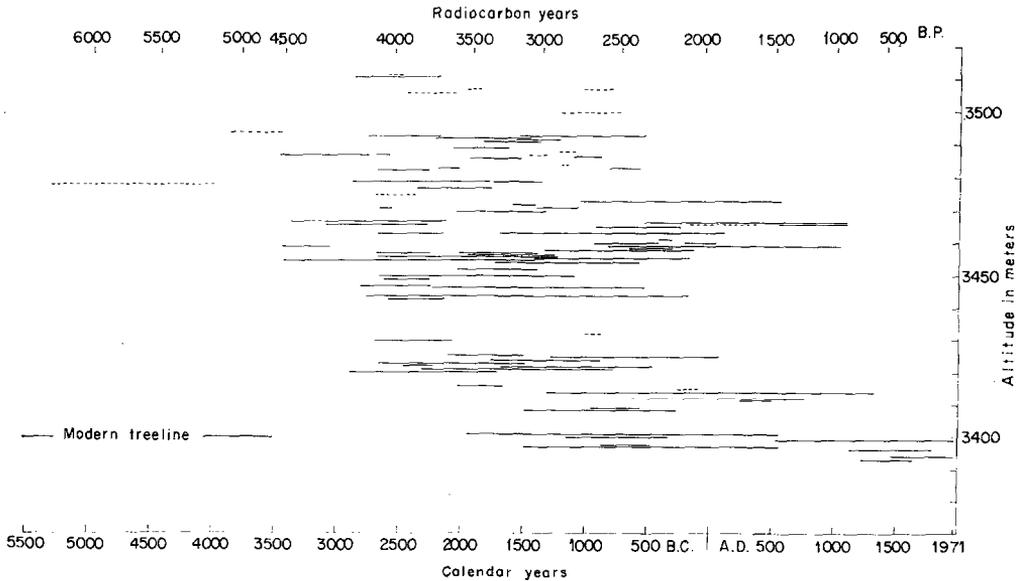


Fig. 16. Ages of dead trees on Campito Mountain. Dashed lines show radiocarbon-based dates.

varying environmental factors. The intricate pattern of tree distribution at high altitude shows that slope direction and inclination, slope stability, substrate composition and texture, wind direction and velocity, snow depth and persistence, soil moisture conditions, and existing vegetation patterns can each be important in deter-

mining where trees may become established. In most treeline areas, the development at high altitudes of dwarfed and krummholz forms of trees that grow erect at lower altitudes adds to the complexity of distribution patterns. However, only relatively few environmental factors may be expected to undergo sufficient change to

cause major changes in distributional patterns over a period of a few thousand years.

An advance of the treeline requires that seedlings become established and survive to maturity at altitudes above the existing treeline. Retreat can take place very rapidly, through death of most or all established trees above a certain altitude, or comparatively slowly through normal mortality. In either case, the treeline will retreat only if dead trees are not replaced by new seedlings. Clearly, reproduction plays a critical role in treeline fluctuations. Unfortunately, little is known of conditions promoting cone production, seed viability, germination, and survival of bristlecone pine seedlings. However, study of the Rocky Mountain bristlecone pine showed a germination rate of 95% for full seeds collected late in the season (Schubert and Rietveld, 1970), and there was no evidence of seed dormancy. In studies of transpiration and wilting coefficients of several montane forest and subalpine conifers, Pearson (1931) found that bristlecone pine seedlings (Rocky Mountain bristlecone pine: *Pinus aristata*) surpassed all others in drought hardiness. He also found bristlecone pine at the top of the list in resistance to winterkilling (winter desiccation under conditions of frozen soil and high air temperatures). Experimental plantings of the same species (Pearson, 1931) indicate that both bristlecone pine and limber pine have a much higher survival rate under exposed conditions than do other subalpine conifers. Field observations of the Great Basin bristlecone pine in the White Mountains generally fit these findings. Reproduction is occurring where thinning has taken place from natural or artificial cause. There are very few young trees in established stands at lower altitudes (LaMarche, 1969) whereas areas cleared by logging and fire have abundant seedlings and saplings. A similar situation is found at upper treeline, where many trees have been eliminated, presumably by adverse climatic changes as shown by the abundance of logs and snags.

Wright and Mooney (1965, p. 282) also observed that areas of bristlecone pine reproduction are in openings within the forest. The related this to gas-exchange experiments at various light intensities, which show that bristlecone pines have relatively high light requirements. They also conclude that the distribution pattern of bristlecone pine are in part determined by inability of bristlecone pine seedlings to compete with sagebrush in sandstone and granite areas.

Although a very few bristlecone pine seedlings are found in the alpine tundra zone over 3600 m altitude on Sheep Mountain, most of the reproduction is occurring at and below treeline. The presence of scattered trees, stumps and logs seems to favor seedlings establishment. The reasons may include lower wind velocities in the lee of these obstructions, and perhaps greater soil moisture content in spring, from melting of drifted snow. Persistent snowdrifts, which can locally preclude seedling establishment in other subalpine areas, are rare in the White Mountains. Fires, logging, and grazing by domestic animals, factors that are thought to be important in causing treeline retreat in other regions, can be ruled out as important contributing factors in the White Mountains. Fires have occurred in both study areas as indicated by charred logs and charcoal fragments. Few of the remains on Sheep Mountain show evidence of fire damage. The wide spacing of trees and very sparse ground cover seem to prevent all but lightning-caused fires that may burn individual trees. Evidence of fire is more widespread on Campito Mountain. Here, the denser ground cover, including shrubs, is probably capable of supporting local ground fires. However, most of the remains show no signs of fire.

The study areas have been little affected by logging, since bristlecone pine is not a commercial timber species. Some standing snags and living trees were cut just below the sample transect on Campito Mountain during the 1950s, and a few snags were cut in the Sheep Mountain area, probably

somewhat earlier. Large numbers of sheep are said to have grazed in this region during the latter half of the 1800s, and cattle graze seasonally in the subalpine meadows in the White Mountains at the present time. This activity does not seem to have caused reduced reproduction at upper treeline, but in fact coincides in time with a period of high reproduction rates.

#### *The Role of Temperature*

Daubenmire (1954) reviewed a number of theories on the causes of the upper treeline, and examined climatological data for upper treeline areas. He concluded (p. 133) the most promising theory is that "timberline . . . represents a point on the scale of diminishing heat supply where solar energy is adequate only to meet the annual requirements of respiration plus the requirements for foliage renewal, with a result that none is left to permit the development and maintenance of a large mass of non-productive cells as comprise the stem and root system of a normal tree." Results of physiological experimentation seem to support this conclusion. The most thorough studies of physiological processes in high altitude conifers have been those of Tranquillini and his co-workers in the Alps. From results of gas-exchange measurements and field observations of pine, spruce, and larch, Tranquillini (1964, 1967) believes that the upper treeline does indeed mark a physiologically critical altitude, above which annual net photosynthesis is insufficient for maintenance and growth of trees because of the unfavorable temperature regime.

There are three main ways in which the changing temperature regime with increased altitude may limit dry-matter production in high altitude pines. First, lower daytime temperatures during the warm season cause a decrease in average rates of photosynthesis at high altitudes. Second, the later occurrence of spring warming and earlier onset of winter cold increasingly limit the period when the trees are capable of photosynthesis. Finally, loss of photo-

synthates during the period of winter dormancy may increase with increasing length of the dormant period.

Net photosynthesis represents the balance between two processes whose rates are temperature dependent. Photosynthesis, in which atmospheric CO<sub>2</sub> is assimilated and transformed into carbohydrates, increases with increasing temperature, provided that adequate moisture and light are available. However, respiration, which uses up carbohydrates and causes CO<sub>2</sub> loss, also increases with increased temperature. Net CO<sub>2</sub> uptake describes a curve, convex upward, that reaches a peak in some temperature region of maximum net photosynthesis. Mooney *et al.* (1966) found from field measurements of gas exchange in bristlecone pine seedlings and saplings that these trees attain peak rates of net photosynthesis at about 15°C (59°F), but that rates were generally high in the range 10 to 20°C (40–68°F). At upper treeline, the estimated mean maximum temperature of the warmest month (July) is 58.5°F, about the same as the temperature producing maximum net photosynthesis. Thus, the average daily temperature range in the warmest part of summer corresponds to the rising limb of the net photosynthesis curve. As a result, the decrease in daily maximum temperatures that are associated with increasing altitude should result in a decrease in daily net photosynthesis.

Photosynthesis in high altitude pines is limited to the warmer months of the year. Although some features of the seasonal changes of physiological processes seem unrelated to the external environment (Bamberg *et al.*, 1967), temperature is very important. The cold nights of autumn cause changes in the needles that reduce peak rates of net photosynthesis. Such changes are in part reversible, so that a few cold nights followed by warm weather permits some recuperation. However, as the season advances, and nights become progressively colder, photosynthetic rates gradually decline. According to Tranquillini, the critical

temperature is  $-4^{\circ}\text{C}$  (about  $25^{\circ}\text{F}$ ), at which point the water in the needles freezes. In a study of wintertime photosynthesis in bristlecone pine, Schulze, Mooney, and Dunn (1967) found that peak photosynthetic rates in November were only 40% of the peak summer rate, and that maximum net photosynthesis was reached at a higher temperature than in summer. By midwinter (January), net photosynthesis had dropped to zero, to remain there through April. Resumption of photosynthesis in spring takes place gradually, and presumably depends at least in part on increased nighttime temperatures.

Examination of estimated temperatures at upper treeline shows that average minimum are below  $25^{\circ}\text{F}$  from late October to early May. Because of young bristlecone pines studied by Schulze *et al.* are within the cold-air "pocket" near Crooked Creek Laboratory, nighttime temperatures at this site are probably similar to those at upper treeline. Thus, the length of the season of photosynthetic dormancy in the experimental plants may be similar to that of trees at upper treeline.

Loss of stored photosynthates by respiration during the winter period of photosynthetic dormancy is an important component of the annual  $\text{CO}_2$  balance in high-altitude evergreen conifers (Tranquillini, 1964). Considering only  $\text{CO}_2$  loss from the foliage, Schulze *et al.* (1967) calculate that for the bristlecone pines studied, 117 hr of photosynthesis at peak summer rates are required to equalize this loss. They estimate that about half of the summer's net production of photosynthates in the experimental plants is lost by dormant season respiration. The duration and severity of winter suppression of photosynthesis are strongly dependent on altitude. Stone pine at low altitudes (600 m) in the Alps are able to maintain a positive  $\text{CO}_2$  balance throughout most of the winter, whereas at upper treeline (1900 m), the same species suffer net  $\text{CO}_2$  loss for 5 mo of the year. The increase in negative components of the annual  $\text{CO}_2$

balance with increased altitudes is thought to play an important part in determining the altitude of upper treeline (Schulze *et al.*, 1967).

The "inverted treeline" at Crooked Creek Laboratory provides considerable support for the idea that nighttime minimum temperatures may partly control the distribution of trees, probably through their effect in the photosynthetic capacity of the foliage. The slopes of the valley in which the Laboratory is located support bristlecone pine and limber pine on the south side, and mountain mahogany on the north side. The valley floor and lower slopes are un-forested. The lower tree limit is approximately horizontal, whereas the valley itself slopes downward to the east, so that the lower limit lies about 10 m above the valley floor at the upper end of the valley but about 30 m above it at the lower end of the valley. There is no apparent change in slope angle, substrate type, soil texture, or drainage that might explain the absence of trees on these lower slopes. However, there is an important microclimatic boundary at about this position. As discussed previously, a nocturnal temperature inversion frequently develops in the valley as a result of cold air drainage. Measurements suggested that it often lies between instrument stations at 17 and 51 m above the valley floor, or at roughly the lower tree limit.

Nocturnal minimum temperatures average about  $7^{\circ}\text{F}$  colder in the valley than on the forested slopes above, but daytime temperatures are normal for this altitude because the cold air is quickly dissipated in the early daylight hours. The importance of the inversion seems to lie in the persistence of cold nights in spring and early occurrence of low nighttime temperatures in fall. In terms of night temperatures, spring is delayed about 1 mo and autumn comes 1 mo early in comparison with the normal seasonal march of temperatures at this altitude. This microclimatic anomaly may have an important influence on the  $\text{CO}_2$  balance of trees by substantially in-

creasing the period of photosynthetic dormancy, and thus decreasing the period when the trees are capable of photosynthesis at peak rates. The unforested lower slopes around Crooked Creek Laboratory can be equated with slopes above treeline in a fairly direct way. Mean minimum temperatures in the valley bottom are lower than those estimated for the upper treeline in all but 1 mo of the year. The recent history of this "inverted" treeline also appears similar to that of the upper treeline. Seedlings and saplings are locally abundant on the slopes below the lowest full-sized trees, perhaps corresponding to the establishment of seedlings above upper treeline in recent decades. The saplings experimentally studied by Mooney *et al.* (1962) near Crooked Creek belong to this pioneering age class. If these speculations are valid, they indicate that low nighttime temperatures alone can determine the altitudinal limits of tree growth, probably through their influence on the annual CO<sub>2</sub> balance of young trees. Billings (1954) similarly ascribes the lower boundary of pinyon-juniper woodland in many western Nevada valleys to nocturnal temperature inversions.

Low temperatures can influence trees in ways other than through CO<sub>2</sub> balance. Richardson (1964) reviews some of the affects of temperature on wood cell characteristics. He found that tracheid length, cell-wall thickness and lumen diameter in seedlings were all related to temperature in the range 7–23°C. However, the magnitude of the differences in cell characteristics were small compared with the differences between normal earlywood and latewood components of the annual ring. Air temperature, and particularly nighttime temperature, also has an important influence on rates of shoot growth in conifers. Larson (1964) concluded that environmental factors, including temperature, exert this influence directly on the crown, and only indirectly on wood formation. That is, growth regulators and photosynthates produced in

the crown, in turn influence cambial activity and cell characteristics. However, Zahner (1968) emphasizes the important contributing role of water stress in regulating cell numbers and characteristics under some conditions.

Temperature may be very important in determining the timing of phenological events such as bud swelling and initiation of cambial activity, and low temperatures can greatly reduce total seasonal height growth in conifer seedlings (Kozlowski, 1971).

Temperature events, rather than average conditions, can also influence seedling survival. Severe damage to plant tissues can occur when temperatures fall well below freezing during or shortly after the growing season. Such events are recorded in frost-damage zones in the tree rings, and occur most frequently in the stem and branches of young trees. Severe frost damage, particularly if it extends to the bark and needles, could be fatal to young seedlings.

Another process related to temperature is winter desiccation of foliage, which occurs when the ground and all or part of the stem are frozen, while high leaf temperatures promote water loss. This phenomenon seems largely responsible for development of krummholz forms of Engelmann spruce (Wardle, 1968), and is probably also true for other species. Tranquillini (1967) relates the stunting of stone pine and development of krummholz to late winter desiccation of the foliage. Needles of high altitude trees in most areas are apparently unable to mature sufficiently to control transpiration or to resist desiccation damage. Although the dry summer climate of the White Mountains apparently promotes resistance to winter desiccation in bristlecone pine (LaMarche and Mooney, 1972), limber pine are noticeably affected. Winter desiccation could be a major cause of death of seedlings in the White Mountains because of the normally shallow winter snow and frequent occurrence of snow-free conditions during the winter.

## CLIMATIC IMPLICATIONS OF TREELINE FLUCTUATIONS

### *Recent Trends*

The unusually high reproduction rate at and above the upper treeline within the past 100 yr can be evaluated in the light of known climatic trends and should provide some basis for interpretation of tree-line fluctuations in terms of past climate. There was a well-documented general warming trend in the Northern Hemisphere from the mid-19th through mid-20th centuries (Mitchell, 1961). Although trends varied between seasons and were more pronounced in some regions than in others, there is general agreement that temperatures were about 1–2°F warmer in the period 1850–1940 than they had been for at least several decades previously. Although many areas have experienced cooling since about 1940, the warming trend continued in western United States through the 1960s (Namias, 1972).

Climatic trends since the 1850s in the interior western United States are difficult to document because of the scarcity of long homogeneous weather records. However, from examination of fragmentary records from military camps, Wahl and Lawson (1970) concluded that temperatures in the 1850s and 1860s were warmer than the current climatic normal (1931–1960) especially in summer. The region of positive temperature anomaly may have been centered in Nevada to the east of the White Mountains.

The nearest long climatic series is that from Mina, Nevada, about 80 km north of the study area. Temperature observations were begun at this cooperative station in 1907, and only one station relocation has been recorded (1950). Using Colfax, California for comparison, double mass analysis of precipitation records, and comparison of plotted cumulative temperature differences indicate that the Mina record is fairly homogeneous. There is little visual evidence for trend in precipitation, except possibly

for slight increase in summer (June, July, August) precipitation since 1950. There is evidence for temperature change in autumn (September, October) and in summer. Autumn temperatures show a pronounced increase in recent years, being noticeably higher after 1940. A *t* test shows that the change of 1.6°F in mean temperature between the period 1907–1930 and the standard normal period 1931–1960 is significant at the 5% confidence level. It is confirmed by similar differences at other stations in the region. Summer temperatures appear to have increased from 1907 until about 1930, and to have decreased since.

Both increment core samples and diameter measurements indicate that a large number of bristlecone pines have become established in the upper treeline area since about 1850, with a preponderance of those in the Sheep Mountain area having been established since 1940. This contrasts strikingly with the very low reproduction rates that prevailed in both areas from about 1700 to 1850. In view of the close relationship between warm-season temperatures and CO<sub>2</sub> balance in bristlecone pine, the high reproduction rates in recent decades must be at least partly related to higher temperatures. Warmer summers may have been important throughout this period, as well as warmer autumns, particularly since about 1940.

### HOLOCENE CLIMATIC VARIATION

The importance of warm-season temperature in determining the level of the upper treeline in the White Mountains is suggested by several lines of evidence. Low precipitation may be an additional limiting factor, especially on Campito Mountain. Thus, if some important qualifications are kept in mind, past changes in treeline level can be interpreted in terms of climatic variation. First, only the minimum altitude of the treeline can be reconstructed, because trees may have been living above the altitude of the highest remnant remaining from any particular time. Complete disintegra-

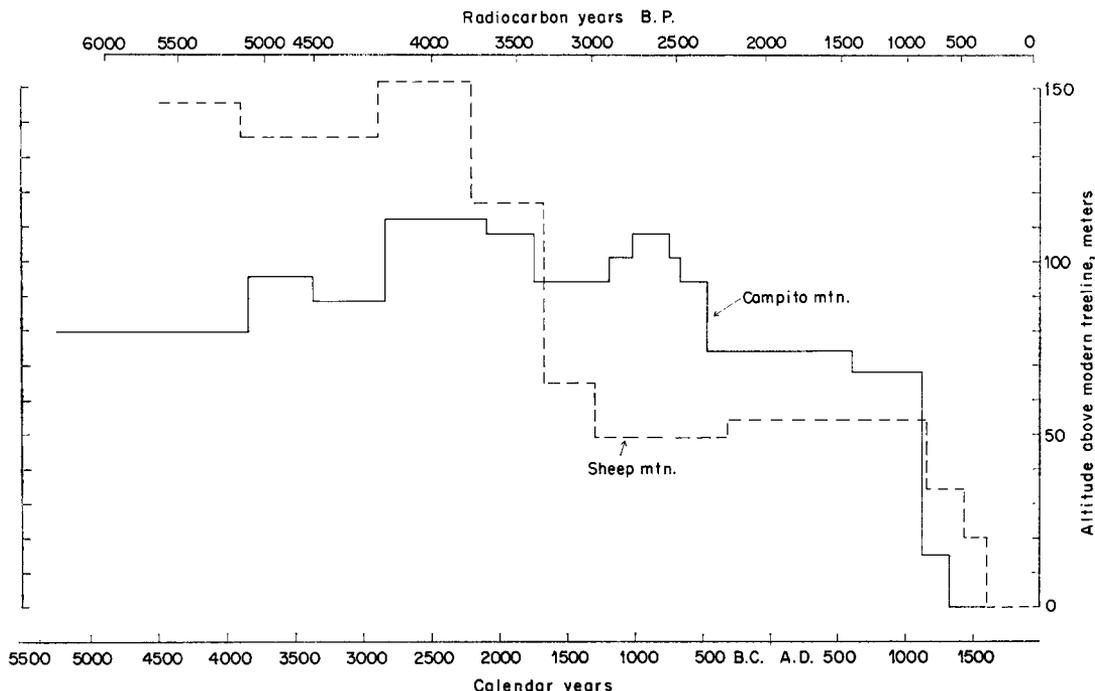


FIG. 17. Minimum past treeline altitudes in the White Mountains.

tion of the wood would leave no record of such occurrence. Second, the exact timing of climatic transitions cannot be determined, because of the incomplete growth records preserved in most of the remnants, and because the response of the treeline probably lags behind climatic fluctuations. That is, established trees can survive at altitudes above the upper limit of reproduction during periods of adverse climate. The treeline will slowly descend as these trees die, if they are not replaced by new seedlings. The events of the last few decades indicate that upward movement of the treeline under favorable climatic conditions is also relatively slow, mainly because of the harsh microenvironment for seedlings in the unforested areas above treeline. Finally, brief climatic episodes, lasting several decades to a few hundred years may leave no record because of these same lagging relationships.

The middle to late Holocene history in each of the two study areas is summarized in Fig. 17 by an envelope curve represent-

ing the minimum altitude of the upper tree-line throughout the past several thousand years. The two curves are similar in their gross features, but also show potentially important differences. The Campito Mountain curve begins earliest—about 5400 B.C. In this early period, it is based on a single large remnant at 3478 m alt, 40 m below the summit. The remnants at the highest elevations date in the period 2000–500 B.C., when trees grew at the highest possible altitudes on Campito Mountain, on a flat only seven meters below the rocky summit. The climatic treeline probably lay above the altitude of the summit during this period. After this, the curve drops to a lower level, maintained until about A.D. 1100. The curve then drops about 70 m to present treeline level.

On Sheep Mountain, the oldest remnant dates back to about 4500 B.C. A high tree-line level was maintained until about 2200 B.C., after which the curve begins to drop, reaching a new level about 100 m lower by 1700 B.C. This level was apparently main-

tained until at least A.D. 1100, after which a further drop of 50 m culminated about A.D. 1550, bringing treeline down to its present level.

One important difference between the Sheep and Campito curves is in the interval between 1700 and 500 B.C., when the Campito Mountain treeline apparently remained at relatively high levels. Also, from 4500 to 2500 B.C., the Sheep Mountain treeline remained at a high constant level, whereas there is some suggestion that the Campito Mountain treeline rose during this interval. If we assume that the Sheep Mountain treeline is mainly controlled by late spring, summer, and early autumn temperatures, and that both low temperatures and low precipitation affect the treeline on Campito Mountain, then the two curves taken together suggest that the period 5400–2000 B.C. was one of relatively high summer temperatures.

There is some suggestion of a favorable climatic period beginning about 3000 B.C. that lasted at least 1000 yr. The highest wood remnants in both study areas have inside dates between 2800 and 2600 B.C. There is also an unusually large number of remnants with inside dates about this time at lower altitudes, suggesting a very high rate of reproduction. These observations may be related to a period favorable for reproduction at high altitudes. This could have been a period of unusual summer warmth combined with fairly high precipitation. Summer cooling apparently began between 1500 and 1000 B.C., causing a drop in the Sheep Mountain treeline. Higher precipitation may have partly offset the adverse effects of lower temperature on the Campito treeline, which remained at high levels until about 500 B.C. The apparent lowering of the Campito treeline about this time is not reflected in the Sheep curve and may have been a response to drier conditions. The very abrupt drop in both curves after A.D. 1100 is nearly synchronous. The outside rings of the best preserved of these dead trees give dates shortly after A.D.

1500. Weathering and consequent loss of wood could account for outside dates of A.D. 1100–1200 on many of these trees, which may have died in the interval A.D. 1300–1600. Although the dating is not exact, the death of large numbers of trees in both localities at upper treeline a few centuries ago indicates an abrupt climatic deterioration. Since both areas were equally affected, the climatic change seems to have involved both temperature and precipitation. This was either a change to much colder summers, or to fairly cold summers and drier springs, autumns, and winters. The decline in reproduction seems to have occurred somewhat later than the accelerated mortality of established trees. Reproduction was at a minimum between 1700 and 1850, whereas most of the trees apparently died before A.D. 1600.

Evidence for climatic variations in the White Mountains can be compared with evidence for climatic events in the nearby Sierra Nevada. Pollen data for the Sierra northwest of the White Mountains has been interpreted by Adam (1967) as indicating a postglacial warm period beginning about 10,000 radiocarbon y.a. (BP), and terminating about 2900 BP with the onset of cooler and wetter conditions. This is consistent with the treeline changes observed in the White Mountains.

Several kinds of evidence for Holocene climates in the Sierra are evaluated by Curry (1969, 1971). He recognized three periods of Neoglacial advances and dated the terminal moraines by lichenometry. The earliest are those of the Recess Peak glaciation (Birman, 1964). Major Recess Peak advances were dated by Curry at about 2650 and 2000 BP. However, other workers (Birkeland *et al.*, 1971) correlated the Recess Peak advances with the Temple Lake advances of the Rocky Mountains. Stratigraphic nomenclature for late Quaternary glacial deposits in the Rocky Mountains is now undergoing revision (Birkeland and Miller, 1973). The type Temple Lake deposits in the Wind River Mountains may

be of late Pinedale age, and it is possible that early Neoglacial deposits elsewhere in the Rockies have been incorrectly designated as Temple Lake. According to Benedict (1968), the "Temple Lake" advances in the Front Range of Colorado may have begun as early as 4500 BP, and ended prior to about 2500 BP. Richmond (1962, 1965) correlated dated alluvial deposits with the twofold "Temple Lake" moraines in the La Sal Mountains of Utah. These deposits have radiocarbon dates of about 3100 and 1800 BP, respectively. However, the younger of these deposits may be correlative with the "Arikaree" of Benedict (1968). Lichenometric data in the Sierra suggest two closely spaced periods of glacial advance, one about A.D. 950 and another about A.D. 1050. These unnamed advances may also correspond to the Audubon Stade ("Arikaree" of Benedict, 1968) of the Front Range (Mahaney, 1972, 1973). There appears to have been no treeline recession in the White Mountains associated with this period of glacial activity.

The most recent Neoglacial episode is termed the Matthes glaciation (Birman, 1964) in the Sierra Nevada. Curry dated major advances at A.D. 1330, A.D. 1620, and A.D. 1700, and a minor readvance at about A.D. 1895. This period may have been not only cool, but relatively dry. Thus, except for the Recess Peak, the times of glacial events in the Sierra Nevada correspond in part with periods of low warm-season temperatures defined by treeline decline in the White Mountains.

The climatic inferences obtained from study of the upper treeline agree well in many respects with other paleoclimatic evidence from western North America. Among the best such evidence is that based on study of Cordilleran glaciers (Denton and Porter, 1967). The period of highest treeline levels on Sheep Mountain corresponds to a period of retracted glacier termini. The drop in the Sheep Mountain treeline after about 1500 B.C. may have coincided with

the initial period of Neoglacial readvances observed throughout the Cordillera, and which culminated about 900 B.C. The abrupt treeline decline between about A.D. 1100 and A.D. 1600 clearly coincides with renewed glacial activity of the late Neoglacial.

The most significant feature of the history of the White Mountains treeline with respect to Neoglacial events is the relatively high treeline levels maintained from about 5500 B.C. until a few centuries ago. Examination of Figs. 15 and 16 shows that living trees existed 100–200 m above modern treeline levels on Campito Mountain up to about A.D. 1500. On Sheep Mountain in the past 5000 yr, treeline could have been at or below present levels only between 800 B.C. and 100 B.C., and since about A.D. 1550. Thus, trends in treeline altitude in the White Mountains are opposite to trends in temperature in the Rocky Mountains inferred by Richmond (1972), from relative altitudes of glacier termini during successive periods of glacial advance during the past several thousand years. Furthermore, considering data on glacial activity over a much broader geographic area, Porter and Denton (1967) found that glacier termini generally reached early Neoglacial limits that were only slightly higher in altitude than those reached in late Neoglacial time. In many cases, glaciers reached their maximum downvalley extent during the earlier Neoglacial. Although the glacial record would suggest that similar climate prevailed about 900 B.C. and again about A.D. 1500–1850, the treeline history indicates important differences between these time periods. The discordant response of the Sheep Mountain and Campito Mountain treelines may mean that the early Neoglacial cooling was also associated with increased precipitation. Such conditions would be favorable for growth of mountain glaciers. The synchronous and abrupt treeline depression in both areas during the late Neoglacial episode may

have been associated with an unusually cool but relatively dry climatic regime.

Inferences about the timing of past climatic variations in the White Mountains can also be compared with dates of climatic change proposed by Bryson and others (Wendland, 1971; Bryson, Baerreis, and Wendland, 1970). These dates are based on the statistical analysis of a large number of radiocarbon dates associated with evidence for environmental changes during Late Pleistocene and Holocene time. The analysis appears to show the clustering of dates of environmental change within restricted time periods. These are regarded as times of transition between longer episodes characterized by relatively stable climate (Bryson and Wendland, 1967). These episodes are inferred to correspond with the classic Blytt-Sernander subdivisions for late-glacial and postglacial time in northwestern Europe (Bryson *et al.*, 1970). The treeline data for the White Mountains encompass only the last three episodes in this sequence—the Atlantic, sub-Boreal, and sub-Atlantic. The Atlantic sub-Boreal transition, dated by Wendland (1971) at 4075 B.C. (corrected for radiocarbon age–calendar age discrepancies), falls in time period represented by very few wood specimens. Treeline may have risen after 4000 B.C. on Campito Mountain, but the evidence is too scanty to determine whether this presumably worldwide climatic transition had important ecological effects in the White Mountains. The date for the sub-Boreal sub-Atlantic transition given by Wendland is 970 B.C. This date falls midway between periods of major decline in treeline altitude. However, there is a minor climatic transition between early and late sub-Boreal time, dated by Wendland at 1710 B.C., that coincides with the major decline of treeline altitude on Sheep Mountain. In northern North America, this is reflected in retreat of the limits of the northern boreal forest (Bryson and Wendland, 1967; Bryson *et al.*, 1965).

## THE ALTITHERMAL

The nature of the climate of southwestern United States during the Holocene has been subject to considerable controversy. That western North America has experienced climatic variations during the past 10,000 yr cannot be seriously questioned. However, there has been lively discussion regarding not only the magnitude, but the direction of some of these changes, as well as their biological and cultural impact (Aschmann, 1958; Martin, 1963).

The history of the White Mountain tree-line strongly supports Antevs' (1948, 1955) concept of an "altithermal age" in the Great Basin and contiguous areas from about 5000 to 2500 B.C. Based mainly on the presumed disappearance of playa lakes and of many mountain glaciers, Antevs argued that the climate of this period was both warmer and drier than that of the succeeding period, which he termed the "medithermal age," and which lasted from about 2000 B.C. to present. Relative summer warmth prior to about 1500 B.C. is shown by the high treeline position, particularly on Sheep Mountain.

Martin (1963, p. 67) found no palynological evidence for a dry "altithermal" in Arizona and New Mexico. He further argued that the increased gullying in this region could be attributed to increased frequency of intense convective summer thunderstorms, rather than to aridity, as postulated by Antevs. However, it should be noted that a great deal of Antevs' evidence for "altithermal" drought came from northerly areas, particularly in southeastern Oregon. As Martin emphasized, increased summer precipitation in the southerly areas is meteorologically consistent with increased warmth and aridity in the northern Great Basin—a region of winter and spring precipitation maxima.

The difference in summer temperatures between "altithermal" time and the late Neoglacial can be estimated from the

difference in treeline altitudes on Sheep Mountain. About 2500 B.C. the treeline was at or above 3650 m alt. The treeline reached its lowest altitude about A.D. 1700. At that time, the potential treeline, located at the upper limit of reproduction, was at 3450 m, about 50 m lower in altitude than the highest surviving mature trees. Thus, the total amplitude of change in treeline altitude approximate 200 m. Since the maximum surface temperature gradient in the White Mountains in July is 1.73°F per 100 m, the difference in treeline altitudes may correspond to a difference in July temperatures of about 3.5°F. Determining the warmth of the "altithermal" relative to the recent decades of instrumental weather records is much more difficult. The altitude of the potential treeline today is certainly higher than during the late Neoglacial, as shown by the abundant saplings now established a few meters above the mature treeline. However, it is difficult to predict what altitude would be reached by newly established trees if recent climate persisted for a period of several hundred years. The recent climatic amelioration has probably been too brief to permit development of an "equilibrium" treeline on Sheep Mountain. The presence of a seedling at 2630 m in the study area, and of a few other seedlings at similar altitudes nearby, could indicate recent summer warmth nearly as great as during the "altithermal" period of high treeline levels. However, their survival to maturity is problematical, and such seedlings cannot as yet be taken to represent a new, high treeline elevation.

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