CHAPTER 10

RECONSTRUCTION OF FOREST AND ALPINE ENVIRONMENTS OVER THREE MILLENNIA IN THE HIGH TOQUIMA RANGE

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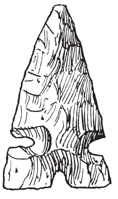

In the context of high-elevation archaeological investigations, knowledge of past and present tree lines and their proximity to alpine villages can provide insight not only into the climates of the sites, but also to potential resource use. Combined with contemporary temperature measurements, I offer observations and data about Alta Toquima and Dakabah to improve understanding of the high Toquima Range.

Alpine villages have existed in very few mountain ranges in western North America and attract special interest for being situated in alpine environments (fig. 10.1). While popularly understood as describing high mountain areas in general, "alpine" technically refers to environments above temperate-zone tree lines, that is, areas unable to support development of upright tree forms due to harsh conditions. As a result, instead of upright trees, cold-adapted and often ground-hugging vegetation characterizes the alpine zone. Although ecologists long assumed that tree lines were related to weather and climate, the exact nature of the constraints—whether temperature, precipitation, soil, snowpack, and/or wind, and how these constraints varied for alpine tree lines globally—was poorly understood until quite recently.

Through systematic studies at tree lines around the world, ecologist Christian Körner described factors that consistently relate to limits of tree growth at high elevations. Körner and colleagues elaborated on those factors and ecological processes, emphasizing that they pertain to *climatic* tree lines, that is, environments where atmospheric conditions enforce the limits of tree growth (Körner and Paulsen, 2004; Körner, 2012; Paulsen and Körner, 2014). They distinguished this from locally acting *topographic* tree lines, conditioned, for instance, by avalanche chutes or cliffs that prohibit tree growth (Körner, 2012: fig. 2.5). Climatic tree lines were further described as the highest extent of trees growing at least 3 m in height and where trees grow close enough together to form more or less continuous canopies, thus excluding solitary outliers. Tree height, it turns out, is a critical factor that allows cano-

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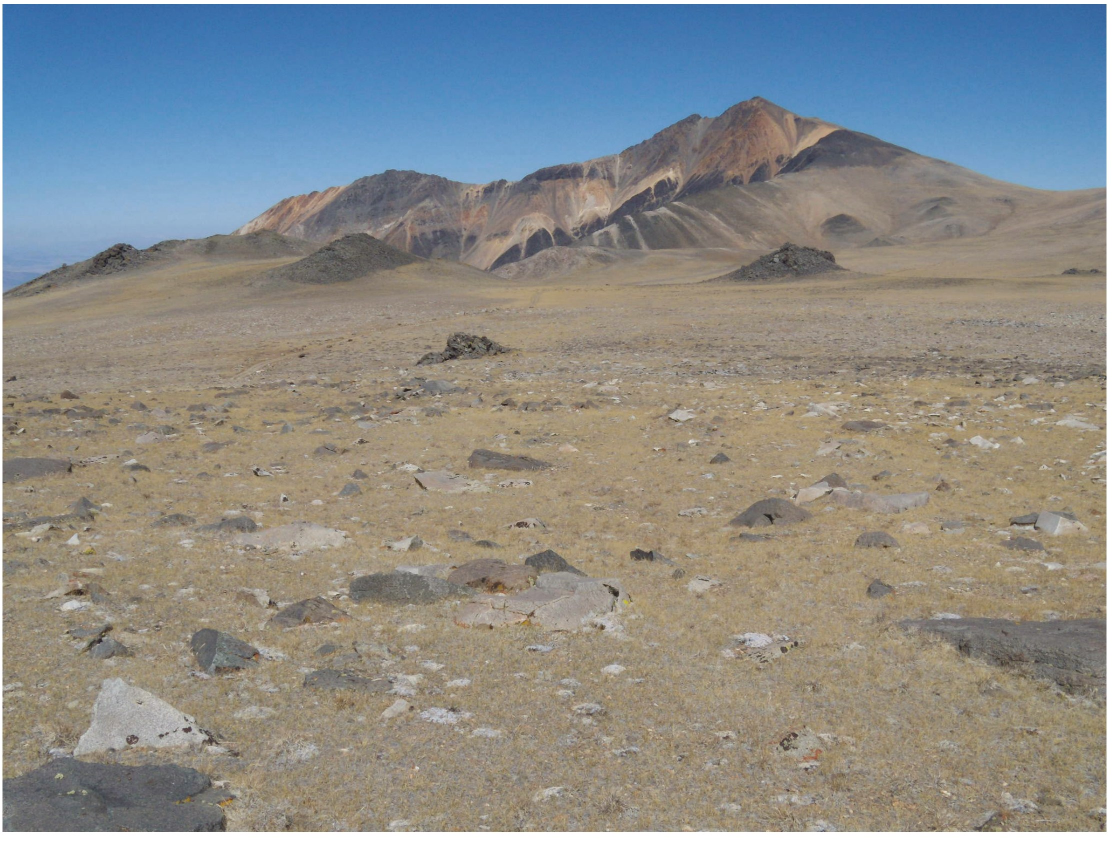

FIG. 10.1. Alpine village sites in the White Mountains, California, occur on the broad, treeless plateau beneath White Mountain Peak.

pies to couple to, and interact with, regional atmospheric circulation.

Given these conditions, Körner defined tree lines as occurring at the position on the landscape where a growing season of at least four months duration attains a mean temperature of 6.7° C (Körner and Paulsen, 2004). For mountain ranges experiencing Mediterranean climates, the mean critical temperature was slightly higher, 7°–8° C. While the exact mechanisms that limit upright tree growth at this threshold remain unclear, an inability of carbon-production processes to build the upright tree form appears to be the primary constraint. Individual trees sometimes occur scattered above this climatic tree line and often are limited to seedlings and saplings. Assuming that climate conditions are unchanged, however, individuals exposed to temperatures below the threshold do not persist to become tall upright trees (i.e., they die), or they develop into stunted, shrubby forms called *krummholz* ("embattled wood") that compose the uppermost "species line." For plants of low stature, growth processes and microclimates are different than those for the upright tree form, with microclimates decoupled from regional atmospheric circulation.

STUDY QUESTIONS

Recent visitors to the Mt. Jefferson plateau would observe that Alta Toquima, situated on a knob at the western edge of the summit plateau (3355 m), lies just above the extent of limber pine forests (*Pinus flexilis*; fig. 10.2). Mature trees grow

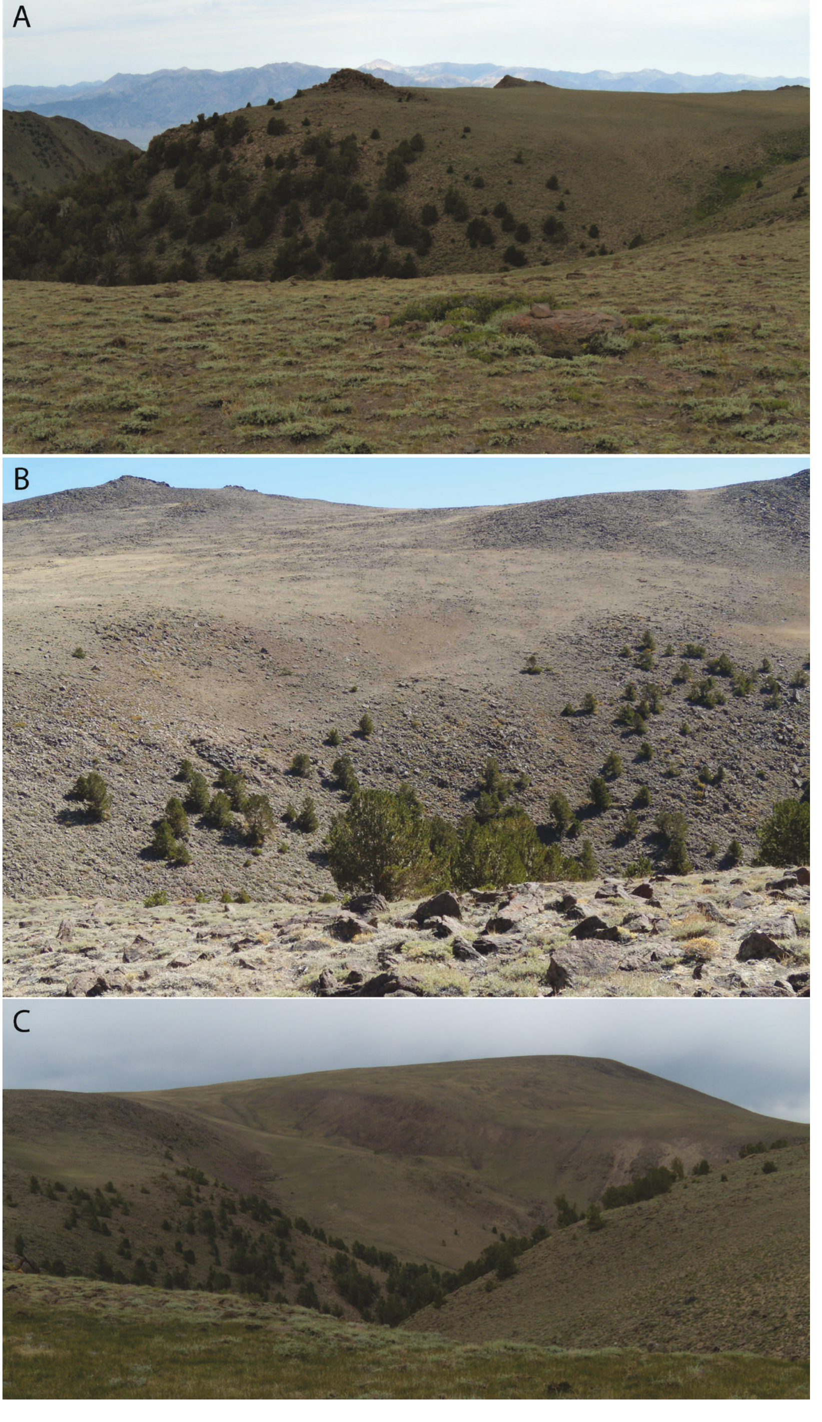

FIG. 10.2. Location of Alta Toquima in the upper Barker Creek watershed and just above the growth of limber pines: **A.** View of Alta Toquima from the east; Toiyabe Range with Arc Dome in the background (July 2014). **B.** View from Alta Toquima toward the southeast to Barker Creek headwaters (September 2008). **C.** View south down Barker Creek from springs; Alta Toquima is to the right (July 2014).

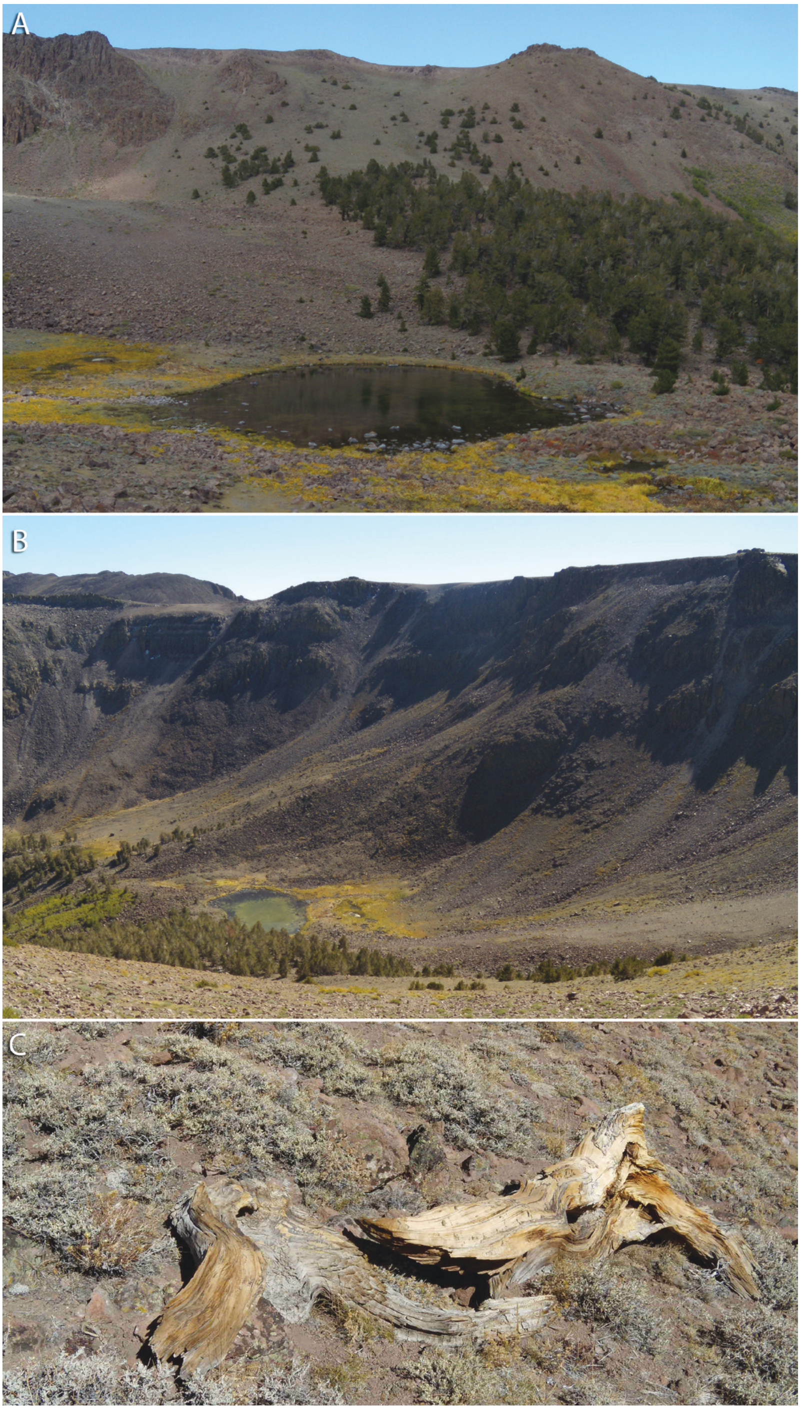

FIG. 10.3. Location of Dakabah in the cirque base of the South Fork Pine Creek: **A.** View north across tarn toward current southern aspect upper subalpine forest context for the site (September 2011). **B.** View south from the northern crest of the cirque, with mature upper subalpine forest sheltering Dakabah at left center (September 2010). **C.** Remnant wood on the southern aspect slope.

on the slopes below Alta Toquima, while young pines occur in the area of the cultural site to 3365 m. The alpine plateau of Mt. Jefferson expands north and east of Alta Toquima. Dakabah, by contrast, sits on the east side of the range, in the base of the South Fork Pine Creek cirque (3295 m). At present, Dakabah is within, but at the edge of, dense upper subalpine forest (fig. 10.3). Adjacent to and above the site, all but the south-aspect cirque walls are currently treeless. On the south-aspect cirque slope, young limber pines are establishing to 3500 m, and abundant remnant deadwood is scattered on the slope below.

This study addresses several questions:

(1) How much, if at all, has the extent of pines changed in the vicinity of Alta Toquima, Dakabah, and on the slopes around them over time?

(2) What is the relationship of limber pine in the vicinity of Alta Toquima and Dakabah to the climatic tree line and temperatures as described by Körner's (2012) thresholds?

(3) Can we apply information on prior climatic tree lines combined with contemporary temperature observations to approximate seasonal and annual temperatures at Alta Toquima and Dakabah during earlier periods?

(4) Do the ages and distributions of live and dead trees in the vicinity of the sites provide insight into resource use by Alta Toquima and Dakabah residents?

METHODS

To gain insight into the distribution of trees over time in the vicinity of the two sites, in 2008 and 2010, I sampled and dated live and dead mature limber pine stems near the cultural sites and along elevational transects, below Alta Toquima and above Dakabah. I used standard field tree-ring methods, as described by Graybill (appendix D: https://doi.org/10.5531/sp.anth.0104) and Holmes et al. (1986), to obtain increment cores from live trees and remnant wood. At Alta Toquima, I sampled 30 stems below the site extending from 3346 m to 3264 m along the southeastern aspect slope below the site. At Dakabah, I sampled 30 stems extending from near the village site at 3293 m to 3410 m on the southern aspect slope of the cirque. Cores were brought to the laboratory, processed, and dated using standard cross-dating methods (Holmes, 1986). Because the deadwood core samples could not be dated, an additional 15 wood cross sections were collected from deadwood stems on the upper cirque slope at Pine Creek. When these also could not be cross-dated, 15 wood samples were sent to the U.S. Forest Service Carbon, Water and Soils Lab in Houghton, Michigan, for standard radiocarbon dating (using methods detailed in Millar et al., 2014). Calibrated date ranges for each sample were determined from $F^{14}C$ values using the IntCal calibration curve (Reimer et al., 2004) and the software program OxCal 4.1.7 (Bronk Ramsey, 2009). Date ranges are reported as 95% confidence intervals and take into account the analytical error associated with each measurement.

To establish when pine trees began growing above the current tree line at Alta Toquima and Dakabah, I counted branch nodes of young limber pine trees that were <5 cm diameter at 0.5 m height (using dating methods in Millar et al., 2004). These juvenile trees were located on the knob at Alta Toquima and extended around the archaeological cultural site, from 3340–3356 m. At Dakabah, juvenile trees were high on the southern aspect slope of the South Fork Pine Creek cirque, from 3370–3480 m.

In addition to samples collected to date live and dead trees, abundance of deadwood was estimated for the cultural sites and along elevational transects below Alta Toquima and above Dakabah. The transects were divided into 0.01 ha plots, 5 m wide (parallel to slope) × 20 m length (perpendicular to slope). Only downed wood (stems on the ground) and stems that had lost bark and fine branches were counted, and only remnants with stems >15 cm diameter and >0.5 m length were included. Sizes of the deadwood remnants were not measured.

For purposes of other studies, I have been measuring modern temperatures along elevational transects of the South Fork Pine Creek watershed of the Toquima Range with minidataloggers (iButtons, Maxim, device type 1921 and

TABLE 10.1

Ages and Dates of Limber Pine in the Toquima Range

Age of live limber pines and inner-ring dates of live and dead stems cored at and around alpine villages in the Toquima Range. Dates are calendar years. Line breaks separate apparent age clusters at sites.

Upper Barker Creek (Alta Toquima Vista)				
Tree number	Live or Dead	Elevation (m)	Inner Ring (year)	Age in 2019
ATV-E 1	Live	3346	1928	91
ATV-E 2	Live	3344	1850	169
ATV-E 3	Live	3344	1888	131
ATV-E 4	Live	3341	1788	231
ATV-E 5	Live	3340	1873	146
ATV-E 6	Live	3342	1845	174
ATV-E 7	Live	3334	1781	238
ATV-E 8	Live	3335	1922	97
ATV-E 9	Live	3329	1938	81
ATV-E 10	Live	3326	1927	92
ATV-E 11	Live	3306	1928	91
ATV-E 12	Live	3302	1923	96
ATV-E 13	Live	3299	1922	97
Subtotal		*3330*	*1885*	*133.8*
ATV-E 14	Live	3296	1768	251
ATV-E 15	Live	3296	1608	411
ATV-E 16	Live	3292	1608	411
ATV-E 17	Dead	3292	1608	na
ATV-E 18	Dead	3286	1744	275
ATV-E 19	Live	3280	1742	277
ATV-E 20	Dead	3277	1632	na
ATV-E 21	Dead	3271	1621	na
ATV-E 22	Live	3274	1601	418
ATV-E 23	Dead	3268	1599	na
ATV-E 24	Live	3269	1604	415
ATV-E 25	Live	3266	1645	374
ATV-E 26	Dead	3264	1669	na
Subtotal		*3279*	*1650*	*254*
Total		**3305**	**1768**	**217.4**

TABLE 10.1 *continued*

South Fork Pine Creek Cirque (Dakabah)				
Tree number	Live or Dead	Elevation (m)	Inner Ring (year)	Age in 2019
Pine Cr 1	Live	3293	1623	396
Pine Cr 2	Live	3300	1633	386
Pine Cr 3	Live	3298	1644	375
Pine Cr 4	Live	3302	1655	364
Subtotal		*3298*	*1639*	*380.3*
Pine Cr 5	Live	3311	1780	239
Pine Cr 6	Live	3317	1788	231
Pine Cr 7	Live	3314	1795	224
Pine Cr 8	Live	3319	1790	229
Pine Cr 9	Live	3315	1779	240
Subtotal		*3315*	*1786*	*232.6*
Pine Cr 10	Live	3326	1885	134
Pine Cr 11	Live	3322	1874	145
Pine Cr 12	Live	3320	1880	139
Pine Cr 13	Live	3330	1890	129
Pine Cr 14	Live	3327	1883	136
Pine Cr 15	Live	3331	1894	125
Pine Cr 16	Live	3331	1892	127
Subtotal		*3327*	*1885*	*133.6*
Total		**3316**	**1793**	**226.2**

1922; the first year 1921Z units were used, which do not record <-5° C). These were programmed for four-hour intervals, starting at noon, midsummer 2008 and exchanged annually. Two locations are relevant to the present study, that is, within the subalpine limber pine forest at the tree line near Dakabah (3263 m), and near the upper limber-pine species line on the southern aspect of the cirque above Dakabah (3436 m).

Dataloggers were hung at 1.8 m height in shaded tree canopies and further protected in radiation shields. I used the criteria of Paulsen and Körner (2014): at least 94 days with a daily mean temperature >0.9° C and a mean of 7.5° C across days, as the thermal threshold for the upper tree line, substituting a mean temperature of 7.5° C rather than 6.4° C for tree lines in Mediterranean regions (Körner and Paulsen, 2004). To estimate how this threshold compared with current temperatures at the tree line in the cirque (at Dakabah) and at the upper species line, I calculated the number of days (as above) with temperatures ≥7.5° C using the datalogger records.

RESULTS

Tree Ages and Deadwood at Alta Toquima

Counts of 40 young limber pines in and above Alta Toquima indicated a mean age of 34.8 years (relative to 2019) with a standard deviation (SD) of 10.1 years. Establishment was episodic, concentrated between 1973–1997, and no seedlings <15 years old were found. Young pines occurred on all aspects, with S-SE favored.

TABLE 10.2

Calibrated Ages of Toquima Range Limber Pine

Calibrated ages from radiocarbon assessments of limber pine wood above current treeline, South Fork Pine Creek cirque, Toquima Range. Calibrated ages based on IntCal13 calibration curve (Bronk Ramsey, 2009; Reimer et al., 2013).

Sample Number	**CAMS Number**[1]	**Elevation (m)**	**^{14}C age (B.P.)**[2]	**Calibrated Age (cal A.D.)**[3]
A	155587	3368	1845 ± 40	A.D. 70–250
B	155588	3374	1825 ± 25	A.D. 125–250
E	155591	3473	1775 ± 25	A.D. 140–340
G	155593	3316	1665 ± 25	A.D. 270–420
H	155594	3383	1595 ± 35	A.D. 400–540
I	155595	3379	1485 ± 25	A.D. 540–640
J	155596	3375	1375 ± 25	A.D. 620–680
K	155597	3352	1355 ± 25	A.D. 640–760
L	155598	3319	1355 ± 25	A.D. 640–760
M	155599	3367	1340 ± 25	A.D. 650–760
N	155600	3339	1320 ± 25	A.D. 650–760
O	155601	3338	1240 ± 25	A.D. 690–870
C	155589	3436	280 ± 30	A.D. 1570–1800
D	155590	3475	255 ± 25	A.D. 1520–1800
F	155592	3382	155 ± 25	A.D. 1670–1880

[1] Sample numbers from radiocarbon measurements conducted at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Lab, Livermore, California.
[2] ^{14}C age is in radiocarbon years using the Libby half-life of 5568 years and following the conventions of Stuiver and Polach (1977).
[3] Calibrated age ranges are the 95% confidence interval of fitted data and include analytical error.

TABLE 10.3

Mean Temperatures Recorded at Treeline and Species Line

Mean temperatures summarized from datalogger records, 1.8 m height, at limber pine treeline near Dakabah (3263 m) and at upper species line (3436 m) at South Fork Pine Creek cirque, Toquima Range. DJF = December, January, February; JJA = June, July, August. Records summarized over 2010–2018.

Position	Mean Annual	Mean Annual	Mean Annual	Mean DJF	Mean DJF	Mean DJF	Mean JJA	Mean JJA	Mean JJA
	T (°C)	Tmin (°C)	Tmax (°C)	T (°C)	Tmin (°C)	Tmax (°C)	T (°C)	Tmin (°C)	Tmax (°C)
Treeline	2.3	-1.2	6.1	-5.4	-8.3	-2.5	11.9	7.8	16.6
Species line	1.0	-2.3	5.1	-6.2	-9.1	-3.0	10.6	6.9	15.3

Mature live and dead limber pines below Alta Toquima reflected a relatively short series given the lifespan capacity of the species (~1500–1700 years); despite the shorter lifespan, most cores reached the pith (birth year). Overall, the live trees had a mean age of 217.4 years (relative to 2019), with a mean inner-ring calendar date for all samples of 1768 (range, 1601–1922; table 10.1). Trees sampled above ~3300 m (live) had a mean age 133.8 years and a mean inner-ring date of 1885 (range, 1781–1938). Samples below ~3300 m (live and dead) were older, with a mean live-tree age 354.0 years and a mean inner-ring date for live and dead stems of 1650 (range, 1599–1768).

Deadwood was lacking on the slope between the Alta Toquima house rings and ~3300 m. Below that, deadwood stems and remnant pieces increased in abundance with decreasing elevation, averaging 3.7 pieces/0.01 ha (standard deviation [SD] = 4.3).

Tree Ages and Deadwood at Dakabah

Counts of 40 young limber pines on the upper southern aspect slope of South Fork Pine Creek above Dakabah indicated a mean age of 29.7 years (relative to 2019) with a standard deviation of 6.2 years. Although ages were slightly more spread than at Alta Toquima, recruitment ages indicate an episodic period of establishment, with dates clustered in the years 1979–1998. Again no seedlings younger than 15 years old were encountered. There were, however, scattered solitary trees on the upper slope that were too large to be accurately aged by the node-count method. While I did not core those trees, their small sizes, coupled with experience elsewhere in the Great Basin, suggest they are <100 years old (Millar et al., 2015).

As at Alta Toquima, mature live trees in the vicinity of Dakabah—and on the slope above it (southern aspect of the cirque)—were relatively young, with an overall mean of 226.2 years (relative to 2019) and a mean inner-ring date for all samples of 1793 (range, 1623–1894; table 10.1). These mature, live trees grouped into three apparent cohorts related to elevation. The oldest group was in and around Dakabah, which had a mean age of 380.3 years and a mean inner-ring date of 1639 (range, 1623–1655). Samples at midelevation of the mature tree stand were older, with a mean age of 232.6 years and a mean inner-ring date of 1786 (range, 1799–1795). The highest mature live trees were the youngest, with a mean age of 133.6 and a mean inner-ring date of 1885 (range, 1874–1890).

Although solid cores were retrieved from deadwood stems on the southern aspect slope above the mature forest in the cirque, I was unable to date them against local limber pine chronologies or other long regional records (e.g., bristlecone pine from the White Mountains). This was most likely due to the small number of rings in the series. Fifteen wood samples collected in 2011 (3316–3475 m) and sent for radiocarbon analysis returned calibrated ages ranging from cal A.D. 70–250 to cal A.D. 1670–1880 (table 10.2).

These dates were clustered in three age groups. The largest number of samples fell in the date range of ~cal A.D. 540–870 (seven samples); another group dated to ~cal A.D. 70–540 (five samples); the remaining were much younger, cal A.D. 1520–1880 (three samples). The first two groups overlap in radiocarbon dates, so I considered them as one cohort hereafter. Although the number of samples was small and no statistical relationships were found with elevation, the group of youngest trees grew at elevations above 3382 m, while the oldest samples were at midelevation on the slope (~3350 m).

Deadwood was relatively abundant in the Dakabah vicinity, with a mean of 6.8 pieces/0.01 ha (SD = 6.2) and mean 3.5 pieces/0.01 ha (SD = 5.2) on the upper cirque slope.

Modern Temperatures: South Fork Pine Creek Cirque

After deleting incomplete 2008 records, iButton dataloggers provided nine years of temperature data (2009–2018) at the upper limber-pine

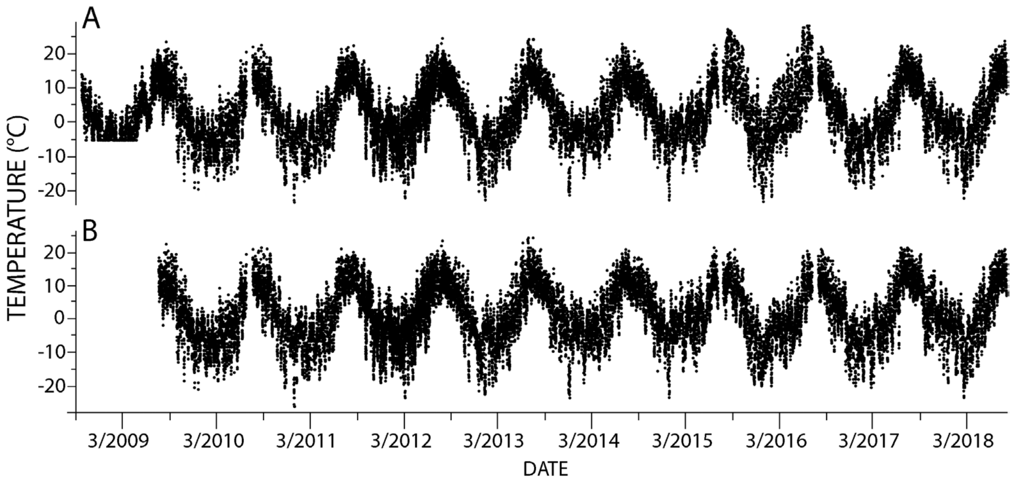

FIG. 10.4. Mean daily temperatures, 2009–2018, South Fork Pine Creek cirque: **A.** Current tree-line location near Dakabah (3263 m); **B.** Upper species line, southern aspect cirque slope (3436 m). Recorded with iButton Maxim, version 1921 and 1922, programmed for 4 hour intervals starting at noon.

species line (near the highest krummholz) and at the tree line (near Dakabah) in the South Fork Pine Creek cirque (table 10.3; fig. 10.4). Due to memory limitations of some instruments used (11.3 months) and collecting dates in subsequent years, short gaps occurred in records of some years. We used our highly correlated ($r > 0.95$) records from the same ecological and equivalent altitudinal positions in the White Mountains, Mono County, California (Upper Cottonwood Canyon and Crooked Creek) to cover the same time span to regress data into the Pine Creek record gaps. This allowed better estimation of temperatures for the nine years.

Using the Paulsen and Körner (2014) threshold criteria for the upper tree line, the Toquima records indicate 106 growing-season days and a mean of 12.2° C at the current upper tree line (Dakabah) and 93 growing-season days and a mean of 11.1° C at the upper species line. Mean annual temperatures over the nine recording years were 2.3° C (tree line) and 1.0° C (species line) with respective mean winter temperatures of -5.4° C and -6.2° C and respective mean summer temperatures of 11.9° C and 10.6° C (table 10.3).

INTERPRETATION

Prehistoric Forest Extent and Wood Use

The ages and distribution of live and dead limber pines currently in the vicinity of Alta Toquima and Dakabah provide insight into the environmental context and resource use near the cultural sites during past centuries. In reconstructing the forest extent, I made several assumptions. First, I assumed that undisturbed limber pine deadwood can remain on the arid landscapes of high Great Basin mountains for as long as 4000 years before decomposition (Millar et al., 2019). Although bristlecone pine (*Pinus longaeva*) deadwood in the White Mountains, California, has persisted for more than 10,000 years (Salzer et al., 2019), there is no evidence that limber pine has this durability. Fire would remove remnant wood, but I have found no evidence for landscape-scale fire in the upper limber pine forests of the Barker Creek or Pine Creek watersheds, which is similar to situations in other arid high-elevation Great Basin locations (Millar et al., 2015, 2019). Grayson and Millar (2008) proposed that wood for cooking and heating fires would be a rare resource for residents of alpine villages, readily harvested, and thus removed from the landscape, obliterating the record. I discuss that possibility below. The occurrence of remnant wood ~2000 years old above the current tree line in Pine Creek near Dakabah shows that limber pine deadwood can persist at least several millennia in the Toquima Range.

Several factors related to pine ecology are important for inferring prehistoric forest distribution. Establishment events in high-elevation Great Basin pines occur during episodic periods of climate favorable for seedling germination and persistence (LaMarche and Mooney, 1967; Millar et al., 2015). Once established, Great Basin pines such as bristlecone and limber pines have very high survival rates (>90% after the first few years; Barber, 2013), and individuals are able to persist throughout centuries of high climate variability (Millar et al., 2019; Salzer et al., 2019). Thus, correlations to climate are strongest for dates of establishment and weakest (or absent) during the subsequent lifetime of mature trees. Although annual radial growth has been used widely to reconstruct past climates (as Graybill infers, appendix D), radial growth does not strongly correlate with stand-establishment events (Smithers et al., 2017; Millar et al., 2019). That is, periods of high growth (implying favorable climate for growth) do not necessarily indicate times of forest establishment, and vice versa.

There is no evidence that the Mt. Jefferson summit plateau (>3380 m) has had forest cover (or even scattered tree growth) during the Late Holocene. From surveys, I have found no remnant wood on the plateau (other than obvious modern-transported sawn boards). By reasons of high elevation, the Toquima plateau appears to have been too cold for tree growth during the past 4000 years. Of equal importance, the plateau of the Toquima Range (as for other low-relief plateaus on high Great Basin ranges) imposes severe constraints even if temperatures were permissive. These constraints include thin, rocky soils with fine-grained clasts, no protection from direct solar radiation, extreme exposure to wind and storms, and resulting high evaporative stress and low soil moisture, which together combine to create conditions inimical for tree establishment. A similar situation occurs in the Wassuk Range and White Mountains, where we surveyed the high plateaus and found no remnant wood (Millar et al., 2015, 2019). Thus, during the three millennia of cultural occupation, the Toquima plateau has likely been in alpine condition (meaning above the tree line).

Below the plateau is a different matter. The upper slopes of the eastside cirques and upper Barker Creek watershed present conditions for climate to control tree growth, given deeper soils, protection from winds, and opportunities for relief from solar radiation due to aspect. On these slopes, we might expect shifts in tree-line elevation in response to climate changes over the past three millennia.

Consider first the forest extent and timing for South Fork Pine Creek cirque near and above Dakabah. Radiocarbon ages of deadwood on the southern aspect cirque slope above the archaeological site corroborate that the tree line has been higher in the past than the conditions we witness at present. Similar to findings for limber pine in the nearby Wassuk Range (Millar et al., 2019), prior occurrences of mature trees above the current tree line were episodic. At the Dakabah site, two periods of wood occurrence were ~cal A.D. 110–870 and ~cal A.D. 1520–1880, with a greater cluster of dates ~cal A.D. 625–870 and possibly a short gap ~cal A.D. 500–650. Reconstructions of paleoclimate for the last 3000 years in the central Great Basin (Millar et al., 2019; chaps. 29, 30), suggest that forests established above the current tree line during wetter intervals, and in particularly cool/cold-wet periods, if temperature was permissive.

The Late Holocene Dry Period (LHDP), an interval of ~950 years of extreme aridity in the Great Basin (Mensing et al., 2013) ended at the time when the oldest remnant wood period began, ~A.D. 150. While the available records for the central Great Basin are scanty for the centuries from the end of the LHDP to ~cal A.D. 900, what information does exist (and, by implication, extremes that are not in the record) suggests this period was relatively cool and precipitation was average to above average, with a glacial maximum in the Sierra Nevada at ~1600 years B.P. (Stine, 1994; Reinemann et al., 2009; Bowerman and Clark, 2011).

The end of the early above-tree-line deadwood record in Pine Creek cirque corresponds to the start of the Medieval Climate Anomaly (MCA), ~cal A.D. 850, a multicentury period of extreme aridity in the Great Basin (Stine, 1994). The deadwood record picks up 650 years later, ~cal A.D. 1500, which marks the start of the Little Ice Age (LIA), widely indicated in the Great Basin by glacial, lake sediment, river, and lake levels, pollen diversity, and tree-line elevation in the Sierra Nevada and White Mountains (references in Millar et al., 2019). Decreases in summer minimum temperature of 0.2–2° C and increases in winter precipitation of 3–26 cm relative to modern times have been interpreted to explain glacial conditions in the Sierra Nevada (Bowerman and Clark, 2011). Rapid cooling began ~cal A.D. 1600, with maximum cold ~cal A.D. 1700–1900; summers significantly cooler than the present persisted to ~cal A.D. 1930 (Feng and Epstein, 1994).

A widespread prediction is that mountain species move uphill with warming (Beniston, 2003; Körner, 2012), making the interpretation of past forest shifts upward with cool/cold-wet climate in the Toquima Range perhaps unexpected. In semiarid regions such as the Great Basin, however, moisture has repeatedly been found to be an important determinant of tree establishment (Crimmins et al., 2011; Millar et al., 2018, 2019). Southern aspect slopes, as in the Pine Creek cirque, may well have been warm enough during the past 3000 years for tree line advance (sensu Körner, 2012), but since they are drier than other aspects, they are more sensitive to precipitation and have lower available soil moisture (Stephenson, 1998).

Considering the cultural context during the earliest occupation of the alpine village at Dakabah, residents experienced extreme dry, if not excessively warm (Mensing et al., 2013), conditions of the LHDP, when the cirque walls above Snow Water Tarn were treeless. Around cal A.D. 110, seedling pines began advancing upslope on the southern aspect, growing to maturity; a mature forest appears to have persisted and become dense on the slope from cal A.D. 650–870. Around that time, as aridity increased, pines on the cirque walls began to die, leaving the slopes again barren of mature trees. With increasing cool and precipitation of the LIA, pine seedlings again established upslope and a mature forest appears to have persisted into the early historic period. The late 20th-century (1979–1998) expansion of pines after the cultural period includes trees growing at the highest elevation in the record. While this has been a warm period, precipitation relative to LHDP or MCA levels has remained high (Graumlich, 1993).

Considering the context at the cirque floor and in the vicinity to Dakabah, the forest most likely has been present through the past three millennia. The environment is well sheltered and, given discussion above and further below, likely temperatures have been above thermal tree-line thresholds throughout the late Holocene. By contrast to southern aspect slopes, soil water would likely be adequate to support tree establishment and forest growth, given low-relief and deeper soils (despite underlying ground-moraine rocky substrates). Cold-air drainage into the cirque base would reduce evapotranspiration pressures, further allowing persistence of pines. Studies in the high Sierra Nevada document changes in forest density corresponding to warm/wet versus cool/wet conditions (Dolanc et al., 2014). Thus, forests around Dakabah might have been sparser during the centuries of the LIA than at present—and potentially sparser also in cooler centuries prior to the MCA. The current ages of mature trees in the cirque-floor forests indicate establishment during the LIA and likely correspond to establishment dates for the last pulse of forest occurrence on the high cirque slopes prior to the 20th century.

What can be said about the use of pine stems as fuelwood by residents of Dakabah? The presence of very old remnant wood on the high southern slope of Pine Creek cirque as well as the abundance of deadwood in the forests around Dakabah suggests that cultural use for fuel did not obliterate the record. Although decomposition would reduce the size of deadwood over millennia, the small sizes of many of the old remnant pieces suggest that they were not avoided because they were rooted or too large to be used by residents. More likely, the large extent of limber-pine forest on the cirque floor and slopes below provided adequate fuel to sustain the small number of residents that appear to have inhabited Dakabah. This is unlike the alpine villages in the White Mountains, California, where large percentages of bone were used for fuel (Grayson, 1991), and any fuelwood available was likely rapidly expended.

Evidence from the South Fork Pine Creek cirque adds clues for interpreting forest extent on upper Barker Creek slopes and around Alta Toquima. The very different topographic setting for Alta Toquima relative to Dakabah exposed the former to much harsher weather conditions. Not only is Alta Toquima at the edge of the alpine plateau, but it is higher than Dakabah, perched on the verge of the western Toquima escarpment, and faces the dominant storm tracks. As discussed above, the Mt. Jefferson plateau is likely to have been above the tree line throughout the period of Alta Toquima occupation, meaning that alpine conditions were always at the backdoor. Shifting tree lines over the past centuries on the slopes of upper Barker Creek likely relegated the Alta Toquima site as alternatingly closer to, and farther from, the continuous forest below it. Lack of remnant wood around the village site or on the knob above it suggests that mature forest did not grow at this location in at least the past 3000 years. Even if all useful ancient remnant wood were removed for use by villagers (Grayson and Millar, 2008), any large snags that occurred at the village would likely have persisted as relics, if rare (i.e., too large to use). The current expansion of young pines into the village site parallels the event high in the Pine Creek cirques; these pines extend above the elevation of any of the ancient deadwood. Thus, the view of the site one encounters at present, with shrubby young pines growing near the house rings, is unlikely to represent conditions during any of the cultural periods.

Similarly the lack of old deadwood within the mature current forest directly below Alta Toquima, combined with establishment dates of the live trees, suggests that the upper forest border has been near this site for only the past several hundred years. Above 3330 m, live trees established in the late cultural period (end of the LIA) show that mature forest might have been just below the village site as residents were last occupying—and vacating—it. In the slopes below 3330 m, live tree establishment dates to the LIA, paralleling the pulse at Dakabah and on the upper slopes of Pine Creek cirque. Lack of deadwood above 3330 m suggests either that remnant wood from an older forest was removed by villagers (or, more likely, given implications from Dakabah), mature forest did not extend this high in prior centuries. Deadwood increases in abundance below 3330 m, although none that was older than the LIA. Perhaps if additional samples had been sent for radiocarbon analysis from this location, the 1100–1900 year old pulse of forest might also have been found.

In sum, with high probability, the context of Alta Toquima faced an alpine plateau extending north and east from the site throughout the three millennia of occupation, whereas the village itself was at or just above mature forest. Forest boundary appears to have been closest to the site during the LIA centuries, while during the MCA and dry periods at the end of the LHDP, Alta Toquima was more likely situated in isolated alpine context, with forest at some distance below it.

Temperature Reconstruction

The 10-year records from the South Fork Pine Creek cirque at current upper tree line and upper species line yield information not only about current conditions but provide insight into temperatures during the prehistoric cultural millennia. Most relevant for that context are summer temperatures, given the season of use at the alpine villages. For comparison, the current 10 year mean annual temperature and mean summer temperature at Dakabah (2.3° C and 11.9° C, respectively) are approximately the same as temperatures measured in the Sierra Nevada for 1987–1999 at the Ellery Lake, California along SR 120, 2910 m, 3 km northwest of the Yosemite National Park, Tioga Pass boundary (2.6° C and 10.9° C; Western Regional Climate Center [WRCC], accessed June 6, 2019). Whereas Dakabah is currently situated at the upper tree line, the Ellery Lake location is considerably below the Sierran local tree line. Relative to the Körner (2012) threshold temperature for the upper tree line, the Dakabah site is ~5° C warmer (12.2° C vs. the 7.5° C threshold), and even the upper species line currently is ~4° C warmer (11.1° C). One explanation is that recent temperature increases have outpaced the ability of pines to reach equilibrium with the tree-line threshold temperatures. Significant increases (+0.2° C/yr; $p < 0.001$) observed in summer maximum temperatures for the 10 year cirque record support that possibility. Further, as discussed above, temperature appears to have less critical control on tree growth (within range) than precipitation/moisture availability.

What can be inferred about temperatures during the millennia before present? Using Great Basin regional paleoclimate proxies (summarized in Millar et al., 2014, 2019; see also chaps. 29, 30), the warmest and coldest intervals ranged approximately + 2° C and -2° C, respectively, relative to mid 20th-century means. The best-known cold interval in the past 3000 years, the LIA, is estimated as 0.2°–2.0° C colder for the Sierra Nevada (Bowerman and Clark, 2011). Assuming ~1.0° C increase in temperature since the mid 20th century (Millar et al., 2014 and references therein) at the Toquima residential sites, LIA summers might be expected to have had mean temperatures ~9.0° C. During warm intervals, such as the MCA, mean summer temperatures might have been as warm as ~13.0° C. This compares to 15.8° C interpreted for the MCA mean summer temperature at Whitewing Mountain, Sierra Nevada, California (Millar et al., 2006), which, at ~245 m lower than Dakabah, would be expected to be ~2.5° C warmer due to elevation (by standard lapse rate). For past centuries of the cultural period other than the cold and warm intervals, temperatures might have been comparable to those of the mid 20th century.

SUMMARY

Combining tree-ring data and modern temperature observations with paleoclimate proxies and ecological evidence from other Great Basin ranges provides insights into the environmental context of the alpine villages in the Toquima Range during the three millennia of occupation. Throughout this time, the Mt. Jefferson summit plateau above 3380 m, north and east of Alta Toquima and above Dakabah, appears to have been too cold and too harsh to have supported trees. The current alpine condition of the plateau, therefore, is likely to be similar to that in prior millennia. Alta Toquima is located at what appears to be a transition zone of upper pine tree line and alpine conditions. The current young pines established during the late 20th century in the cultural site and on the knob above the house rings are likely the highest extent of pine expansion for >3000 years, meaning the Alta Toquima occupation was likely to have been directly surrounded by alpine conditions (no trees). Mature limber pine forest, however, is likely to have been very close to (below) the cultural site on the slopes of the upper Barker Creek watershed, especially during cool-wet periods, such as the LIA, or warmer-wet periods. This alternated with lower tree line and mature forest ≤3330 m during dry periods, such as the MCA, LHDP, and possibly dry periods within the LIA. At other times, forest was likely intermediate in elevation.

Dakabah was most likely within mature subalpine forest throughout the past 3000 years, although forests might have been sparser than encountered in the early 21st century, and Dakabah was likely always near the edge of the forest. Above Dakabah, pine growth on the cirque walls was unlikely except the southern aspect slope. The pine tree line advanced upslope to near the cirque top (but not as high as pines that established in the late 20th century) several times, following the LHDP from ~cal A.D. 110–870, and again in the LIA, from ~cal A.D. 1515–1590. During dry intervals (MCA, LHDP), the southern aspect slopes were likely treeless.

Modern temperatures measured from 2008–2018 in the South Fork Pine Creek cirque yield mean annual temperatures of 2.3° C (Dakabah) and 1.0° C (upper cirque) and mean annual summer temperatures of 11.9° C (Dakabah) and 10.6° C (upper cirque). Interpolating from evidence for paleo-temperatures elsewhere in the Great Basin suggests that cold/warm extremes were +/– ~2° C for the MCA and LIA, respectively. Modern temperatures and inferences for past temperatures corroborate that thermal conditions were unlikely to constrain tree lines in the Pine Creek and Barker Creek watersheds and that moisture availability had the most influence on tree growth.

Abundance of downed remnant wood dating to ~cal A.D. 70 on the slopes above Dakabah, and old deadwood in the mature forests around Alta Toquima and Dakabah, suggest that villagers had adequate fuelwood to support their needs. The archival record of ancient wood (per Grayson and Millar, 2008) appears to be intact, although wood no doubt was removed for use during the cultural period, likely influencing at least density of remnant stems.

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