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# Late-Holocene upper timberline variation in the southern Sierra Nevada

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**Alpine timberline has been shown to be a definite tension zone between trees and climate where trees invade higher ground during favourable climatic periods and retreat during periods of deteriorating conditions[1]. These movements are indicative of an upper forest limit sensitively adjusted to climatic variation. Here I present absolutely dated dendrochronological records from living trees and standing snags and radiometric dates from relict logs of foxtail pine at Cirque Peak, southern Sierra Nevada, California, providing the first detailed record of temperature-induced mid- to late-Holocene fluctuations in Sierran timberline. Marked declines in timberline correspond to lichen-dated cold periods and/or glacial advance.**

Chronologies of variation in altitude of upper timberline reflecting late-Holocene climatic change have been established for several alpine areas in western North America[2-6]. These timberlines are characterized by zones of standing snags at and just above present timberline, rooted and fallen snags above this zone, and small deeply weathered remnants at the highest limit of relict wood. Similar conditions exist in several areas of the Sierra Nevada, with relict timberlines being especially well preserved in the drier southern portion of the range.

Foxtail pine (*P. balfouriana* Grev. and Balf.) is found at the timberline on Cirque Peak in the southern Sierra Nevada (Fig. 1). This species is closely related to the Great Basin bristlecone pine (*P. longaeva* Bailey) found 60 km northeast in the White and Inyo Mountains. Foxtail pine is characterized by high temperature sensitivity at its upper growth limit, excellent cross-dating qualities, and a relatively long lifespan. Living and relict individuals with lifespans exceeding 1,200 yr have been found at Cirque Peak[7].

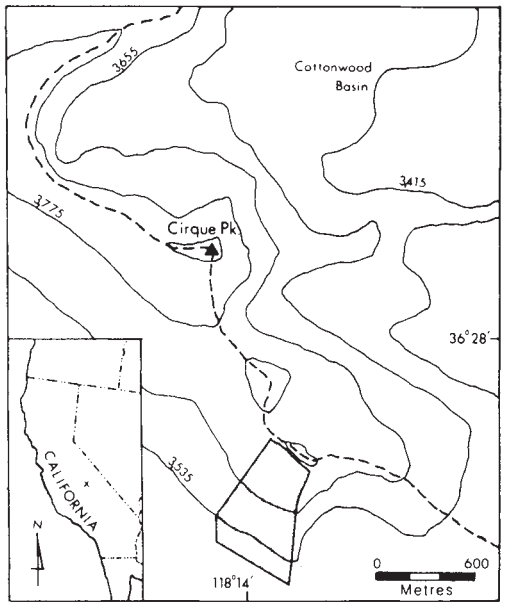


**Fig. 1** Topographic map showing the Cirque Peak upper timberline site (shaded) and its relationship to Cottonwood Basin. Elevations in metres.

Computer-aided cross-dating[8] of relict wood above the present timberline permitted the construction of an absolutely dated 3,031-yr chronology of ring-width variation for the Cirque Peak site[7]. Samples from 6,300-3,100 yr BP were dated radiometrically using the earliest portion of the remnant. Sample elevation was recorded at the time of collection and used in conjunction with dendrochronological and calibrated[9] radiometric sample ages to produce a chronology variation in timberline elevation (Fig. 2).

Timberline was defined as the upper limit at which trees were continually established, a position now indicated by a sharp transition from upright trees to isolated outlier krummholz forms. The minimum timberline position for each time period was inferred from five to six cross-dated samples of upright, non-krummholz wood.

The oldest and highest sample located is a small weathered remnant 68 m above the present timberline, radiocarbon dated[9] at 6,300 ± 300 yr BP (UCLA 2418-A). The wide growth rings of this and other cross-dated remnants at this elevation are indicative of warm, highly favourable growing conditions during the Altithermal. A date[9] of 3,530 ± 50 yr BP (UCLA 2463-C) on a sample 65 m above the present timberline indicates that maximum levels were maintained until at least 3,500 yr BP.

The possibility of a higher Altithermal timberline, similar to that documented in the White Mountains[2,3], was explored at length. Slopes with suitable environmental factors, and lacking physical characteristics that would inhibit upward movement of the timberline, extend nearly to the crest of the range (240 m above the present timberline). But so far no relict wood has been found higher than 70 m above present levels for up to 1 km from the study site. In the light of the observed excellent sample preservation and lack of fire scars it appears unlikely that the timberline at Cirque Peak was much higher than 70 m above its present level at any time since 6,300 yr BP. Relict timberlines on other local peaks suggest that this may represent the maximum Altithermal timberline elevation for the region.

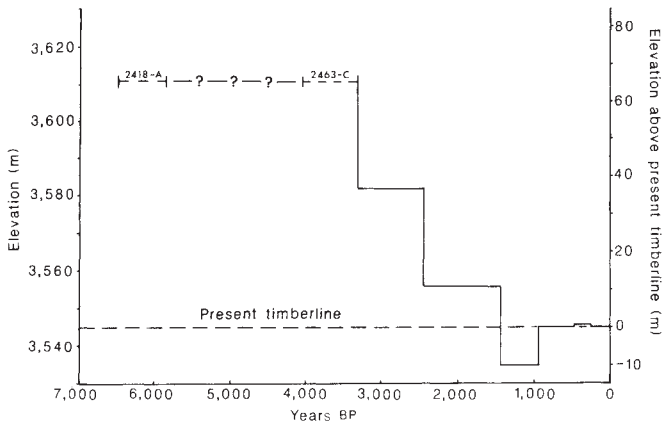


**Fig. 2** Elevation of mid- to late-Holocene timberline at Cirque Peak. Sample numbers of UCLA radiocarbon dates are shown at the highest level of remnant wood 65–68 m above the present timberline.

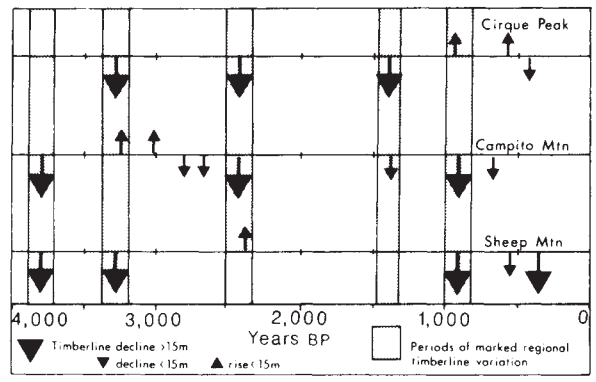


**Fig. 3** Major timberline elevation changes at Cirque Peak and neighbouring White Mountain sites. Periods of synchronous timberline variation are indicated at approximately 3,800, 3,400, 2,400, 1,400 and 900 y BP, indicating possible regional climatic forcing of the upper timberline position.

High Altithermal levels were followed by a rapid decline in timberline of 30 m between 3,400 and 3,200 yr BP. Extrapolation of sample ages to pith dates shows that a large number of trees were established 30–37 m above present levels between 3,200 and 2,800 yr BP. This suggests that the timberline stabilized ~35 m above present levels by 3,200 yr BP and possibly several hundred years earlier.

Many trees, especially those at elevations greater than 20 m above the present timberline, died between 2,500 and 2,300 yr BP. A marked decrease in ring widths in all samples at 2,400 yr BP is suggestive of colder conditions leading to decreased growth and regenerative potential. A study of late-Holocene glaciation in the adjacent Cottonwood Basin[7] indicates that this period was one of marked glacial advance, correlating to the earliest Recess Peak glaciation in the Sierra Nevada[10]. The timberline fell ~25 m to 12 m above the present timberline at this time, where it stayed for ~900 yr. Between 1,400 and 1,300 yr BP the timberline fell rapidly to 10 m below its present level. This decrease coincides with a sharp decline in ring widths for all trees from 1,400 to 1,000 yr BP. Similar small ring widths are also found between 1,300 and 1,050 yr BP at Sheep Mountain in the White Mountains[11]. Lichenometric dating of deposits in the adjacent Cottonwood Basin[7] and the Mammoth Lakes region further north[10] indicates possible increased glacial activity during this interval.

The period 950–850 yr BP was one of increasing tree establishment during which the timberline rose 10 m to its present level. A few trees were established marginally above present levels at 450 yr BP, suggesting that the timberline may have peaked at this time. The onset of Matthes 'little ice age' advances at 350 yr BP does not appear to have significantly affected timberline position. The establishment of some small erect seedlings 5–10 m above the present timberline since 100 yr BP suggests a renewed rise in timberline due to recent warmer conditions[2,3] or possible increases in atmospheric carbon dioxide concentration[12]. It remains to be seen if these trees will survive to maturity or if they represent short-term variations in timberline that are not resolvable in the context of the coarser record of timberline.

Comparison with timberline records from the White and Rocky Mountains shows several points of similarity as well as some divergence between the records. Of note is the net difference in timberline elevation between present and past levels, especially from 6,300 to 3,500 yr BP. The Sierra Nevada and White Mountain timberlines were both at maximum elevation during this period, but the Cirque Peak timberline was only 70 m above its present level whereas the Campito and Sheep Mountain timberlines were 110 and 150 m respectively above their present levels[2]. Pollen evidence of coarser resolution from the Rocky Mountains indicates that timberline was then 70–100 m above present levels.

The regular nature of the current Cirque Peak timberline, which is characterized by a sharp transition from upright trees to treeless conditions and a smooth drop in elevation from southwest to northwest slopes, suggests that this timberline is a true 'climatic' timberline. The upper limit of remnant wood parallels the current timberline and also shows a similar distinct boundary. The sharply defined timberline and apparent lack of site specific microclimatic and lithological forcing of timberline position is in marked contrast to other more variable upper timberline limits in western North America. This regularity, as well as differences in defining timberline position, may account for a portion of the observed net elevation difference between localities.

A timberline 10 m below present at Cirque Peak between 1,400 and 950 yr BP may be a reflection of the shorter average lifespan of foxtail pine than bristlecone pine. This difference in longevity makes foxtail pine less likely to survive unfavourable periods, and thus more sensitive (ring width) and responsive (elevation change) to climatic variation than longer-lived species. Thus, the Cirque Peak record for this period may indicate cold conditions and a related glacial advance not readily apparent in other upper timberline records.

Mid- to late-Holocene variations of Cirque Peak timberline mirror the timing of major changes in timberline elevation in the White Mountains[3] and, with the exception of the rise to current levels at 950 yr BP, the direction of specific timberline changes at Campito Mountian (Fig. 3). A similar decreasing trend in timberline elevation similar to that at Cirque Peak has been observed in the Rocky Mountains[6]. This correspondence supports a view of regional climatic forcing of timberline elevation. An additional correspondence of timberline decline with glacial advance in the Cirque Peak region[7] suggests that the chronology of the Cirque Peak timberline can provide a link to the evaluation of climatic conditions leading to glacial advance and retreat in the Sierra Nevada and possibly the western United States.

Long, continuous and precisely dated records of timberline variation are uncommon and are especially valuable in the Sierra Nevada where, due to lack of absolutely datable material, little radiometric dating of climatically induced events such as glaciation has been possible. The Cirque Peak timberline and associated annual ring-width variation record, in conjunction with pollen and relative-age-dated deposits, will provide additional information about the physical environment in the Sierra Nevada over the past 6,300 yr. The integration of this record with those from the White Mountains will help isolate the

principal mechanisms responsible for climatic fluctuations during the mid to late Holocene and allow the evaluation of climatic spatial variability.

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# Decrease in precipitation acidity resulting from decreased $SO_4^{2-}$ concentration

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**The effect of decreases in $SO_2$ emissions on precipitation acidity has received much attention[1-10], but there has been no direct quantification of how recent decreases in $SO_2$ emissions in the northeastern and midwestern United States have affected precipitation acidity at a local site. Yet such quantification is an important step in assessing the effectiveness of control measures for $SO_2$ emissions. It is thought that recent decreases in $SO_4^{2-}$ concentration in precipitation at the Hubbard Brook Experimental Forest (HBEF), New Hampshire, USA, result from decreases in $SO_2$ emissions. The effect of the $SO_4^{2-}$ decrease on precipitation acidity is obscured by long-term trends in other ions, which also influence acidity. Here we show that, given the observed trends in concentration of other ions, the $H^+$ concentration in 1983 would have been nearly two-thirds higher than the measured values if the $SO_4^{2-}$ concentration had not decreased.**

During the 20-year period 1964-1983, decreases in concentration and deposition of $SO_4^{2-}$ (Fig. 1*a*) in precipitation at HBEF have been attributed to decreases in $SO_2$ emissions in the northeastern and midwestern USA (Environmental Protection Agency regions I, II and V)[10,11]. Significant decreasing trends in $SO_4^{2-}$ concentrations have also been shown at 5 out of 8 National Atmospheric Deposition Program monitoring sites in the northeastern and midwestern USA since their inception in 1978[12]. There is also evidence of a close relationship between $SO_2$ emission and $SO_4^{2-}$ deposition from the western USA[7], and indications of a similar relationship in Europe[13].

Air masses from the Atlantic Ocean contribute <3% to the total $SO_4^{2-}$ deposition at HBEF[14]. Locally derived soil dust is a small component[15] and unlikely to contribute significant amounts of $SO_4^{2-}$. Atmospheric sulphur in the northeastern USA derives almost entirely from anthropogenic $SO_2$ emissions: this is further evidence that the decreases in $SO_4^{2-}$ (Fig. 1*a*) at HBEF are due to decreases in emissions of $SO_2$ (refs 8-10, 16-19).

Here we quantify the effect of these decreases in $SO_4^{2-}$ on precipitation acidity, using precipitation chemistry from bulk

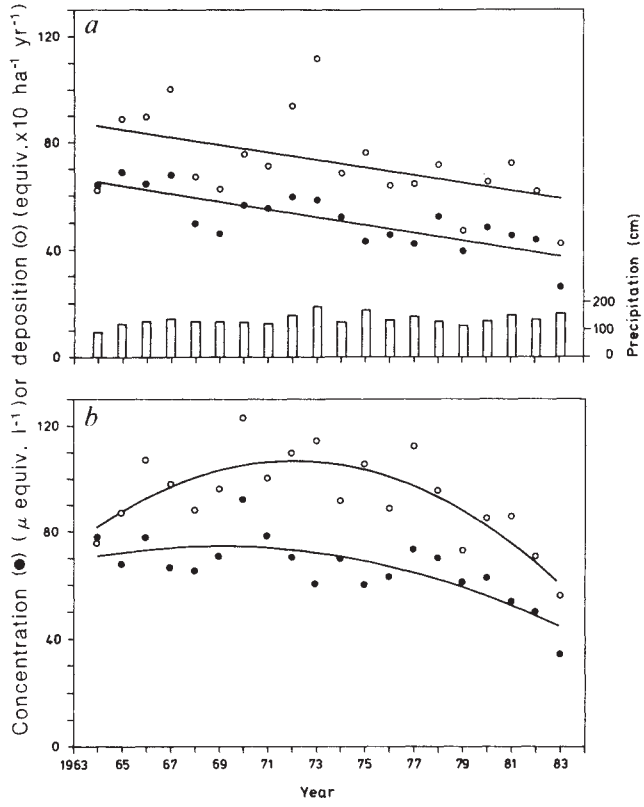


**Fig. 1** Annual volume-weighted average ion concentration (●) and deposition (○) for $SO_4^{2-}$ (*a*) and $H^+$ (*b*) in precipitation at watershed 6 of HBEF for 1964-83. Lines represent significant ($P \leq 0.05$) linear or curvilinear regression trends. The calculation of volume-weighted averages is described elsewhere[20]. The histogram in *a* shows annual precipitation values at HBEF.

precipitation monitors during a 20-year period at HBEF. We emphasize, however, that although we assume that the decreases in $SO_4^{2-}$ (Fig. 1*a*) at HBEF are a result of decreases in $SO_2$ emissions, our calculations are not dependent on an understanding of the specific shape of the relationship between $SO_2$ emission and $SO_4^{2-}$ deposition, nor on a knowledge of the relative contribution of local versus distant emission sources. Our sampling and analytical methods have been described elsewhere[20].

Both concentration and deposition of $SO_4^{2-}$ at HBEF show statistically significant ($P \leq 0.0001$ and $P \leq 0.03$) linear declines over the 20-year period (Fig. 1*a*, Table 1). The average rates of decrease in $H^+$ concentration and deposition, based on linear regression analysis of data from 1964 to 1983, are not statistically different from those of $SO_4^{2-}$ ($0.9 > P > 0.5$; *t*-test). However, in contrast to $SO_4^{2-}$, the regression trends for $H^+$ concentration and deposition (Fig. 1*b*) have significant quadratic terms ($P \leq 0.03$ and $P \leq 0.0001$), and are best described by curvilinear regressions (Table 1). The trends in concentration and deposition of $H^+$ show modest increases during the beginning of the sampling period followed by sharp declines towards the end (Fig. 1*b*), whereas the $SO_4^{2-}$ trends show constant rates of decrease throughout the period (Fig. 1*a*).

The absence of a precise correlation between long-term trends in $SO_4^{2-}$ and in $H^+$ has led some authors to argue that the relationship between $SO_4^{2-}$ and precipitation acidity is unclear, and that further reductions of $SO_4^{2-}$ concentrations will not affect precipitation acidity[5,6]. However, this ignores the complexity of the chemical relationship between precipitation acidity and $SO_4^{2-}$ concentration. Decreases in $SO_4^{2-}$ concentration would result in stoichiometric reductions in $H^+$ concentration only if other strong acid anions and base cations remain unchanged. In fact, precipitation acidity at HBEF has been